The effects of footwear on lower limb biomechanics in individuals with kne e pathology: A literature systematic review.

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Abstract

Background

Acute knee injuries and chronic knee pain are prevalent lower limb pathologies. These pathologies are often associated with abnormal lower limb biomechanics, reduced physical function and poor quality of life. Footwear has been advocated as an intervention for pathology affecting the knee due to its ability to alter lower limb biomechanics and loading at the knee joint. Footwear has been shown to influence lower limb biomechanics in healthy populations, however, it is unclear if these changes are seen in people with knee pathology. Therefore, the purpose of this study was to systematically review the current literature on the effects of footwear on lower limb biomechanics for people with knee pathology.

Methods

A search of electronic databases was undertaken in August 2022. Studies were eligible for inclusion if they reported on biomechanical findings of the use of footwear for knee pathology. Key exclusion criteria were studies where footwear was used in combination with removable insoles or orthoses, or those not investigating lower limb biomechanics. The methodological quality of included studies was assessed using the National Heart Lung & Blood Institute Study Quality Assessment Tools. Data extracted from the included studies was reported in tables and summarised qualitatively.

Results

2,800 studies were identified for screening with 36 studies included for this review. Most studies investigated knee osteoarthritis (32), but also included were patellofemoral pain syndrome (2), anterior cruciate ligament injury (1) and meniscus injury. Footwear interventions included minimalist footwear (12), laterally wedged footwear (2), variable stiffness footwear (10), motion-control footwear (4), cushioned footwear (3), rocker-soled footwear (5) and other footwear (2). For people with knee osteoarthritis, minimalist footwear and variable stiffness footwear were associated with significant reductions in peak knee adduction moment compared to participant's own footwear, other footwear and conventional footwear. Motion-control footwear was associated with lower medial tibiofemoral contact forces compared to minimalist footwear in people with knee osteoarthritis. For people with patellofemoral pain syndrome, minimalist footwear was associated with reduced patellofemoral joint stress and patellofemoral joint reaction forces compared to cushioned footwear. For people with anterior cruciate ligament injury, rocker-soled footwear was associated with increases in knee flexion. For people with meniscus injury, no differences in knee adduction moments were between laterally wedged, motion-control, cushioned and conventional footwear.

Conclusions

This systematic review has identified diversity in footwear interventions used in individuals with knee pathology to reduce knee loading. The results have shown that this conservative strategy may help to offload the knee joint slow disease progression at the knee. Further research is required to determine the most effective footwear intervention for people with knee pathology.

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Attestation of Authorship

‘I Fiona Lee here by declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning’.

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Chapter 1 : Introduction

1.1 Dissertation overview

This dissertation presents the results of a systematic literature review. This Chapter introduces knee pathology and knee mechanics and the use of footwear as an intervention for knee pathology. Chapter 2 presents a literature review of the effects of footwear on knee joint biomechanics in healthy populations. Results from this literature review helped to inform the aim for the current systematic literature review as outlined in Chapter 3. Chapter 4 details the methods adopted to perform the systematic literature review, while Chapter 5 presents the results. Chapter 6 discusses the findings of the review in relation to current practice and Chapter 7 concludes the dissertation.

1.2 Knee pathology and knee biomechanics

Approximately a quarter of adults suffer from knee pain, making the knee one of the most common sites of lower limb pathology [1]. Knee pathology can arise from a number of causes including acute sporting injuries, overuse injuries and degenerative changes, such as osteoarthritis [2]. Knee pathologies are associated with reduced physical function, and negatively affect activities of daily living and mental health [2]. The knee is an important load-bearing joint and helps control muscle movement while performing weightbearing tasks such as walking, running, and squatting [3]. The biomechanics of the knee primarily involve flexion and extension in the sagittal plane, with internal-external rotation between the tibia and femur in the frontal plane also contributing to the stability of the knee joint during walking [4]. Additionally, the knee adduction moment (the horizontal distance of the medial ground reaction force to the centre of the knee joint) is an important indicator of knee joint loading during weightbearing activities [4].

Knee pathology is associated with changes to lower limb biomechanics, including lower knee flexion angles and higher knee contact pressures [2]. Excessive knee joint contact pressures during weightbearing activities may contribute to the development and progression of knee pathology including osteoarthritis and patellofemoral pain syndrome (PFPS). Knee osteoarthritis affects almost 40% of older adults, with the medial compartment of the knee most affected (4:1 ratio compared to lateral knee) [5, 6]. Biomechanically, knee osteoarthritis is characterised by an increase in the external adduction moment acting at the knee joint [7]. Research has also shown that a 1% increase in the peak adduction moment increases the risk of knee osteoarthritis progression by 6.5 times [7]. Additionally, people with medial knee osteoarthritis display reduced walking speed, shorter step length, longer stance and double support time, reduced cadence, stride length and knee flexion, compared to controls [8].

PFPS is the most prevalent running pathology affecting about 3 to 15 % of runners [9]. In a healthy knee, activities involving larger degrees of knee flexion do not necessarily translate to pathological knee joint contract pressures [10]. People with PFPS display reduced knee flexion compared to healthy controls, which is an altered movement pattern used to lower knee joint contact pressure. Although this may be a strategy to reduce pain at the knee, it also alters the biomechanics of the knee [10], resulting in pathological compressive stress to the patella [9].

Knee ligament injuries are common in sports that involve jumping and rapid changes in direction, such as netball and basketball [2]. The anterior cruciate ligament (ACL) is the most injured ligament in the knee, with the mechanism of injury being valgus collapse in combination with external knee rotation [11]. People with an injured ACL demonstrate smaller peak knee flexion, increased patella-femoral contact force and greater peak knee adduction forces [12]. Additionally, the meniscus may also be injured when coupled with ACL injury, and is associated with increased tibiofemoral contact stress, reduced knee joint stability and reduced joint range of motion [13].

1.3 Footwear as an intervention for knee pathology

As abnormal biomechanics are associated with knee pathology, appropriate treatments targeted at improving lower limb biomechanics are essential. Non-surgical treatment options for knee pathology include exercise, bracing, taping, and footwear [14]. Footwear provides protection to the foot and can alter the lower limb biomechanics during weightbearing activities [6, 15]. Footwear is also associated with patient reported outcomes such as knee pain. While high-heeled footwear aggravates knee pain [16], appropriate footwear has been shown to reduce knee pain [17], by altering lower limb biomechanics. This is because stable supportive footwear can control excessive foot pronation leading to less internal rotation of tibia and have been shown to reduce the risk of developing knee pathologies, such as PFPS [18]. Footwear with laterally stiffer midsoles have been shown to significantly reduce medial knee loads through reduction of the external knee adduction moment (EKAM) [19]. Wedged footwear can reduce knee malalignment [20], and rocker bottom footwear working on the principle of natural instability have been shown to reduce loading at the knee joint and improve symptoms from knee pain [21]. Minimalist footwear has also been shown to reduce the EKAM and knee joint loading during walking [22]. These differences in reported findings makes it difficult to appreciate the effects of footwear for people with knee pathology, there is no comprehensive review evaluating the effect of various footwear on lower limb biomechanics in people with knee pathology.

Chapter 2 : Literature review of the effect of footwear on knee mechanics in healthy runners

2.1 Introduction

Recreational running is among the most popular physical activities and continues to grow in popularity [23]. With numerous health benefits, running five to ten minutes per day associated with reduced risk of cardiovascular disease and mortality [23]. However, running is associated with a high prevalence of developing lower limb injuries, with between 37-56% of runners developing injuries each year [24]. The knee is the most common site of injury, representing 40% of all running related injuries, and patellofemoral pain syndrome (PFPS) accounts for 46-62% of this [25]. PFPS is caused by abnormal patella tracking during knee flexion and extension, leading to pathological loading of the joint [26]. The pathological compressive stress to the patellar facets results from excessive knee frontal plane motion, rearfoot eversion, hip internal rotation and increased loading forces acting on the knee [9]. People with PFPS display reduced knee flexion compared to healthy controls and over 90% report difficulty with running [26] leading to restriction in participation in training activities. Typically, PFPS persists for many years, and it has been identified that 45-64% of patients with PFPS later present with knee osteoarthritis [27]. The management of running related injuries is multi-factorial, with interventions such as patellar taping, bracing, exercise prescription and footwear advocated to target abnormal biomechanics [28]. As the main interface between the runner's foot and the ground, footwear potentially plays a role in managing repetitive external mechanical loads applied to the knee [29, 30]. Running footwear contains characteristics that aim to provide comfort whilst offering biomechanical benefits [31], including cushioning to improve shock attenuation and lower impact on the lower limb [32], and stabilising features such as a firmer dual-density midsole and a wider heel flare to alter rearfoot biomechanics [18]. However, running in cushioned footwear has also been shown to increase forces acting at the knee [24, 32, 33] and regarding motion-control footwear, there is no direct evidence to support the link between excessive rearfoot pronation and PFPS during running [34]. In recent years, minimalist footwear has been suggested as a strategy to reduce knee joint stress [25], however, there is no clear answer about whether running in minimalist footwear is injury preventative or causative [35]. Whilst different footwear appears to influence running biomechanical and performance-related variables, it is difficult to appreciate the consistency of the literature [36]. Therefore, the aim of this review was to investigate the effects of footwear on knee joint biomechanics in healthy runners.

2.2 Search strategy

Electronic databases (MEDLINE, SCOPUS and CINAHL) were searched in September 2021. Inclusion was limited to studies published in in the last 10 years (from 2011 to 2021), due to the rapid technological advancements in running footwear design, and to reduce heterogeneity in the data synthesis [35]. The search strategy comprised of the following keywords: knee, *AND* run*, *AND* footwear or shoes.

Studies were included if they met the following criteria: participants over the age of 18 years; randomised trials, prospective studies or cross-sectional studies; studies reporting on biomechanical findings of footwear interventions in runners (including kinematic, kinetic data, temporal-spatial); peer-reviewed publications; and published in English. Studies were excluded if they: investigated outcomes not affecting the knee (such as the ankle or hip); investigated outcomes during walking; investigated runners with current lower limb injury; used a case study or case series design; reported findings where footwear was not standardised for participants; reported findings where footwear was used as a control condition for foot orthoses or gait analysis.

2.3 Results

2.3.1 Search results

A total of 773 studies were identified through the search. Following screening of the studies against the above inclusion/exclusion criteria, a total of 37 studies were included in the final review.

2.3.2 Study characteristics

A summary of the study characteristics is presented in **Table 2.1** and **Table 2.2**. Of the total 37 studies, 36 were cross-sectional studies [24, 27, 37-71], and one was a randomised controlled trial [72]. There were 728 participants across the included studies. Most runners were experienced with a running history ranging from 6 to 10 years and running volume ranging from 10 to 105 km per week. All participants were healthy runners with a BMI ranging from 21 to 24 kg/m^2 and age ranging from 18 to 65 years. Nineteen studies assessed outcomes at a self-selected running speed [27, 37-39, 41, 43, 47, 50, 52, 53, 58-60, 62, 64, 69, 71, 72], 18 studies assessed outcomes at a controlled running speed ranging from 2.22 m/s to 4.48 m/s [24, 40, 42, 44-46, 48, 51, 54, 55, 57, 61, 63, 65-68, 70]. Eighteen studies included male participants only [24, 27, 40, 41, 43, 45-47, 50, 52-54, 60, 61, 63, 65, 66, 68], six studies included female participants only [37, 42, 48, 51, 67, 71], and 12 studies included both men and women [38, 39, 44, 55-58, 62, 64, 69, 70, 72]. One study did not report the participants' gender [59].

Table 2.1 A summary of characteristics of included studies

Author (Year) [ref]	Study design	Sample size (F %)	Participant characteristics	Experimental condition	Footwear characteristics	
					Comparison	Footwear characteristics
*Wilhoite (*2021) [38]	Cross-sectional study	12(50)	Recreational runner - Age range: 18-45 - Age (yrs): 24.8 (8.4) - Height (m): 1.741 (0.097) - Weight (kg): 70.05 (9.3) - Running volume (km/wk): 26.4 (12.6) - Running History (yrs): 6.7 (2.4) Rearfoot strikers	Unclear length, indoor lab runway - Self-selected pace - 2.9 (0.3) m/s - 31 min Time between trial - 48-72 hrs Three trials in intervention shod	1) Own running shoe 2) Minimalist 3) Maximalist	1) Habitual shoes (8.2 (5.8) months) 2) Minimalist (Nike Flex) 3) Maximalist (Hoka One One).
Stoneham (2021) [39]	Cross-sectional study	15 (33)	Recreational runner - Age range: 18-45 - Age (yrs): 25 (6) - Height (m): 1.74 (0.1) - Weight (kg): 69 (10.9) - Running volume (km/wk): 26.4 (12.6) - Running History (yrs): 6.7 (2.4)	Indoor track running - Self phase - 30 min Time between trial - 24 hrs	1) Barefoot 2) Minimalist 3) Maximalist	1) Minimalist - Vivo Barefoot VR Stealth II - Non-cushioned - Highly flexible 4mm EVA sole - Thin mesh upper - 0mm heel-to-toe drop height 2) Maximalist shoe - Hoka One One Clifton 2 - An enlarged EVA midsole - 29 mm heel stack - 5 mm heel-to-toe drop

Sanno (2021) [40]	Cross-sectional study	18 (0)	Recreational runner - Age range: NR - Age (yrs): 24.4 (3.7) - Height (m): 1.83 (0.06) - Weight (kg): 77.1 (8.3) - Running volume (km/wk): long distance - Running History (yrs): NR Heel-strikerF	10 km treadmill runs - maximal effort - 3.6 (1.1) m/s Time between trial - 7days Two triasl in intervention shod	1) Racing flat 2) Cushioned running shoe	1) Racing flat - Adizero Pro 4 (Adidas AG, Herzogenaurach, Germany) - mass (g): 170 - MI: 60 - Bending stiffness (N/mm): 0.296 - Energy storage (J): 7.5 (63.9 %return) 2) Cushioned running shoe - Glycerin 10 (Brooks Sports Inc., Seattle, WA) - Mass (g): 340 - MI: 18 - Bending stiffness (N/mm): 0.864 - Energy storage (J): 12 (73.1 %return)
Kim (2021) [41]	Cross-sectional study	20 (0) BF 10 Shod 10	Recreational runner (BF/Shod) - Age range: NR - Age (yrs): 33.1/26.5 (9.1/1.5) - Height (m): 1.75/1.76 (0.1/0.02) - Weight (kg): 71.8/70.3 (9.6/3) - Running speed 5 km (km/h): 9-12 - Running History (yrs): NR Heel-striker	Familiarisation time: 7 min walk 5 km treadmill runs - self-selected speed	1) Barefoot 2) Own shoes	1) Barefoot 2) Own shoes -Cushioned, traditional shoe
Borgia (2021) [42]	Cross-sectional study	20 (100) Young age 10	Recreational runner (Yong (Y)/master (O)) - Age range: 18-35/45-65 - Age (yrs): 31.7/55.2 (3.02/6.70)	15-m runway - Preferred pace (C1)	1) Traditional shoes 2) Maximal cushioning shoe 3) Own running shoes	1) Traditional shoes - Brooks Ghost 7, TRAD 2) Maximal cushioning shoe

		Masters ages 10	- Height (m): 1.68/1.69 (0.1/0.12) - Weight (kg): 66.14/71.01 (11.94/13.7) - Running volume (mile/wk): 22.7/22.1 (14,21/13.37) - Running History (yrs): 13.6 (8.12)/23.6 (15.8) Heel-striker	- Controlled pace (C2): 4.0 ms ± 5 % in shod 8 trials		- Hoka One One Bondi 4, MAX 3) Own running shoes, OS
Weir (2020) [43]	Cross-sectional study	13(0)	Heathy recreational runner - Age(yrs): 24.0 (4.4) - Height (m): 1.78 (0.05) - Weight (kg/m2): 70.3 (7.8) - Running history: NR - Running volume (km/wk): Heel-strike runners	Treadmill running - 21 min in neutral shoe Time between condition - 2min Treadmill running - 21 min in neutral shoe or stability shoe	1) Neutral shoe 2) Stability shoe	1) Neutral shoe - Brooks Defyance 9, Seattle, WA 2) Stability shoe - Exact same construction with an added medial post - Brooks Adrenaline GTS-16, Seattle, WA
Borgia (2020) [44]	Cross-sectional study	15 (53)	Heathy recreational runner (M/F) - Age(yrs): 24.8/24.8 (3.7/3.6) - Height (m): 1.65/1.61 (0.09/0.04) - Weight (kg/m2): 67.6/57.7 (8.5/3.0) - Running history: at least 3 run/wk - Running volume (mile/run):20	Time for familiarization - 9 min Treadmill - 3.0 m/s - 10 min Time between condition - 5 min	1) Racing flat 2) Traditional neutral cushion 3) Ultra-cushioning	1) Racing flat MIN - New Balance 1400v3 2) Traditional Neutral cushioning shoe NEUT - Nike Air Zoom 3) Ultra-cushioning shoe UTRA - Hoka OneOne Bondi4

Yang (2019) [45]	Cross- sectional study	15 (0)	Recreational runners - Age range: NR - Age (yrs): 31.4 (6.6) - Height (m): 1.74 (0.063) - Weight (kg): 73.2 (9.8) - Running history (yrs): 4.6 - Running volume (km/wk): 20 Rearfoot striker No experience of BF running	Time for familiarization - 5 min Over ground three trial - 3.33 m/s (5 %) - 20 min Time between trial - 5 ~10 min	1) Minimalist shoe 2) Cushioned shoe	1) Minimalist shoe - INOV-8 Bare-XF 210 V2 - Weight (g): 227 - Heel drop (mm): 0 -Heel stack (mm): 3 - MI (%): 86 2) Cushioned shoe - Nike Air Zoom Pegasus 34 - Weight (g): 285 - Heel drop (mm):7 -Heel stack (mm): 30 - MI (%): 26
Richert (2019) [46]	Cross- sectional study	15 (0)	Recreational runners - Age range: NR - Age (yrs): 24.7 (1.8) - Height (m): 1.78 (0.059) - Weight (kg): 77.2 (6.4) - Running frequency (no/week): 1.3 (0.8) - Running time (min): 44.3 (22.5) Rearfoot striker (RFS)	Time for familiarization - self report to readiness (5min) Treadmill trial: four trials/ 32 attempts - 3 m/s for 3 min - 4 m/s for 1 min Time between trial - NR	1) BF 2) 12 HTD 3) 8 HTD 4) 4HTD	Standardized running footwear 240-269 g (New Balance Germany, Inc) - 12 HTD: model 880v4, sole thickness rearfoot 22 mm, sole thickness forefoot 10 mm - 8 HTD: model 890v5, sole thickness rearfoot 19 mm, sole thickness forefoot 11 mm - 4HTD: model 980v2, sole thickness rearfoot 16 mm, sole thickness forefoot 12 mm)

Langley (2019) [47]	Cross-sectional study	28 (0)	Recreational runners - Age range: NR - Age (yrs): 26 (7) - Height (m): 1.77 (0.05) - Weight (kg): 79(9) - Running frequency (no/week): 2-3 - Running time (min): NR	Time for familiarization - 10 min Treadmill trial - Self-selected pace 2.9 (0.6) m/s - 3 min - Data collect final 30 sec of each trial Time between trial - NR	1) Motion control 2) Neutral 3) Cushioned	1) Motion control (ASICS Gel-Forte, Kobe, Japan) - Weight (g): 377 - Heel drop (mm): 13 -Heel stack (mm): 39 2) Neutral (ASICS GT 2000 2) 3) Cushioned (ASICS Gel-Cumulus 15)
Jafarnezha (2019) [48]	Cross-sectional study	26 (100)	Recreational runners - Age range - Age (yrs): 24.1 (5.6) - height (m): 1.65 (10.2) - weight (kg): 64.2(12.1) - Running volume (wk): 2 or 3 times, 45 min - Running history (yrs): over 3 Excessive foot pronation (FPI>10, Navicular drop >10 mm	Time for familiarization - 10 min Runway with forced plate 5 times - 3.3 m/s Fatigue protocol on the treadmill - 6 km/h→1 km/h increase every 2 min→steady state running (exertion>13) Time between trial - 7 days	1) Anti-pronation shoes 2) Neutral running shoes	Heel height of 25 mm, a forefoot height of 12 mm, and a heel to toe drop of 13 mm. 1) Anti-pronation shoes - ASICS Women's GEL-Kayano 24 Running Shoe 2) Neutral running shoes - ASICS Women's GEL-Nimbus 19 Running Shoe
Karsten (2019) [72]	RCT	60 (51.7) 53 complete - BF 19 - Shod 18	Healthy active runners - Age range: 18-35 - Age (yrs): 25.4 (3.3) - Height (cm):176.3 (7.9) - weight (kg): 70.4 (10.5) - BMI (kg/m^2): 22.6 (2.1)	7 section 1w apart treadmill section Treadmill running with BF or shod - 15 min - 70% VO_2 max Balance task	Randomised group 1) BF 2) Footwear 3) Control	1) Interventional shoe Available cushioned running shoe Asics - 17, 10 mm heel drop - Neutral arch support -Mass (g) 336

		- Control 16	- Running volume (km/wk): NR - Running history: NR			2) Passive control group -own footwear
Frank (2019) [50]	Cross- sectional study	24(0)	Novice or trained runners (Novice/Trained) - Age range: - Age (yrs): 21/23.3 (2.71/5.82) - Height (m): 1.77/1.75 (0.06/0.05) - weight (kg): 75.8/68.3(9.8/5.1) - Running volume (km/wk): NR /61.7(28.2) - Running history -novice runner: less than 10km/last yr -trained runners: minimum of 30 km/wk No previous experience of BF or minimalist	Time for familiarization - RPE guideline - Until Rating of Perceived Exertion (RPE) 3 Treadmill running - Self-selected phase - 4 min Time between trial - NR	1) Minimal shoe - soft midsole 2) Minimal shoe- hard midsole 3) Traditional shoe- soft midsole 4) Traditional shoe- hard midsole	1) Minimal shoes - Stack height was 13m m - Heel to toe drop was 4 mm - Midsole stiffness: 40 Asker C (Soft)/70 (hard) - Nike 2) Traditional shoes - Stack height was 20 mm - Heel to toe drop was 12 mm. - midsole stiffness: 40 Asker C (Soft)/70 (hard)
Borgia (2019) [51]	Cross- sectional study	15 (100)	Recreational runners - Age range: NR - Age (yrs): 23.5 (2.2) - Height (m): 1.68 (0.19) - Weight (kg): 76.5 (4.5) - Running volume (mile/week): 20	Time for familiarization - NR Treadmill running - 3.0 m/s (5%) - 10 min Time between trial - 5 min	1) Minimal cushioning shoe 2) Traditional running shoe 3) Ultra-cushioning shoe	1) Minimal cushioning shoe MIN - New Balance 1400v3 - MI 52 % 2) Traditional running shoe TRAD - Nike Air Zoom Pegasus 32 - MI 24 % 3) Ultra-cushioning shoe UTRA - Hoka OneOne Bondi 4 - MI 12 %
Besson (2019) [37]	Cross- sectional study	15 (100)	Recreational runner - Age range: - Age (yrs): 23 (6)	Time for familiarization - 5 min - treadmill	1) D_0 2) D_6 3) D_{10}	1) D_0 - Shoe drop 0 mm - thickness 25 mm

			- Height (m): 1.63 (0.05) - Weight (kg): 56.7 (6.0) - Running volume (km/wk): NR - Running History (yrs): NR Heel-striker	15m runway - preferred running speed - 4 min - 5 trials Time between trial - NR		- 246g 2) D_6 - Shoe drop 0 mm - thickness 25 mm - 242g 3) D_{10} - Shoe drop 0 mm - Thickness 25 mm - 236 g
Kulmala (2018) [24]	Cross-sectional study	12(0)	Recreational runner - Age range: NR - Age (yrs): 27 (5) - Height (m): 1.79 (0.04) - Weight (kg): 75 (6.0) - Running volume (km/wk): NR - Running History (yrs): NR Heel-striker	Time for familiarization - 400m warm-up - Treadmill 30m runway track - 10 (0.3) km/h - 14.5 (0.3) km/h - 3 trials Time between trial - NR	1) Maximalist 2) Conventional shoe	1) Maximalist - highly cushioned running shoe - Hoka one one - Heel drop (mm): 6 - Heel stack (mm)43 - Weight (g): 321g 2) Conventional shoe - Conventional cushioned running shoe - Brooks Ghost 6 - Heel drop (mm):12 - Heel stack (mm): 33 - Weight (g): 301
Sobhani (2017) [71]	Cross-sectional study	16 (100) - RF 100 - MF 100	Endurance runners - Age range: 18-55 - Age (yrs): 24 (3) - Height (m): 1.71 (0.06)	Time for familiarization - NR 22 m runway with two force plates - preferred running speed	1) Standard shoes 2) Rocker shoe	1) Standard running - Location of apex: 65% of the shoe length - Weight (g): 541 (44), a pair

			- Weight (kg): 62 (8) - Running history: regular long-distance training - Running volume (km/wk): 10	- 9 min - 5 trials Time between trial - NR		2) Rocker shoes - Location of apex: 53% of the shoe length - Heel stack (mm):22 (0.1) - Weight (g):858 (44), a pair
Hashizume (2017) [52]	Cross-sectional study	10 (0)	Healthy runner - Age (yrs): 24.8 (3.6) - Height (m): 1.75 (0.05) - Weight (kg): 66.7 (8.7) - Running history: NR -Running volume (km/wk): NR	Time for familiarization - 10 min 40 m straight Runway - preferred running speed - 3 m/s - 5 trials Time between trial - 10min	1) Training shoes 2) Racing flat	1) Training shoes (motion control) - GT-2000 NEW YORK 4(ASICS, Hyogo, Japan) - Weight (g) 314 2) Racing flats - SORTIEMAGIC LT (ASICS, Hyogo, Japan) - Weight (g) 144
Jonathan (2016) [27]	Cross-sectional study	20 (0)	Recreational runner - Age range: NR - Age (yrs): 24.24 (3.21) - Height (m): 1.77 (0.12) - Weight (kg): 78.2 (6.32) - Running volume (km/wk): NR - Running History (yrs): NR	Time for familiarization - NR Runway with force platform - preferred running speed - 4 m/s - 5 trials Time between trial - NR	1) Conventional Footwear 2) Minimalist 3) Maximalist	1) Conventional footwear - New Balance 1260 v2, Boston, MA, USA -Mass (g): 0.285 -Heel thickness (mm): 25 -Heel drop(mm): 14 2) Minimalist BFIS - Vibram five-fingers, ELX, Concord, MA, USA -Mass (g): 167 -Heel thickness (mm): 7

						-Heel drop(mm): 0 3) Structured BFIS - Hoka One-One, France -Mass (g): 318 -Heel thickness (mm): 45 -Heel drop(mm): 6
Sinclair (2016) [53]	Cross- sectional study	15(0)	Recreational runner - Age (yrs): 23.5 (2.5) - Height (m): 1.75 (0.05) - Weight (kg/m2): 72.2 (6.7) - Running history: NR - Running volume (km/wk): 35 • heel-strike runners	Time for familiarization - 5min Runway with force platform - preferred running speed - 4 m/s - 5 trials Time between trial - NR	1) BF 2) Conventional Footwear 3) Minimalist BFIS 4) Structured BFIS	2) Conventional footwear - Saucony Pro Grid Guide II (Lexington, KY) 3) Minimalist BFIS - Vibram Five Fingers - Merrell Bare Access (Rockford, MI) - Inov-8 Evoskin (Durham, UK) 4) structured BFIS - Nike Free 3.0 (Beaverton) - Vivo barefoot Ultra (London, UK)
Fuller (2016) [54]	Cross- sectional study	26 (0)	Trained distance runner - Age (yrs): 30.0 (7.9) - Height (m): 1.79 (0.06) - Weight (kg): 75.3 (8.2) -Running volume (km/wk): 27 (15) A habitual rearfoot foot-strike pattern No experience running in minimalist shoes.	Time for familiarization - NR Overground running 40m runway - 18 (1.8) km/h - 5 trials Time between trial - NR	1) Conventional Footwear 2) Minimalist	1) The conventional shoe - Asics Gel Cumulus-14 - Mass (g) :318 - Heel drop (mm): 9 - Heel-stack height (mm): 32 2) The minimalist shoe - Asics Piranha SP4 racing flat - Mass (g): 125

						- Heel drop (mm): 5 - Heel-stack height (mm): 22
da Silva Azevedo (2016) [55]	Cross-sectional study	14 (14)	Recreational runner - Age range:18-40 - Age (yrs): 28.4 (7.3) - Height (m): 1.74 (0.06) - Weight (kg): 72.7 (7.8) - Running volume (km/wk): 88.3 - Running history (yr):7.7 • A habitual rearfoot foot-strike pattern • No experience running in minimalist shoes.	Time for familiarization - 5 min Treadmill running - 9 km/h - 10 min Time between trial - 2 min	1) Conventional shoe 2) Transition shoe 3) Minimalist shoe 4) BF	1) Conventional shoe (CS) - NB 759 - Mass (g) :280 - Heel drop (mm): 18 - Heel-stack height (mm): 45 2) Transition shoe (TrS) (traditional shoe) - NB 890 - Mass (g) :250 - Heel drop (mm): 12 - Heel-stack height (mm): 40 3) Minimalist shoe (MS) - NB Minimus MR 10BG - Mass (g) :209 - Heel drop (mm): 4 - Heel-stack height (mm): 25
Hurchison (2015) [56]	Cross-sectional study	14 (64)	Recreational runners - Age range - Age (yrs): 22.3 (2.3) - Height (m): 1.73 (0.13) - Weight (kg/m):68.9 (14.1) - Running history (yrs): NR - Running volume (km/wk): NR	Time for familiarization Underwent multiple practice trials 20m runway - run along a 20 m instrumented runway - 5 trials Time between trial	1) A neutral shoe 2) Neutral shoe with customised foot othotics 3) Neutral shoe with prefabricated foot orthoses 4) Stability shoe ASICS GEL Foundation	1) A neutral shoe ASICS GEL Pulse 2) Stability shoe - ASICS GEL Foundation

			• FPI>6			
Hollander (2015) [57]	Cross-sectional study	35 (37)	Recreational runners - Age range 18-45 - Age (yrs): 27.9 (6.2) - Height (m): 1.79 (0.084) - Weight (kg/m):73.4 (12.1) - Running history (yrs): 4.6 - Running volume (km/wk): 24.9 (10.9) No previous experience of minimalist Forefoot and rear foot strikers	Time for familiarization - walking on treadmill Treadmill running - 2.22 m/s, 2.78 m/s, 3.33 m/s	1) BF 2)Uncushioned minimalist shoes 3) Cushioned minimalist shoes 4) Standard running shoe	1) BF 2)Uncushioned minimalist shoes - Leguano (LEGUANO, St. Augustin, Germany) - Polyvinyl chloride midsole - Off set(mm):0 - Weight: 137 3) Cushioned minimalist shoes - Nike Free 3.0 (NIKE, Beaverton, OR, USA) - No arch supports -Off set (mm): 4 - Weight (g):189 4) Standard running shoe - Asics GT-2160 (ASICS, Kobe, Japan) - EVA arch support - Off set (mm): 12 - Weight (g) 314
Goss (2015) [58]	Cross sectional study	60 (38)	Recreational runners - Age range: NR - Age (yrs): 34.9 (8.9) - Height (m): 1.74 (0.08) - Weight (kg/m):70.9 (13.4)	Time for familiarization - 5 min Treadmill running - preferred shod - 4 min	(1) Traditional shoes and a rear–foot-strike pattern (TSR) (2) Minimalist shoes and anterior–foot-strike pattern (MSA)	1) Traditional shoes were defined as motion-control, stability, or cushioning shoes with a greater than 10 mm drop from heel height to forefoot height.

			- Running history (yrs): >6m of traditional or minimalist - Running volume (km/wk): NR Forefoot and rear foot strikers	- 5 trials	(3) Minimalist shoes and a rear–foot-strike pattern but self-reported anterior–foot-strike pattern (MSR)	2)Minimalist shoes were defined as any shoes that were very flexible, contained minimal supportive features, and had a heel-to-forefoot drop of 4 mm or less
Fredericks (2015) [59]	Cross-sectional study	26	Recreational runners - Age range :19-46 - Age (yrs): 26.5 (6.1) - Height (m): 1.71 (0.1) - Weight (kg/m):66.6 (11.3) - Running history (yrs): NR - Running volume (km/wk):28.5 (20.7)	Treadmill running - 2.5-4.0m /s - single trial Time between trial - day	1)Personal 2) Standardized traditional running shoe 3) Minimalist shoes 4) Barefoot.	1) Personal traditional running shoe (personal), 2) Standardized traditional running shoe (Nike Air Pegasus+ 27; Nike, Inc., Beaverton, OR) (TRS) 3) Minimalist running shoe (Vibram Five Finger KSO; Concord, MA) (MRS) 4) Barefoot without shoe (barefoot).
Chambon (2015) [60]	Cross-sectional study	12 (0)	Recreational runners - Age range: - Age (yrs): 21.8 (2.0) - Height (m): 1.82 (0.05) - Weight (kg/m):71.8 (5.9) - Running history (yrs): NR - Running volume (km/wk):28.5 (20.7)	Time for familiarization - 7 min Stiff instrumented treadmill - 7 min 15 m runway in which a force platform	1)Do 2)D4 3)D6 4)BF	Rearfoot midsole thicknesses 1) Heel drop 0 mm 2) Heel drop 4 mm 3) Heel drop 8 mm All shoes - Outsole thickness (3 mm of rubber) - Midsole hardness (EVA, 60 Asker C) - Forefoot midsole thickness (2 mm)
Sinclair (2015) [61]	Cross-sectional study	12 (0)	Military recreational runner - Age range: NR - Age (yrs): 26.3 (5.9) - Height (m): 1.75(0.06)	Ran across 22m lab - 4 m/s - 5 min - 5 trial	1) Military boot 2) Cross trainer 3) Running shoe	1) Military boot - Combat scale 95 - Polyurethane midsole - Heel stack (mm): 24

			- Weight (kg): 73.9 (5.2) - Running history: >3yrs - Running volume: NR •Rearfoot striker	Time between trial - 2 min		- Heel drop (mm):11 2)Army issue cross-trainer - PT-03 - EVA midsole - Heel stack (mm): 38 - Heel drop (mm): 15 3)UK running shoe - PT1000, UK gear, Warwickshire, UK) - EVA midsole - Heel stack (mm): 32 - Heel drop (mm): 12
Bonacci (2014) [62]	Cross-sectional study	22 (36)	Trained runners - Age range - Age (yrs): 29.2(6.0) - Height (m): 1.76 (0.07) - Weight (kg): 65.8 (8.8) - Running history: 10km/33min43s (best run records) - Running volume (km/wk): 105 (33)	Time for familiarization - 5 over ground running 20m runway indoor - self-selected speed (90% of best) - 5 min - 20 trial	1) BF 2) Neutral Footwear	1)Barefoot (no shod) 2)Neutral shoe - LunaRacer, Nike -Weight (g): 184.2 (19.4) -Heel stack (mm): 24 -Heel drop (mm): 6
Willy (2014) [63]	Cross-sectional study	14 (0)	Recreational runners - Age range: 18-35 - Age (yrs): 24.8 (3.2) - Height (m): NR - Weight (kg/m): NR - Running history (yrs): NR	Treadmill - 3.35m/s - 10 min	1) Standard cushioned shoe 2) Minimalist shoe	1) Standard cushioned shoe - A Nike Pegasus (Nike, Beaverton, OR) - Heel insole heights of 36.3 mm - Stiffness values of 64.5N/mm[1] 2) Minimalist shoe - Nike Free 3.0

			- Running volume (km/wk): 31.9 (10.5) Rearfoot striker			- Heel insole heights of 17.6 mm - Stiffness values of 88.2 N/mm[1] Standard shoe provided 31 % greater cushioning than the minimalist shoe.
Thompson (2014) [64]	Cross-sectional study	11 (45)	Recreational runners - Age range: NR - Age (yrs): 29 (5.6) - Height (m): 1.63 (0.12) - Weight (kg/m): 62.6 (12.1) - Running history (yrs): NR - Running volume (km/wk): NR	Time for familiarization - 5-10 min Treadmill running 2 sections - Self-selected speed - Stride length was controlled (tape placed along the runway) - 5 trials Time between section - 24h	1) Barefoot 2) Shod conditions.	1) Barefoot (no shod) 2) Shod conditions - Own shoes
TenBroek (2014) [65]	Cross-sectional study	10 (0)	Recreational runner - Age range 18-55 - Age (yrs): NR - Height (m): NR - Weight (kg): NR - Running history: NR - Running volume: NR • Rearfoot striker	Time for familiarization - treadmill warm up Treadmill running - 3m/s, 30min Time between section - 1 day	1) THIN, 2) MEDIUM 3)THICK midsoles	Thin/Medium/Thick - New balance - Same lightweight upper, pliable heel counter and slabs of ethylene-vinyl acetate (EVA) midsole with an average hardness of 61 Asker C - Forefoot thickness (mm) 3/9/12 - Rearfoot thickness (mm)3/14/24 - Heel-forefoot difference (mm) Midsole 0/5/12

						- Width (mm) Mass (g)164/200/237
Chambon (2014) [66]	Cross-sectional study	15 (0)	Recreational runner - Age range - Age (yrs): 23.9 (3.2) - Height (m): 1.77 (0.03) - Weight (kg): 73 (8) - Running history: NR - Running volume: NR	Time for familiarization - 3 min 15 m runway - 3.3m/s (5%) - 5 trials	1) no midsole (0 mm), 2) 2 mm, 3) 4 mm, 4) 8 mm 5) 16 mm	No heel counter, outsole thickness (3 mm of rubber). The midsole had the same thickness under forefoot and rearfoot parts (i.e., 0 mm heel to toe drop). Midsole hardness (60 Asker C). Midsole thicknesses: 1) no midsole (0 mm), 2) 2 mm, 3) 4 mm, 4) 8 mm 5) 16 mm
Lilley (2013) [67]	Cross-sectional study	30 (100)	Recreational runners young/mature - Age (yrs): 21.2/49.7 (2.1/3.7) - Height (m): NR - Weight (kg): 60.5 /58.2 (7.8/5.1) - Running history: more than 3yrs - 10km time (min) 56.5/58.5 (5.2/9.5) -Running volume (km/wk): NR	Time for familiarization - NR 10m concrete runway - 3.5 m/s Time between section	1) Neutral shoes 2) Motion control shoes	1) Neutral shoes - Supernova Glide (Adidas) - Weight (g) 314 2) Motion control shoes - Adidas Supernova Sequence (Adidas) - Medial device prevents over pronation.
Lewinson (2013) [68]	Cross-sectional study	9 (0)	Healthy and physically active runner - Age: 25.2 (2.9) - Height (m): 1.776 (0.075) - Weight (kg/m2): 76.3 (5.1)	30m runway - 4.0 m - 5 to 15 trial Time between section	Medial wedges (mm) 1) 3 2) 6 3) 9	A commercially available long distance running shoe. - Adizero Aegis 2.0; adidas, Herzogenaurach, Germany

			- Running history: NR - Running volume (km/wk): NR Heel-strike runners		Lateral wedges 4)3 5)6 6) 9	All experimental wedge conditions were prepared by placing a wedged insert under the sock liner of this control shoe
Grewal (2013) [69]	Cross-sectional study	12 (50)	Recreational runner - age (yrs): 22.2 (2.2) - BMI (kg/m²) 21.4 (2)	Overground running outside of a gait laboratory (better replicate the natural environment of runners). - Levelled track 800 feet - BF - Own shod	1) Barefoot 2)Own shod	1) Barefoot (no shod) 2)Own shod
Bonacci (2013) [70]	Cross-sectional study	22 (36)	Highly trained runner - Age range - Age (yrs): 29.2 (6.0) - Height (m): 1.76 (0.07) - Weight (kg): 65.6 (8.8) - Running history: 7.6 section/week - Running volume (km/w): 105.3 (33.5)	Warm up - 5 overground running trial 110m indoor running track - 90 % of best speed (10km) - 4.48 (1.6) m/s - 10 over ground running trial	(1) Barefoot (2) Minimalist shoe (3) Lightweight racing flat (4) Regular shoe	(1) Barefoot (2) Minimalist shoe - NIKE Free 3.0 - Offset (4 mm) - Lacks any motion control or stability features. - 195.5 (19.3) g (3) Lightweight racing flat - NIKE LunaRacer2 - Offset (6 mm) -184.2 (19.4) (4) Regular shoe - Own running shoe - 323.0 (63.4) g

RCT, randomised controlled trial; EVA, ethylene vinyl acetate; MI, minimalist index; BF, barefoot; JRF, joint reaction force; IC, initial contact; STC, stance phase; EMG, electromyography; JRF, joint reaction force; TRAD, traditional shoes; OS, own running shoes; MAX, maximal cushioning shoe; MIN, minimalist shoe, NEUT, traditional Neutral cushioning shoe; UTRA, ultra-cushioning shoe; HTD, heel-to-toe-drop; TO, toe-off; HR, heart rate; RPE, rating of perceived exertion; PFM, plantar flexion moment; COM, centre of mass; TrS, transition shoe ; CS, conventional shoe; MSA, minimalist shoes and anterior–foot-strike pattern; MSR, minimalist shoes and a rear–foot-strike pattern but self-reported anterior–foot-strike pattern; TSR, traditional shoes and a rear–foot-strike pattern; GRF, ground reaction force; COP-AJC, centre of pressure to ankle joint centre; PFPS, patellofemoral pain syndrome; KAAI, knee adduction angular impulses; NR, not reported; yrs, years; wk, week.

Table 2.2 A summary of outcomes and findings of included studies

Author (Year) [ref]	Kinetic outcomes	Kinematic outcomes	Other outcomes	Findings
Wilhoite (2021) [38]	Not reported (NR)	No significant footwear effects on knee kinematics over prolonged running (p > 0.05)	NR	There were no differences in ankle and knee sagittal or frontal plane kinematics between minimalist, habitual, and maximalist footwear during a 30-minute run (p > 0.05).
Stoneham (2021) [39]	Peak knee flexion moment: significant - BF< minimalist<maximalist (p = 0.015) Peak dorsiflexion moment: significant - BF=minimalist >>maximalist (p = 0.001)	NR	Spatiotemporal - no significant shoe effect in speed - Main effect on stride length -significant increase in stride length in maximalist ; barefoot < minimalist<maximalist (p < 0.001)	Running in maximalist shoes increases stride length and loading at the knee joint (p ≤ 0 .001).
Sanno (2021) [40]	Negative work at the ankle: significant - Racing shoe>> cushioned shoe (P<0.001) Negative Knee joint work: significant - Racing shoe<< cushioned shoe Maximal ankle dorsiflexion torque at 0-km distance: no significant (p < 0.001) - Racing shoe> cushioned shoe	Ankle plantarflexion ankle at 0-km distance: significant - Racing shoe>> cushioned shoe (p < 0.001)	Spatiotemporal -significant shoe effect in step frequency (p < 0.001).	A typical racing flat shoe (with less cushioning material and lower longitudinal bending stiffness) and a typical cushioned running shoe do not differ in the fatigue-related redistribution of positive work from distal to proximal joints, despite small differences in the timing of the redistribution between shoes.

	Maximal ankle dorsiflexion torque decreased significantly ($p < 0.05$) over the entire run (2-10 km) for both shoe			
Kim (2021) [41]	Peak JRF (joint reaction force) of the hip and knee joints: significant - BF< shoe ($p < 0.001$) Ankle plantarflexion moment.: significant - Racing shoe<< cushioned shoe ($p < 0.001$)	After 5km intervention running - Hip abduction-adduction, hip extension-flexion, knee extension-flexion, ankle dorsi-plantarflexion: significant ($p < 0.001$). Barefoot running induced more knee flexion at initial contact (IC), reduced peak knee flexion at stance phase (STC), and less ankle dorsiflexion at STC compared to shod running.	EMG data in - Muscle activities and peak magnitude (barefoot running and shod running): similar - Muscle force (pre and post running): similar -Barefoot running has higher gastrocnemius forces than shod running, the mid-distance intervention led to a 3.2–5.6% reduction in gastrocnemius force for barefoot runners and 41–45 % increase for shod runners.	Peak JRF of the hip and knee joints were lower in barefoot running compared to shod running, with significant interaction effects that were primarily driven by group effects ($p < 0.0001$). After 5km intervention running muscle forces primarily reduced in the barefoot group and increased in the shod group following running. However, these effects were also driven by group effects.
Borgia (2021) [42]	Peak plantarflexion moment: - TRAD > OS >> MAX ($p = 0.036$) Generated power at ankle: - OS > TRAD >> MAX ($p = 0.006$)	NR	Joint stiffness at ankle and knee: No significant ($p=0.092$)	Ankle and knee joint stiffness values were similar between groups in the TRAD, MAX, and OS conditions
Weir (2020) [43]	NR	NR	No differences in leg stiffness between footwear conditions ($p > 0.05$). No differences between shoe conditions for knee joint stiffness ($p > 0.05$).	Over the course, leg stiffness is maintained, whereas knee stiffness increases and ankle stiffness decreases ($p < 0.05$).

Borgia (2020) [44]	NR	The general pattern of sagittal plane motion at the knee, frontal plane motion at the rearfoot, and transverse plane motion of the tibia was similar across all shoe conditions	During late stance ULTRA shoes resulted in more antiphase coordination than MIN ($p = 0.036$) or NEUT ($p = 0.047$) shoes and less in-phase coordination than MIN ($p = 0.048$) or NEUT ($p = 0.013$) shoes.	Late stance anti-phase coordination occurred more often while in-phase coordination occurred less often in the ULTRA shoes than either the MIN or NEUT shoes ($p < 0.05$).
Yang (2019) [45]	GRF: No significant different ($p > 0.05$) Peak knee extension moment, PFJC, PFJS: significant - Minimalist << Cushioned shoes ($p < 0.01$) Knee loading parameters in middle and late stance phase: significant - Minimalist << Cushioned shoes ($p < 0.05$)	Foot inclination angle: significantly reduced in MI 86% Knee flexion angle in middle and late stance phase: significant - Minimalist << Cushioned shoes ($p < 0.05$)	NR	Wearing high-MI shoes significantly decreases the patellofemoral contact force and patellofemoral joint stress by reducing the moment of knee extension, thus effectively reducing the load of the patellofemoral joint during the stance phase of running ($p < 0.05$).
Richert (2019) [46]	Vertical loading rate increased with a smaller HTD of 4mm compared to 8 mm and 12 mm Maximum ankle moment increased, and the maximum knee moment decreased with a reduced HTD of 4 mm compared to 8 mm and 12 mm.	Ankle and knee kinematics differed between running in shoes and BF Hip kinematics and kinetics did not differ between running in shoes and BF.	Spatiotemporal characteristics differed between running in shoes and BF - Step length: All HTD >> BF - Cadence: All HTD << BF	A lower HTD mainly altered the kinetics of the ankle and knee. Running with a low HTD did not lead to similar lower limb biomechanics as barefoot running.
Langley (2019) [47]	NR	The ankle dorsiflexion upon IC - neutral shoe >> motion control, cushioned shoes Peak ankle joint dorsiflexion	NR	The influence of motion control, neutral, and cushioned running shoes on joint function dissipates moving proximally, with larger changes reported at the ankle compared with knee and hip joints ($p < 0.05$). Although

		- neutral shoe >> cushioned shoe ($p < 0.05$) The ankle inversion at TO - neutral shoe >> motion control shoe ($p < 0.05$) Peak ankle joint eversion - motion control shoe >> cushioned shoe ($p < 0.05$) The ankle adducted upon IC - neutral shoe >> motion control shoe ($p = 0.03$) The ankle abducted upon IC - neutral shoe << motion control shoe ($p = 0.02$) The Knee flexion at TO - neutral shoe >> cushioned shoe ($p = 0.03$) The knee adducted upon IC - neutral shoe >> cushioned shoe ($p = .02$) The knee internal rotate at TO - cushioned shoe << motion control shoe ($p = 0.05$) No significant ($p > 0.05$) differences in hip joint		significant differences were reported between footwear conditions, these changes were of a small magnitude and effect size. The findings of this study demonstrate that different types of conventional running shoes significantly influence knee and ankle joint kinematics during the stance phase of running gait ($p < 0.05$).

Jafarnezha (2019) [48]	Fatigue-induced increases in peak knee flexor moment, peak knee internal rotation moment, peak hip extensor moment, and peak negative ankle joint power, irrespective of the used footwear ($p < 0.03$). Significantly smaller peak ankle dorsiflexor moments, peak knee extensor moments, and peak hip flexor moments as well as larger peak hip extensor moments when running with anti-pronation versus neutral shoes ($p < 0.01$).	Smaller peak ankle eversion angles when running with anti-pronation shoes compared with neutral shoes ($p < 0.03$). Lower peak positive hip power in sagittal plane, peak positive hip power in frontal plane, and peak negative hip power in horizontal plane in anti-pronation vs neutral shoes ($p < 0.03$). Fatigue-related increases in peak ankle eversion angle, irrespective of the used footwear ($p < 0.01$)	Comfort: no significant different Running speed: no significant different Blood lactate: no significant different HR: similar	No significant footwear by fatigue interaction effects for all measures of joint kinetics and kinematics.
Karsten (2019) [72]	After 8 weeks Habituation to BF or Shod - BF: increase of average ground-reaction force, and vertical average loading rate during landing ($p < 0.001$) - No changes were observed in an active group (8-week running intervention in new cushioned footwear) and a passive control group	NR	Foot strike index (After 8 weeks Habituation to BF or Shod) - BF: increase of foot strike index ($p = 0.042$) - no changes were observed in an active group (8-week running intervention in new cushioned footwear) and a passive control group	A habituation to barefoot running led to increased vertical average loading rates ($p < 0.001$).
Frank (2019) [50]	NR	NR	HR: not significant Stability: significant - Trained >> novice ($p < 0.001$)	It appears that midsole design within current design ranges do not have the ability to influence movement stability.

			Speed: significant - Trained >> novice ($p < 0.001$) Increasing both midsole stiffness and thickness did not influence local dynamic stability.	
Borgia (2019) [51]	Negative ankle joint work: significant - UTRA<<TRAD, MIN ($p = 0.015$) Negative knee and hip joint work - UTRA>>TRAD, MIN ($p = 0.001$)	NR	Leg and joint stiffness: no significant Foot strike patterns (FSP): significant - UTRA<< MIN, TRAD ($p = 0.001$)	No differences in leg stiffness between any of the shoe conditions. Compared to the MIN and TRAD shoes, in the ULTRA shoes the ankle performed less negative work while the knee and hip performed more negative work ($p \leq 0.015$)
Besson (2019) [37]	Higher force values were found for D_0 compared to D_6 and D_{10} ($p < 0.01$) The antero-posterior component presented significantly higher braking force values for D0 compared to D6 and D_{10} ($p < 0.01$) Knee external moment during the push-off phase: ($p < 0.05$) - D0 < D6, D10	No effect of shoe was found for knee or hip angles Ankle DF: significant ($p < 0.05$) - D0<<D6< D10 Ankle PF significant ($p < 0.05$) D0>> D6, D10 Foot/ground angle ($p < 0.05$) - D0<< D6, D10	NR	Reductions in shoe drop might minimize strain around the knee and be beneficial in reducing the risk of injury to this joint ($p < 0.05$).
Kulmala (2018) [24]	Highly cushioned shoes increase impact loading during running ($p < 0.05$).	NR	NR	Highly cushioned maximalist shoes amplify impact loading ($p < 0.05$). This finding was increased at faster running speeds (14.5 km/h).

	Highly cushioned shoes change the spring-like mechanics of running ($p < 0.05$).			
Sobhani (2017) [71]	Running with rocker shoes caused a reduction of 16% in the positive work (power generation) ($p < 0.001$), and a reduction of 32 % in the negative work (power absorption) ($p < 0.001$) at the ankle. Net work at the ankle remained unchanged ($p = 0.476$). At the knee joint the positive work and network increased with rocker shoes by 1 4% ($p < 0.001$) and 19% ($p = 0.036$), respectively, while the negative work remained unchanged ($p = 0.163$). At the hip joint, the network was the only variable which was affected by rocker shoes with a reduction of 17 % ($p = 0.005$) for this variable. Regarding the joint moments, running with rocker shoes significantly ($p < 0.001$) decreased plantar flexion moment (PFM) peak by 11 % (0.36 Nm/kg) and PFM impulse by 12 % (0.051 Nm s/kg). The hip flexion moment impulse was significantly decreased by 13 % ($p = 0.011$) with rocker shoes.	Significant change in the ankle joint - rocker shoes decreased the peak dorsiflexion by 7% ($p = 0.009$).	3% shorter stance time with rocker shoes ($p = 0.012$) compared with standard shoes.	Running with rocker shoes might help to decreases the load on the Achilles tendon ($p < 0.001$). Running with rocker shoes might increase the risk of overuse injuries of the knee joint. Midfoot strike runners seem to benefit more from the effects of a rocker shoes than rearfoot strikers.
Hashizume (2017) [52]	No difference was found in the negative work of the hip and ankle joints between training shoes and racing flats.	NR	NR	These results suggest a higher potential risk of muscle injury around the knee joint for training shoes than for racing flats.

	The negative work of the knee joint was significantly greater (by 12 %) for training shoes than for racing flats ($p = 0.017$). No difference in the moment between the different types of running shoes for the hip and knee joints was found. The plantar flexion moment of the ankle joint was greater for racing flats than for training shoes ($p < 0.01$)			
Jonathan (2016) [27]	Knee contact pressure was significantly greater in the conventional ($p < 0.001$) and maximalist ($p < 0.001$) footwear effect compared with the minimalist footwear Contact force impulse was significantly greater in the conventional ($p = 0.014$) and maximalist ($p < 0.001$) footwear compared with the minimalist footwear	Peak knee flexion was significantly larger in the maximalist ($p = 0.008$) and conventional footwear ($p = 0.009$) compared with minimalist footwear. Knee range of motion was significantly larger in the maximalist ($p = 0.002$) and conventional ($p = 0.001$) footwear compared with minimalist footwear. Ankle was significantly more plantar flexed in the minimalist footwear	The step length was significantly longer in the conventional ($p = 0.02$) and maximalist ($p = 0.03$) footwear.	Patellofemoral force per mile was significantly larger in conventional and maximalist as compared with minimalist ($p < 0.001$)
Sinclair (2016) [53]	Ankle excursion was larger in the BF and Inov-8 conditions compared with the CF, Nike Free, and Vivo footwear ($p < 0.05$). Ankle plantar flexor moments were larger in the BF and Inov-8 conditions compared with the CF and Nike Free footwear ($p < 0.05$).	BF condition was associated with a more plantarflexed ankle position at foot strike ($p < 0.05$) BF and Inov-8 conditions exhibited a larger peak dorsiflexion ($p < 0.05$)	Limb stiffness was larger in the BF, Inov-8, and Merrell conditions compared with the CF and Nike Free ($p < 0.05$). Knee stiffness in the BF condition was larger than the CF and Nike Free	Limb and knee stiffness were greater in BF and minimalist BFIS than in CF ($p<0.05$). CF and more structured BFIS were associated with a greater ankle stiffness compared with BF and minimalist BFIS ($p<0.05$).

	Knee excursion was larger in the CF and Nike Free conditions ($p < 0.05$). BF condition exhibited peak knee extensor moment was greater in the CF and Nike Free footwear in comparison with BF ($p<0.05$).	BF condition exhibited greater knee flexion at foot strike than the CF, Nike Free, and Vivo footwear ($p < 0.05$)	ankle stiffness was larger in the CF, Nike Free, and Vivo footwear compared with the BF and Inov-8 ($p < 0.05$). Limb compression was larger in the CF and Nike Free footwear ($p<0.05$).	Peak ankle plantar flexor moment was shown to be greater in BF and minimalist BFIS and peak knee extensor moment was shown to be larger in CF ($p<0.05$).
Fuller (2016) [54]	Greater negative ($p = 0.03$) and positive work ($p = 0.01$) at the ankle but less negative ($p = 0.03$) and positive work ($p = 0.046$) at the knee with minimalist shoes compared with conventional shoes.	Ankle angle at initial contact was less when running in minimalist	Running in minimalist caused a shift in foot-strike pattern toward a midfoot foot strike ($p = 0.03$). Strike index was greater when running in minimalist. Running in minimalist shoes increased the stride rate but decreased the contact time . Running in minimalist shoes decreased vertical displacement of the whole-body COM (COMvert).	Running in minimalist shoes at a fast speed caused a redistribution of work from the knee to the ankle joint ($p = 0.03$).
da Silva Azevedo (2016) [55]	The Transition shoe (Trs) had smaller first peak of VGRF (Fy1) than CS and higher than Minimalist shoe (MS) and barefoot (BF) ($p < 0.001$).	The TrS and MS induced to lesser knee flexion ($p < 0.001$) and greater dorsiflexion ($p < 0.001$) than CS and BF.	NR	TrS tested seem to promote an intermediate mechanical load condition only for VGRF parameters ($p < 0.001$). TrS tested seem to be effective to promote intermediate condition of impact force compared to conventional and minimal running.

Hurchison (2015) [56]	NR	The knee was significantly less internally rotated in the stability shoe condition compared to all other conditions ($p < 0.05$).	No significant differences in running speed occurred between testing conditions ($p > 0.05$)	The results indicated that a stability shoe alters knee joint kinematics when compared to a neutral shoe and both customised and prefabricated foot orthoses, with less peak internal rotation and greater peak external rotation observed ($p < 0.05$).
Hollander (2015) [57]	NR	The primary outcome was ankle angle at foot strike - The rate of rear-foot strikes was lowest during barefoot running followed by running with un-cushioned minimalist shoes, cushioned minimalist, and standard shoes ($p < 0.001$). Secondary outcomes were knee angle at foot strike, rate of rear-foot strike (RFS), step length and stride frequency There was no statistically significant effect of shoe conditions on the knee angle at foot strike ($p = 0.239$).	Significant differences in step length as well as stride frequency between barefoot running and all shod running conditions ($p < 0.001$).	The most remarkable differences were observed between barefoot and cushioned shoe conditions ($p < 0.001$). The main finding of this study was that minimalist shoes differ in their ability to simulate barefoot running ($p < 0.001$). Ankle dorsiflexion angles and rate of rear-foot strikes were lowest during the barefoot running condition and increased with augmented cushioning properties of footwear ($p < 0.001$). Running kinematics for cushioned minimalist shoes were closer to barefoot running kinematics than those of cushioned minimalist shoes ($p < 0.001$).
Goss (2015) [58]	TSR runners demonstrated greater ankle-dorsiflexion and knee-extension negative work than MSA and MSR runners	NR	All runners wearing traditional shoes demonstrated a rear–foot-strike pattern.	Accuracy of self-reported foot-strike patterns for runners wearing minimalist running shoes was poor.

	The MSA ($p < 0.01$) and MSR ($p < 0.01$) runners demonstrated greater ankle plantar-flexion negative work than TSR runners. The MSR runners demonstrated a greater average vertical-loading rate than MSA and TSR runners ($p < 0.01$).		An anterior–foot-strike pattern was 57.5 %, whereas 42.5 % (17 of 40) demonstrated a rear–foot-strike pattern in Minimalist shoe runners Main Outcome Measure(s): - Only 41 (68.3 %) runners reported foot-strike patterns that agreed with the video assessment	A cohort of runners who wore minimalist shoes for at least 6 months demonstrated a rear–foot-strike pattern and potentially injurious ground reaction force rates of loading. Runners using a rear–foot-strike pattern and wearing traditional shoes demonstrated more overall knee excursion, greater knee-extension negative work, and greater ankle-dorsiflexion negative work than runners wearing minimalist shoes, regardless of foot-strike pattern ($p < 0.01$).
Fredericks (2015) [59]	NR	Plantarflexion was greater in barefoot than MRS ($p = 0.05$) Barefoot and minimalist runners exhibited greater plantarflexion than other conditions ($p < 0.005$) Knee angles had a significant relationship with speed, but not with footwear. Faster speeds resulted in greater knee flexion at foot strike and greater knee extension at toe-off ($p < 0.001$)	There is a clear influence of footwear, but not speed, on foot strike pattern. Relative step length was larger in standard versus minimalist footwear and barefoot conditions ($p < 0.01$) Changing shod condition from TRS to MRS and barefoot increases the frequency of non-rearfoot strike.	Foot strike pattern changes with footwear, but not with speed. Footwear condition and speed affect ankle kinematics, whereas just speed affects knee kinematics ($p < 0.001$).
Chambon (2015) [60]	Barefoot running induced higher loading rates during overground running than the highest drop condition,	Over ground	NR	Shoe drop appears to be a key parameter influencing running pattern, but its effects on

	while it was the opposite during treadmill running ($p < 0.01$). Highest shoe drop condition induced the lowest loading rates during overground running, while it induced the highest loading rates during treadmill running ($p < 0.01$).	- At touchdown, the knee joint exhibited higher flexion angle ($p < 0.01$) during barefoot condition than during shod conditions - During the stance phase, barefoot condition showed higher ankle joint range of flexion ($p < 0.01$) than shod conditions and lower knee joint range of flexion ($p < 0.01$) than shod conditions Treadmill - There was a significant effect of footwear factor on knee angles at touchdown ($p = 0.02$) with higher knee flexion angle for barefoot and D0 conditions than for D8 condition. - During the stance phase, the ankle joint exhibited more flexion ($p < 0.01$) for the barefoot and D0 conditions than for D8 condition Ankle plantar flexion and knee flexion angles at touchdown were higher during treadmill than overground running for all conditions, except for barefoot which did not show any difference between the tasks.		vGRF differ depending on the task (treadmill vs. overground running) and must be considered with caution ($p < 0.01$).

Sinclair (2015) [61]	Knee peak abduction moment was significantly greater in the running shoe condition compared to the cross-trainer and military boot conditions (p < 0.01) KEM (knee extensor moment), PTCF (patellofemoral contact force) and PTCP (patellofemoral contact pressure) was significantly greater in the military boot in comparison to the running shoe and cross-trainer conditions (p < 0.01)	NR	NR	Patellofemoral load was significantly greater in the military boots (p < 0.01). Peak knee abduction moment was significantly greater in the running shoes (p < 0.01).
Bonacci (2014) [62]	Running barefoot decreases patellofemoral joint stress. The peak knee extension moment was 9 % less during barefoot running than shod running (p = 0.000, SMD = 0.7). The PFJ reaction force demonstrated a large effect for condition (SMD = 0.8), with a 12 % reduction in the peak joint reaction force during barefoot running (p = 0.000). PFJ stress was also 12 % less during barefoot running than shod running (p = 0.000), and this change demonstrated a moderate effect (SMD = 0.5).	At foot strike, the ankle was less dorsiflexed during barefoot running compared with shod running (82 %, p = 0.000). Peak knee flexion during stance was greater in the shod condition (4.2 %, p = 0.000). The greater knee flexion angle when shod was associated with a slightly greater peak utilised PF contact area compared with barefoot (0.13 %, p = 0.027).	Stride length was shorter (−2.4 %, p = 0.000) and stride frequency higher (2 %, p = 0.000) during barefoot running compared with the shod condition	Running barefoot decreased peak patellofemoral joint stress by 12 % (p = 0.000) in comparison to shod running. The reduction in patellofemoral joint stress was a result of reduced patellofemoral joint reaction forces (12 %, p = 0.000) while running barefoot. Elevated patellofemoral joint stress during shod running might contribute to patellofemoral pain.
Willy (2014) [63]	Vertical impact peak (p = 0.017) and average vertical loading rate were greater during minimalist shoe running.	At foot strike, greater knee flexion (p = 0.001) and greater dorsiflexion angle (p = 0.025) were noted in the minimalist shoe	Minimalist shoe running resulted in no changes in step length (p = 0.967) or in step rate (p = 0.230)	Minimally cushioned footwear used in the study did not induce a transition to a non-rearfoot strike pattern.

				As runners increased 8h/8ptstheir impact loading, these shoes may increase the risk of injury, especially during this early phase of accommodation.
Thompson (2014) [64]	No significant differences between the barefoot and shod condition for any of the kinetic parameters when subjects ran at identical stride lengths in the barefoot and shod conditions. Vertical GRFs, and sagittal plane knee and ankle joint moments increased with increasing stride length in both the barefoot and shod conditions ($p < 0.05$).	NR	Subjects adopted a significantly shorter stride length and decreased running velocity in the preferred barefoot condition ($p < 0.05$) compared to the preferred shod condition.	Significant main effect for the relationship between stride length and sagittal plane ankle and knee moments ($p < 0.05$). Barefoot running triggers a decrease in stride length, which could lead to a decrease in GRFs and sagittal plane joint moments ($p < 0.05$).
TenBroek (2014) [65]	THICK condition resulted in greater knee excursion than both the THIN and MEDIUM conditions ($p < 0.05$).	At touchdown (TD), kinematics was similar for the THIN and MEDIUM conditions distal to the knee ($p < 0.001$) Knee was in a similar position at TD for both the MEDIUM and THICK conditions, at midstance the knee was more flexed in the THICK condition ($p < 0.001$) There was more internal rotation with the THIN and MEDIUM footwear ($p < 0.001$)	Stance times were similar for the THIN and MEDIUM conditions but greater in the THICK condition No runners displayed midfoot or forefoot strike patterns in any condition	The thinner midsole conditions produced greater eversion as well as tibial and thigh internal rotation ($p < 0.001$).
Chambon (2014) [66]	No significant effect of midsole thickness was observed on ground reaction force and tibial acceleration.	Barefoot running compared to shod running induced ankle in plantar flexion at touch-down, higher ankle dorsiflexion	Increase of 16 mm of midsole thickness induced a 5 % increase of the stance-	Presence of very thin footwear upper and sole was sufficient to significantly influence the running pattern ($p < 0.001$).

		and lower knee flexion during stance phase ($p < 0.001$).	phase duration while the running speed was kept similar ($p < 0.05$).	Keeping zero heel to toe drop, midsole thickness did not affect foot strike pattern but that foot strike patterns were different between barefoot and shod running.
Lilley (2013) [67]	In the neutral shoe, mature females exhibited significantly higher external adductor moments, than the younger females ($p < 0.05$)	In the neutral shoe, mature females exhibited significantly higher peak ankle eversion angles, knee internal rotation angles, than the younger females ($p < 0.05$) For the mature and young females, the motion control shoe resulted in a significant decrease in the peak ankle eversion angle and the peak knee internal rotation angle compared to a neutral shoe ($p < 0.05$).	NR	No significant between-shoe differences were observed in the external adductor moments presented by the either group ($p > 0.05$). Among mature and young females, the motion control shoe significantly reduced peak rearfoot eversion and knee internal rotation.
Lewinson (2013) [68]	A significant negative correlation was found between the centre of pressure to ankle joint centre (COP-AJC) lever arm and Internal knee abduction angular impulses (KAAI) ($p < 0.001$). Specifically, as the COP-AJC lever arm increased, KAAIs decreased KAAI ($p = 0.001$), peak knee abduction moments (MK) ($p = 0.001$), ankle inversion moments at MK ($P = 0.041$), and COP-AJC lever arms at MK ($p < 0.001$)	Knee angle at MK ($p = 0.123$), ankle angle at MK ($p = 0.158$), mediolateral ground reaction force at MK ($p = 0.623$), vertical ground reaction force at MK ($p = 0.509$), and stance time ($p = 0.875$) were not significantly different across footwear conditions.	NR	KAAIs are reduced with laterally wedged footwear because of lateral shifts in the centre of pressure beneath the foot, which then increases ankle inversion moments and decreases peak knee abduction moments. Laterally wedged footwear may therefore offer greater relief to runners with PFPS than medially wedged footwear by reducing KAAIs ($p \leq 0.001$).

	were significantly different across footwear conditions.			
Grewal (2013) [69]	Barefoot running, the tibia vertical impact was reduced on average by 8 % (p = 0.03) and a significant increase (p = 0.01, 24 %) in braking force	Wearing shoes improved knee flexion-extension by 6.4 % (p = 0.008) compared to the barefoot condition	During barefoot running. Other temporal parameters also showed significant reduction during barefoot running. Wearing shoes stabilised knee internal-external rotation by 8.4 % (p = 0.001) compared to the barefoot condition	The significant increase in braking force and reduced vertical acceleration impact may be associated with biomechanical changes during barefoot running leading to a more cautious strategy during foot placement on forefoot/midfoot strike.
Bonacci (2013) [70]	Barefoot: lower peak extension and abduction moments and less negative work at the knee; higher peak power generation and absorption and positive work at the ankle (p < 0.001) Barefoot running demonstrated abduction moments and a 24 % decrease in negative work done at the knee compared with shod conditions (p < 0.001)	Barefoot running demonstrated less knee flexion during midstance, an 11 % decrease in the peak internal knee extension (p < 0.001) The ankle demonstrated less dorsiflexion at initial contact, a 14 % increase in peak power generation and a 19 % increase in the positive work done during barefoot running compared with shod conditions (p < 0.005)	NR	Barefoot running was different to all shod conditions. Barefoot running changes the amount of work done at the knee and ankle joints (p < 0.001). Barefoot: less knee flexion during midstance; less ankle dorsiflexion at ground contact (p < 0.001).

RCT, randomised controlled trial; EVA, ethylene vinyl acetate; MI, minimalist index; BF, barefoot; JRF, joint reaction force; IC, initial contact; STC, stance phase; EMG, electromyography; JRF, joint reaction force; TRAD, traditional shoes; OS, own running shoes; MAX, maximal cushioning shoe; MIN, minimalist shoe, NEUT, traditional Neutral cushioning shoe; UTRA, ultra-cushioning shoe; HTD, heel-to-toe-drop; TO, toe-off; HR, heart rate; RPE, rating of perceived exertion; PFM, plantar flexion moment; COM, centre of mass; TrS, transition shoe ; CS, conventional shoe; MSA, minimalist shoes and anterior–foot-strike pattern; MSR, minimalist shoes and a rear–foot-strike pattern but self-reported anterior–foot-strike pattern; TSR, traditional shoes and a rear–foot-strike pattern; GRF, ground reaction force; COP-AJC, centre of pressure to ankle joint centre; PFPS, patellofemoral pain syndrome; KAAI, knee adduction angular impulses; NR, not reported; yrs, years; wk, week.

2.3.3 Footwear intervention

Footwear interventions included minimalist [27, 38-40, 44, 45, 50, 53-55, 57-59, 62, 63, 70, 73], conventional [24, 27, 42, 43, 50, 51, 53, 55, 56, 58, 59, 62, 63, 67, 71, 74, 75], maximalist [24, 27, 38, 39, 42, 44], motion-control [47, 48, 56, 67, 74, 75], and other footwear [61, 76]. The other footwear category included rocker-soled footwear and cross-trainer footwear. Footwear ranged from commercially available footwear [24, 27, 38-45, 47, 48, 50-56, 59, 62, 67, 68, 70, 72] to footwear that was modified with the use of a rocker profile [71], altered midsole thickness or stiffness [37, 65, 66] or altered heel to toe differential [46, 60].

2.3.3.1 Minimalist footwear

Seventeen studies reported using minimalist footwear [27, 38, 39, 41, 45, 50, 53-55, 57-59, 62, 63, 71, 73]. Minimalist footwear was defined as footwear with a highly flexible sole and upper, weighs ≤ 200 g, has a heel stack height ≤ 25 mm, has a flexible heel counter and a heel-toe differential of ≤ 7 mm [77]. The majority of minimalist footwear had no cushioning, heel drops ranging from 0 to 4 mm, heel stacks ranging from 3 to 25 mm, outsole thickness ranging from 3 to 7 mm [27, 45] and weight ranging from 125 to 246 g [27, 38, 39, 41, 45, 50, 53-55, 57-59, 62, 63, 71, 73].

2.3.3.2 Conventional footwear

Twenty studies reported findings on conventional footwear [24, 27, 42, 43, 50, 51, 53, 55-59, 62, 63, 67, 71, 74, 75]. The category of conventional footwear encompassed traditional, neutral, standard, and cushioned footwear. Conventional footwear was defined as footwear with a heel drop ranging from 10 to 12 mm, a single-density midsole and shock-absorbent materials to provide cushioning [25]. This category of footwear had a heel drop ranging from 6 to 14 mm, heel stack ranging from 19 to 45 mm, and weight ranging from 184 to 318 g.

2.3.3.3 Motion-control footwear

Seven studies reported findings on motion-control footwear [47, 48, 56, 67, 75]. The category of motion-control footwear was characterised by a dual-density midsole (higher density foam on the medial aspect of the shoe) designed to reduce arch deformation and rearfoot eversion [25, 67]. This category of footwear had a heel drop ranging from 12 to 13 mm, heel stack ranging from 25 to 39 mm, and weight ranging from 377 g [47, 74]. None of the studies reported density of the midsole of commercially available motion-control footwear.

2.3.3.4 Maximalist

Six studies reported using maximalist footwear [24, 27, 38, 39, 42, 44]. The category of maximalist footwear was characterised by an ultra-cushioned midsole, greater than 29 mm in thickness [78], to provide additional cushioning and shock attenuation [27]. All maximalist footwear a had heel drop ranging from 5 to 6 mm, heel stack ranging from 29 to 45 mm, and weight ranging from 318 to 321 g.

2.3.3.5 Other footwear

One study reported using rocker footwear [71] with a rolling bottom outsole to investigate joint impact during running. The location of the apex rolling point of the rocker footwear was proximal to the metatarsal region (53 % of the footwear length). Its mean (SD) weight was 541 (44) g with a 22 (1) mm average thickness from the footwear apex to the plantar heel. Army issue cross-trainers (heel stack 38 mm, heel drop 15 mm) were investigated by a final study in comparison with military shoes (heel stack 24 mm, heel drop 11 mm) and conventional footwear (heel stack 32 mm, heel drop 12 mm) [61].

2.3.4 Biomechanical variables

Studies reported outcomes on kinetics, kinematics, spatiotemporal characteristics, joint stiffness and stability.

2.3.4.1 Kinetics

2.3.4.1.1 Knee joint moments and work

Twenty studies reported on knee joint moments [37, 39, 41, 42, 45, 46, 48, 52, 53, 61, 65, 67, 68, 70, 71] and work [40, 51, 52, 54, 58, 59, 70, 71]. Several studies reported that running barefoot significantly reduced knee moments compared to footwear conditions [37, 39, 45, 65, 70]. The peak knee flexion moment increased significantly from barefoot to min imalist footwear, and again from minimalist to maximalist footwear [39]. Minimalist footwear reduced the knee extension moment [45] compared to conventional footwear, and maximalist footwear [39]. Motion-control footwear [48] was associated with a smaller knee extensor moment compared to conventional footwear, but it was not statistically significant. One study reported that laterally wedged footwear reduced the internal knee abduction angular impulse [68]. Negative work (the muscle moment acting in the opposite direction to the joint movement) at the knee joint was significantly less in barefoot [70] and minimalist footwear [53, 54] compared to conventional footwear [54]. In maximalist footwear, the knee performed more negative work [51]. In comparison with conventional footwear, running with rocker-soled footwear significantly increased the positive work, extension moment peak and extension moment impulse at the knee [71].

2.3.4.1.2 Patellofemoral joint stress

Four studies reported on patellofemoral joint stress [27, 41, 45, 62]. Running with footwear increased peak patellofemoral joint stress when compared to barefoot running [41, 62]. One study reported that knee contact pressure and force were significantly greater in conventional and maximalist footwear compared to minimalist footwear [27]. This is consistent with another study which showed that minimalist footwear significantly decreases the patellofemoral contact force and patellofemoral joint stress compared to conventional and maximalist footwear [45]. Knee contact pressure was significantly greater in the conventional and maximalist footwear compared with the minimalist footwear. Contact force impulse was significantly greater in the conventional and maximalist footwear compared with the minimalist footwear [27]. This was consistent with peak joint reaction force of the knee joints being lower in barefoot running compared to running with footwear from the minimalist to maximalist [41]. However, these kinetic results were contrary to another study that reported no significant differences between the barefoot and wearing footwear condition for any of kinetic parameters such as anterior–posterior and vertical ground reaction forces, and sagittal plane knee and ankle moments when subjects ran at identical stride lengths in the barefoot and wearing footwear condition [64].

2.3.4.2 Kinematics

2.3.4.2.1 Barefoot versus minimalist versus conventional footwear

Ten studies reported that running with footwear induced less knee flexion at initial contact and increased peak knee flexion at stance phase compared to barefoot running [41, 45, 46, 53, 59, 60, 62, 66, 69, 70]. The minimalist footwear condition exhibited greater knee flexion at foot strike, and less knee flexion during midstance compared with the maximalist and conventional footwear [27, 55, 63]. This was consistent with another study that reported running in minimalist footwear with zero heel drop and thin midsole (3mm heel stack) or the footwear with medium midsole (14mm heel stack, 5mm heel drop) demonstrated less knee flexed and more knee internal rotation compared to the conventional footwear with thick midsole (24 mm heel stack, 12mm heel drop) condition at midstance [65]. However, this was contrasted by another study that reported knee angles had a significant relationship with speed, but not with footwear [59].

2.3.4.2.2 Conventional versus motion-control footwear

Four studies investigated the effects of a motion control footwear compared with conventional footwear [47, 48, 56, 67]. Significantly less internal rotation at the knee was observed in the motion control footwear condition compared to the conventional footwear [56], and a reduction in peak rearfoot eversion angle was also seen when running in motion-control footwear compared to conventional footwear [48]. For the mature females runners (>45years), the motion-control footwear resulted in a significant decrease in the peak knee internal rotation angle compared to conventional footwear [67]. This was contrary to another study that motion-control shoes more internally rotated knee at toe-off phase when it compared with conventional footwear and cushioned footwear [47].

2.3.4.2.3 Rocker footwear versus conventional footwear

One study reported that rocker footwear increased the peak knee flexion compared to conventional footwear [71].

2.3.4.3 Spatiotemporal characteristics

2.3.4.3.1 Stride length and cadence

Seven studies reported a significant decrease in stride length from maximalist footwear to minimalist footwear, again from minimalist footwear to barefoot [39, 46, 53, 57, 59, 64, 69]. Minimalist, conventional, motion-control and maximalist footwear conditions showed a significantly greater step length and lower cadence than barefoot [46, 57, 59, 64, 69]. The step length was significantly longer in the conventional and maximalist footwear compared to minimalist [27]. However, Willy et al. reported that minimalist footwear running resulted in no changes in step length or in step rate compared with conventional footwear [63].

2.3.4.3.2 Strike pattern

Running in minimalist footwear caused a shift in foot-strike pattern toward a midfoot foot strike, and strike index (the percentile location of the plantar pressure centre relative to the full footprint length) was greater when running in minimalist [54, 59]. All runners wearing conventional footwear demonstrated a rear-foot-strike pattern, while about half minimalist runners demonstrated an anterior-foot-strike pattern [58]. The rate of rearfoot strikes was lowest during barefoot running followed by running with un-cushioned minimalist footwear, cushioned minimalist, and conventional footwear [57].

2.3.4.3.3 Stiffness

Five studies reported findings related to knee joint stiffness [42, 43, 51, 53, 54]. Knee joint stiffness values were similar between groups in the conventional footwear, maximalist, and motion-control footwear [42, 43]. No differences in leg stiffness between maximalist, conventional and minimal footwear were reported [51]. This was contrary to another study that reported limb and knee stiffness were greater in barefoot and minimalist than in conventional footwear [53, 54].

2.3.4.3.4 Stability

Two studies reported the impact of footwear on knee stability [50, 69]. Two levels of midsole stiffness (40 Asker C, 70 Asker C; Asker C is a measuring device to measure hardness with a durometer as stipulated in Society of Rubber Industry [Japan] Standards), and two thicknesses of the footwear (stack height 13 mm with heel drop 4 mm, stack height 20 mm with heel drop 12 mm) did not influence local dynamic knee stability [50] but wearing footwear stabilised knee internal-external rotation compared to the barefoot condition [69].

2.4 Discussion

The aim of this review was to identify and evaluate the relationship between footwear and knee joint biomechanics. The findings of this review support that different footwear was associated with changing knee biomechanics, and with footwear choice influencing stride length and knee joint loads [27, 39, 66, 70]. Despite this, there were inconsistencies in outcomes between studies. This could be due to the variation in experimental protocols such as treadmill [40, 46, 47, 51, 55, 57-59, 63, 64, 72, 76] or overground [38, 54, 62, 69, 70]; preferred running speed [37, 41, 42, 47, 50, 58, 59, 62, 64, 71] or controlled running speeds [24, 48, 54, 55, 61, 64, 67, 68, 72]; short running duration [46, 47, 50, 58, 61, 66] or prolonged running duration [38, 39, 43, 65]; trained runners or novice runners [50]; male participants or female participants [37, 42, 48, 67, 71]; and foot strike patterns [46, 54, 57-59, 71]. Furthermore, there was considerable variation in the type of footwear investigated between studies and the reporting of their characteristics.

Although this review grouped footwear based on their characteristics into five categories (barefoot, minimalist, conventional footwear, maximalist and motion-control), there was inconsistency in the reporting of footwear across studies. For example, terms such as "barefoot inspired minimalist", "non-cushioned minimalist", "cushioned minimalist" and "structured minimalist" were used to describe minimalist footwear [27, 53, 57] Classification tools such as the Minimalist Index (MI) have been used in studies to define a minimalist shoe [40, 45], although several studies provided limited information about the specific characteristics of the footwear used. The lack of information reported about the footwear makes it difficult to determine if the differences in outcomes are related to the 'footwear' or specific characteristics of the footwear [77].

Several studies demonstrated that barefoot running significantly reduces knee moments [37, 39, 45, 65, 70] and peak patellofemoral joint stress [41, 62] compared to shod conditions including minimalist, conventional and maximalist footwear. Both variables are risk factors for the development of patellofemoral pain syndrome [45, 62] however, barefoot running may not be feasible outside of the laboratory [35]. Smaller reductions in knee joint moments and patellofemoral joint stress were seen in minimalist shoes compared to conventional footwear, which may be due to the reduced heel drop [27]. A lower heel drop (0 mm to 8 mm) resulted in a lower range of knee flexion [37, 60, 65] compared to footwear with a heel drop greater than 12 mm [65]. This suggests that if the goal of treatment is to reduce knee excursion, then selecting footwear with a lower heel drop may be beneficial to the patient.

Increases in stride length were consistently seen when using maximalist shoes compared to minimalist footwear [27, 39, 46, 53, 57, 59, 64, 69]. This may be due to the minimalist footwear promoting midfoot and forefoot strike patterns [54, 59]. In runners with maximalist footwear, peak vertical ground reaction forces decrease significantly with decreases in stride length [79], resulting in decreased lower extremity joint moments [80]. Foot-strike pattern is associated with attenuating external ground reaction forces and the physical load at the knee joint [35]. These observations may explain why running in minimalist shoes reduces knee moments. However, running in minimalist shoes is often but not always associated with adopting a midfoot or forefoot strike, simply because landing on the heel is uncomfortable. For individuals who land on their rearfoot despite running barefoot, have greater loading rates [58]. Importantly, loading rate may be reduced during barefoot running if a forefoot strike pattern is employed [81]. This suggests that a combination of foot-strike pattern and stride length are associated with the physical load at the knee joint.

To reduce impact loading, the addition of heel cushioning has become a standard characteristic of running footwear [31]. However, recent studies demonstrated that shock attenuation strategies using ultra-cushioning increased stride length and knee joint loading although it decreased negative work at the ankle [39, 51]. Also, higher patellofemoral joint stress presented in maximalist footwear compared to minimalist footwear [27]. This suggests that if the goal is to reduce knee excursion, then avoiding maximalist footwear may be beneficial to the runners [33, 43, 51].

Motion-control footwear is often recommended in the management of lower limb injuries [82]. Running in motion-control footwear was shown to reduce internal rotation of the knee at midstance [56] but is increased at toe-off [47] which may be related to the reductions in rearfoot eversion associated with this type of footwear [67]. Knee injuries such as PFPS have been associated with foot pronation and tibial rotation, and motion control footwear can modulate the tibial and femoral rotation by controlling excessive foot pronation [25]. However, there was insufficient data presented to suggest that motion control footwear can control the amount of knee moment during running [47, 67].

There are some limitations in this review. The methodological quality of the included publications was not assessed so the findings presented may be subject to bias.

Biomechanical changes at other lower limb joints (ankle and hip) are not reported. The findings are specific to healthy runners and may not apply to injured populations. Further work needs to explore if the changes in knee biomechanics are associated with improvements in patient-reported outcomes for commonly seen knee problems, such as PFPS or knee osteoarthritis. More standardised reporting of footwear characteristics may help with the translation of research findings to clinical practice. Several studies reported on single-gender samples whilst others included a range of genders. Gender-specific differences have been observed in knee pathology, which may warrant further investigation with regards to footwear choice.

In conclusion, different footwear is associated with changes in knee biomechanics during running. Where the goal is to reduce knee joint moments in runners, it may be beneficial to select footwear with a low heel stack height and heel drop. There is limited evidence to support the use of motion-control footwear as a tool to influence knee joint mechanics in runners.

Chapter 3 : Aims

3.1 Rationale

The findings of the review from Chapter 2 demonstrate that footwear can alter the biomechanics of the knee and lower limb in healthy populations. With differences in the structure and biomechanics of the knee joint reported between healthy and injured populations, the effects of footwear on lower limb biomechanics may be different between these groups. Further investigation into the effects of footwear on people with knee pathology is warranted.

3.1 Aims

The aim of this study was to evaluate published evidence for the effectiveness of footwear on lower limb biomechanics in people with knee pathology.

Chapter 4 : Methodology

4.2 Study design

This study was a systemic review that adhered to the PRISMA guidelines [83].

4.3 Ethical approval

This systematic review did not require ethical approval based on the Auckland University of Technology Ethics Committee (AUTEC) decision tree.

4.4 Search strategy

Electronic databases (MEDLINE, CINAHL, SPORTDiscus, SCOPUS and the Cochrane library) were searched during August 2022 without limitation of the publication date. The search strategy comprises of keywords displayed in **Table 4.1**.

Table 4.1 Search strategy

Search		Key words
#1	Knee	knee OR patellofemoral OR patellar OR "patello-femoral" OR tibiofem oral OR "tibio-femoral" OR "knee osteoarthritis"
#2	Biomecha nics	biomechanic* OR kinetic OR stress OR force OR kinematic OR torque OR moment OR motion OR rom OR function OR "walking speed" OR "walking velocity" OR cadence OR "stride length" OR "step width" OR "double support" OR "stance duration" OR "swing duration"
#3	Footwear	Footwear OR shoe
Final search term: #1 AND #2 AND #3		

4.5 Inclusion and exclusion criteria

Studies were included if they met the following criteria: participants with musculoskeletal knee pathology including knee osteoarthritis (OA), patellofemoral pain syndrome (PFPS), knee ligament injury and meniscus injury studies; being a randomised trial, prospective study, or cross-sectional study; studies assessing the impact of footwear on lower limb biomechanics (hip, knee, ankle foot), including kinematic, kinetic, and/or spatiotemporal data; peer-reviewed publication; conference abstracts; published in English. Publications were excluded if they investigated outcomes not affecting the lower limb; investigated healthy individuals without knee pathology; participants knee pathology due to systemic or neuromuscular disease; or reported findings where footwear was used in combination with removable insoles or orthoses.

4.6 Selection process and data extraction

4.6.1 Selection process

All articles identified from the database searches were exported into Rayyan, an online systematic review software tool, developed by Qatar Computing Research Institute (QCRI) and is currently accessible at www.rayyan.ai. After the removal of duplications, two independent reviewers (FL, MF) reviewed titles and abstracts of the included articles against the inclusion and exclusion criteria. Any disagreements were resolved by consensus. Full texts of all included articles were independently reviewed by the two reviewers (FL, MF) to confirm eligibility.

4.6.2 Data extraction

A standardised form was used to extract data from all included studies by two independent reviewers (FL, MF). Study characteristics were extracted including: first author surname, year of publication, country of recruitment, and study design. Participant characteristics were also be extracted for each group, including: a description of the study population and knee pathology(s), sample size, age, gender, and BMI. A description of the footwear intervention(s) (and control/comparator intervention, as required) was extracted. Finally, data relating to lower limb biomechanics were extracted, including the biomechanical parameters measured, and the study findings.

4.6.3 Data synthesis

Data extracted from the included studies was reported in tables and summarised qualitatively.

4.7 Quality assessment

Methodological quality was independently assessed by two reviewers (FL, MF). The methodological quality of the included papers was assessed using the National Heart Lung & Blood Institute (NHLBI) Study Quality Assessment Tools [84]. These are tailored quality assessment tools specific to certain study designs. ‘Quality assessment tool for controlled intervention studies’, ‘Quality assessment tool for observational cohort and cross-sectional studies’, and ‘Quality assessment tool for before-after (pre-post) studies with no control group’ were used in the current review for randomised controlled trials (RTC), cross-sectional studies and prospective studies, respectively. The checklist for measuring study quality was reported as ‘yes’, ‘no’, and others (CD, cannot determine; NA, not applicable; NR, not reported). Any disagreements between the two reviewers (FL, MF) were resolved by discussion.

Chapter 5 : Results

5.1 Introduction

This chapter presents the findings from the systematic review.

5.2 Search results

The search strategy identified 4097 records (**Figure 5.1**). Following the removal of duplicates, the title and abstracts of 2,800 records were then screened against the inclusion and exclusion criteria which resulted in the removal of 2,744 papers. Full-text records of the remaining 56 articles were obtained and assessed against the exclusion criteria. Twenty studies were excluded at the full-text screening stage and reasons for exclusion are summarised in **Figure 5.1**. In total, 36 articles were included in the systematic review. Of the included studies, a total 32 studies assessed participants with knee osteoarthritis (OA), two studies assessed participants with patellofemoral pain syndrome (PFPS), one study assessed participants with anterior cruciate ligament (ACL) reconstruction and one study assessed participants with meniscus injury (post-meniscectomy of the knee). Of the included studies, eight were randomised controlled trials, three were prospective observational intervention studies, and 25 studies were cross-sectional studies.

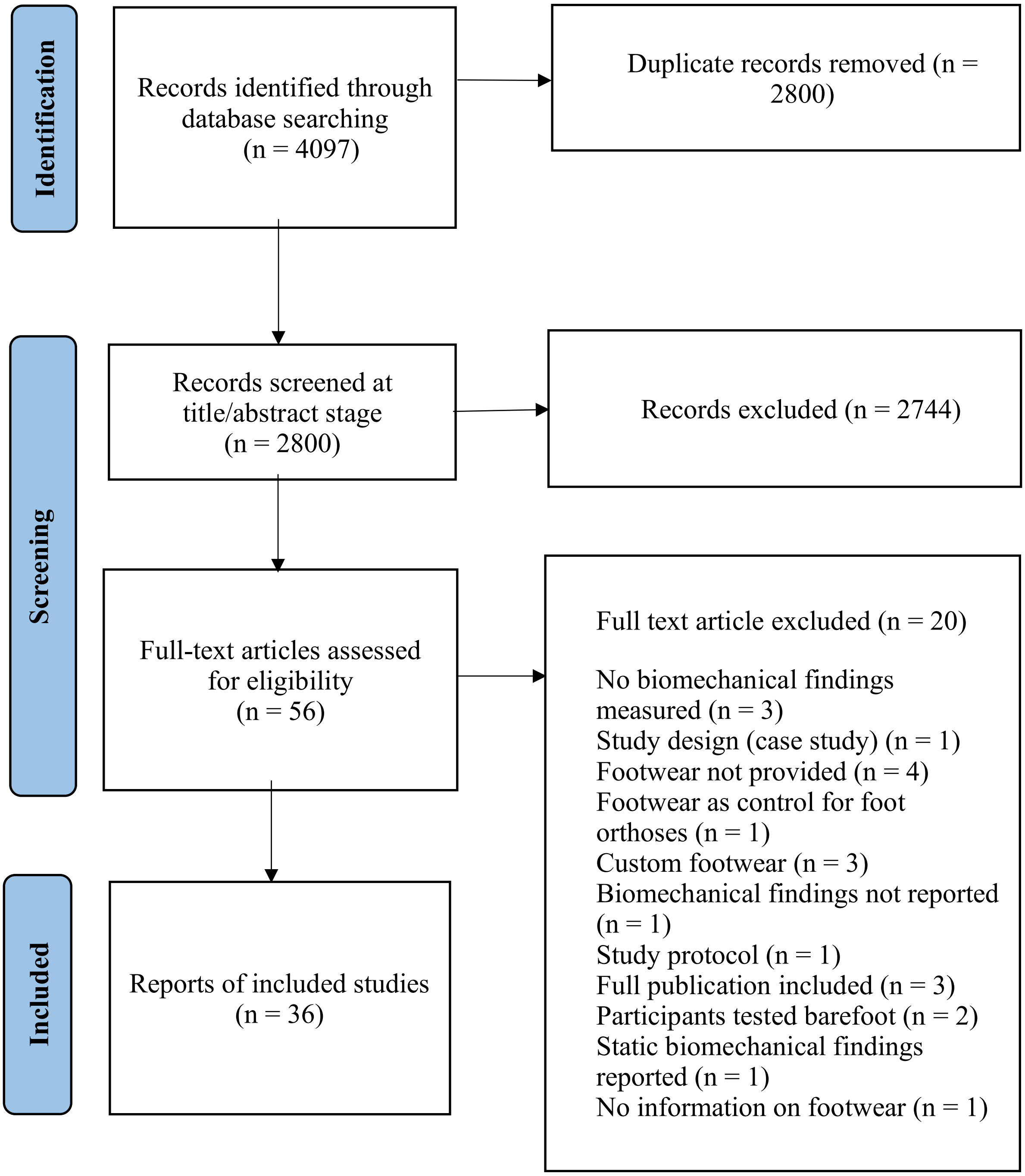

Figure 5.1 PRISMA flow diagram of search strategy

5.3 Methodological quality

The methodological assessment of the included studies is displayed in **Table 5.1, Table 5.2**, and **Table 5.3**, using a traffic light system to allow for the appreciation of the diversity across studies (green: yes (Y); red: no (N); yellow: cannot decide (CD), not reported (NR), not applicable (NA)). The quality assessment of randomised controlled trials (RCT) [85-92] is shown in **Table 5.1**. For RCTs, 75% blinded participants to footwear allocation, while 38% blinded participants and assessors to footwear allocation. In 75% of RCTs, outcomes were assessed using reliable and valid measures. Fifty percent of RCTs were powered and analysed using an intention-to-treat dataset. The quality assessment of prospective observational intervention studies [93-95] is shown in **Table 5.2**. For prospective observational interventions studies, no studies blinded assessors to footwear allocation. All studies provided p-values for the pre-to-post changes; however, no studies were adequately powered. The quality assessment cross-sectional studies [16, 96-119] is shown in **Table 5.3**. For cross-sectional studies, all clearly defined outcomes measured; however, no studies blinded assessors to footwear allocation. Forty percent of studies were appropriately powered, however, 56% did not account for confounding variables in their statistical analyses.

Table 5.1 Quality assessment of randomised controlled trials

	[85]	[86]	[90]	[91]	[87]	[92]	[89]	[88]
1. Was the study described as randomised, a randomised trial, a randomised clinical trial, or an RCT?	Y	Y	N	Y	Y	Y	N	Y
2. Was the method of randomisation adequate (i.e., use of randomly generated assignment)?	Y	Y	NR	NR	Y	NR	NR	Y
3. Was the treatment allocation concealed (so that assignments could not be predicted)?	Y	Y	NR	NR	Y	NR	NR	Y
4. Were study participants and providers blinded to treatment group assignment?	Y	Y	Y	NR	Y	Y	NR	Y
5. Were the people assessing the outcomes blinded to the participants' group assignments?	N	N	Y	NR	Y	Y	NR	NR
6. Were the groups similar at baseline on important characteristics that could affect outcomes (e.g., demographics, risk factors, co-morbid conditions)?	Y	Y	CD	NR	Y	NR	NR	Y
7. Was the overall drop-out rate from the study at endpoint 20% or lower of the number allocated to treatment?	N	N	NR	NR	Y	NR	NR	Y
8. Was the differential drop-out rate (between treatment groups) at endpoint 15 percentage points or lower?	N	N	NR	NR	Y	NR	NR	Y
9. Was there high adherence to the intervention protocols for each treatment group?	Y	Y	NR	NR	Y	NR	NR	Y
10. Were other interventions avoided or similar in the groups (e.g., similar background treatments)?	Y	Y	NR	NR	Y	NR	NR	N
11. Were outcomes assessed using valid and reliable measures, implemented consistently across all study participants?	Y	Y	Y	NR	Y	Y	NR	Y
12. Did the authors report that the sample size was sufficiently large to be able to detect a difference in the main outcome between groups with at least 80 % power?	Y	Y	NR	NR	Y	NR	NR	Y
13. Were outcomes reported or subgroups analysed prespecified (i.e., identified before analyses were conducted)?	Y	Y	NR	NR	Y	NR	NR	Y
14. Were all randomised participants analysed in the group to which they were originally assigned, i.e., did they use an intention-to-treat analysis?	CD	CD	Y	NR	Y	Y	NR	Y

Table 5.2 Quality assessment of prospective observational interventions studies

	[95]	[93]	[94]
1. Was the study question or objective clearly stated?	Y	Y	Y
2. Were eligibility/selection criteria for the study population prespecified and clearly described?	N	Y	Y
3. Were the participants in the study representative of those who would be eligible for the test/service/intervention in the general or clinical population of interest?	Y	Y	Y
4. Were all eligible participants that met the prespecified entry criteria enrolled?	NR	Y	CD
5. Was the sample size sufficiently large to provide confidence in the findings?	NR	N	NR
6. Was the test/service/intervention clearly described and delivered consistently across the study population?	CD	Y	Y
7. Were the outcome measures prespecified, clearly defined, valid, reliable, and assessed consistently across all study participants?	CD	Y	Y
8. Were the people assessing the outcomes blinded to the participants' exposures/interventions?	NR	N	N
9. Was the loss to follow-up after baseline 20% or less? Were those lost to follow-up accounted for in the analysis?	NR	N	N
10. Did the statistical methods examine changes in outcome measures from before to after the intervention? Were statistical tests done that provided p values for the pre-to-post changes?	Y	Y	Y
11. Were outcome measures of interest taken multiple times before the intervention and multiple times after the intervention (i.e., did they use an interrupted time-series design)?	N	N	Y
12. If the intervention was conducted at a group level (e.g., a whole hospital, a community, etc.) did the statistical analysis take into account the use of individual-level data to determine effects at the group level?	N	Y	N

Table 5.3 Quality assessment of cross-sectional studies

	[96]	[97]	[99]	[98]	[100]	[101]
1. Was the research question or objective in this paper clearly stated?	Y	Y	Y	Y	Y	Y
2. Was the study population clearly specified and defined?	Y	Y	Y	Y	Y	Y
3. Was the participation rate of eligible persons at least 50%?	NR	NR	NR	NR	NR	NR
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?	Y	Y	Y	Y	Y	NR
5. Was a sample size justification, power description, or variance and effect estimates provided?	NR	Y	NR	NR	NR	NR
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?	Y	Y	Y	Y	Y	Y
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?	Y	Y	Y	Y	Y	Y
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?	NA	NA	NA	NA	NA	NA
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Y	Y	Y	Y	Y	Y
10. Was the exposure(s) assessed more than once over time?	NA	NA	NA	NA	NA	NA
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?	Y	Y	Y	Y	Y	Y
12. Were the outcome assessors blinded to the exposure status of participants?	N	N	N	N	N	N
13. Was loss to follow-up after baseline 20% or less?	NA	NA	NA	NA	NA	NA
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?	N	Y	N	N	N	NR

	[102]	[103]	[119]	[104]	[105]	[106]	[107]	[108]	[109]	[110]	[111]	[112]	[113]	[114]	[115]	[116]	[117]	[16]	[118]
1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	YI
2	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	N	NR	NR	NR	NR
4	Y	Y	Y	Y	Y	N	Y	Y	Y	NR	Y	NR	Y	Y	Y	Y	Y	Y	N
5	Y	N	N	NR	N	N	Y	Y	Y	NR	NR	Y	Y	Y	Y	Y	N	N	N
6	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
7	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
9	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
10	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
12	NR	N	N	N	N	N	N	N	N	N	N	N	N	N	N	NR	N	N	N
13	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
14	N	Y	Y	Y	N	N	Y	Y	N	N	Y	N	Y	Y	Y	N	Y	N	NR

1. Was the research question or objective in this paper clearly stated?
2. Was the study population clearly specified and defined?
3. Was the participation rate of eligible persons at least 50%?
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?
5. Was a sample size justification, power description, or variance and effect estimates provided?
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?
10. Was the exposure(s) assessed more than once over time?
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?
12. Were the outcome assessors blinded to the exposure status of participants?
13. Was loss to follow-up after baseline 20% or less?
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?

5.4 Study characteristics

The characteristics of the included studies are displayed in **Table 5.4**, **Table 5.5** and **Table 5.6**. The study characteristics of the included RCTs [85-92] are shown in **Table 5.4**. The study characteristics of the included prospective observational interventions studies [93-95] are shown in **Table 5.5**. The study characteristics of the included cross-sectional studies [16, 96-119] are shown in **Table 5.6**. A total of 1,062 participants with knee pathology were included across the studies (1,030 knee OA, 15 PFPS, 10 ACL reconstruction, 7 meniscal injury). In OA studies, most participants had a Kellgren-Lawrence (KL) OA grade from 2 to 4. In the two PFPS studies [98, 99], the same participants were recruited (recreational runners with knee pain >30/100). In the ACL study, participants were 4 to11 months post ACL-reconstruction. In the meniscus injury study [118], participants were less than 6 months post-meniscectomy.

Table 5.4 Study characteristics and findings for randomised controlled trials

	Author	Year	Country	Footwear Interventions		Follow up	Participant characteristics						Study findings
				Control	Intervention		Study population	knee pathology	Sample size	Age (SD)	Female (%)	BMI	
[85]	Erhart	2010	USA	Conventional footwear	Variable stiffness footwear	6-months	Medial knee osteoarthritis symptoms	knee OA	40 (Intervention)	59.8 (9.0)	16(40)	NR	• At baseline intervention footwear significantly reduced the peak KAM (-3.5%) compared to the control footwear (p = 0.001). • At 6-months the intervention footwear reduced the peak knee adduction moment (-6.6%) comparted to the control footwear (p < 0.001). • Participants had a reduced knee adduction moment at 6 months compared to baseline o At baseline, 23 out of the 34 subject (68%) had a decrease in KAM with intervention footwear o At 6 months, 29 out of the 34 subject (85%) had a decrease in KAM with intervention footwear
									39 (control)	60.7 (10.7)	22 (55)		
[86]	Erhart	2012	USA	Conventional footwear	Variable stiffness footwear	12-months	Medial knee osteoarthritis symptoms	knee OA	40 (Intervention)	59.8 (9.0)	16 (40)	NR	• Peak KAM was significantly reduced with the intervention footwear compared to the control footwear. o At baseline -4.4%, (p < 0.001) o At 12 months -5.5%, (p < 0.001)
									39 (control)	60.7 (10.7)	22 (55)		
[90]	Lidtke	2014	USA	Conventional footwear	Minimalist footwear	12-,24-weeks	Symptomatic medial knee OA (KL ≥2)	knee OA	22 (intervention)	55 (7)	13 (59)	NR	• There was a strong correlation between the reduction in the KAM and torsional stiffness of the footwear from baseline to 24 weeks in intervention footwear (0.88) and control footwear (0.89) (p = 0.03). o Tortional stiffness of the footwear: intervention 0.25 (0.07), control 0.94 (1.05) • Intervention footwear significantly reduced KAM while the control footwear significantly increased KAM (p = 0.002). o Differences in peak KAM (Nm/(BW x Ht)%) (SD): intervention -0.25 (0.95), control 0.09 (0.95)
									28 (control)	55 (8)	21 (75)	NR	
[91]	Matias	2014	Brazil	Own footwear	Minimalist footwear	3-, and 6-months	Knee OA (KL ≥2)	Knee OA	28 (intervention)	NR	28 (100)	NR	• There was no interaction effect for knee early flexion (p = 0.293), knee final flexion (p = 0.742), knee extension (p = 0.337), and sagittal range of the knee (p = 0.417) with the intervention footwear
									28 (control)		28 (100)		
[87]	Paterson	2018	Australia	Conventional footwear	Variable stiffness footwear	6-months	Medial knee OA (KL ≥2), 4/10 pain	knee OA	83 (intervention)	65.2 (6.9)	42 (50)	29.7 (3.6)	• Intervention footwear significantly reduced peak KAM (p = 0.02) and KAAI (p < 0.001) at 6 months compared to control footwear. o Peak KAM (Nm/BW x Ht%) (95% CI): intervention

									81 (control)	63.3 (7.9)	42 (50.6)	29.7 (3.7)	4.36 (4.04, 4.67), control 4.54 (4.24, 4.83) ○ KAAI (Nm.s/BW x Ht%) (95% CI): intervention 1.42 (1.32, 1.52), control 1.46 (1.36, 1.57)
[92]	Shakoor	2012	USA	High heel footwear	Minimalist footwear	12-, and 24-weeks	Symptomatic medial knee OA (KL grade ≥2)	knee OA	22 (intervention)	55 (7)	13 (59)	NR	• Intervention footwear significantly reduced KAM at 24 weeks (p=0.002) by 20% while the control resulted in no reduction in KAM (p=0.361). ○ KAM (% BW x Ht) (SD): intervention baseline 3.06 (1.22), intervention at 6 months 2.44 (0.72) ○ KAM (%BW x Ht) (SD): control baseline 3.13 (0.81), control at 6 months 3.00 (0.66)
									28 (control)	55 (8)	21 (75)	NR	
[89]	Trombini-Souza	2013	Brazil	Own footwear	Minimalist footwear	24-weeks	Knee OA (KL 2, 3)	Knee OA	16 (intervention)	NR	16 (100)	NR	• Intervention footwear significantly reduced first peak KAM by 18% (p = 0.043), midstance KAM by 39% (p = 0.025) and KAM impulse by 29% (p = 0.041) compared to control footwear.
									12 (control)	NR	12 (100)	NR	
[88]	Trombini-Souza	2015	Brazil	Own footwear	Minimalist footwear	24-weeks	Medial knee OA (KL 2, 3)	knee OA	28 (intervention)	66 (5)	28 (100)	NR	• For peak KAM a significant interaction effect (F = 12.955, p < 0.001) was observed in the control group at follow up. ○ Peak KAM1 (%BW x Ht) (SD): Intervention T0 2.57 (1.02), Intervention T6 2.30 (0.90), control T0 2.33 (0.96), control T6 2.69 (1.18) • For KAAI, a significant interaction effect (F = 7.773, p = 0.007) was observed with the intervention footwear. KAAI reduced in intervention footwear by 21.8% at follow up. ○ KAAI (%BW x Ht x sec) (SD): intervention T0 0.87 (0.40), intervention T6 0.74 (0.37), control T0 0.75 (0.42), control T6 0.80 (0.48)
									28 (control)	66 (4)	28 (100)		

OA, osteo arthritis; NR, not reported; KAM, knee adduction moment; KAM1, 1st peak knee adduction moment; KL, Kellgren-Lawrence; KAAI, knee adduction angular impulse, BW, body weight; Ht, height; SD, standard deviation; CI, confidence interval.

Table 5.5 Study characteristics and findings for prospective observational interventions studies

Ref	Autor	Year	Country	Intervention	Follow up	Participant characteristics						Study findings
						Study population	**Knee pathology**	**Sample size**	**Age (SD)**	**Female (%)**	**BMI**	
[93]	Erhart	2021	USA	Variable stiffness footwear	6-months	Medial knee osteoarthritis symptoms (KL grade 0-4)	knee OA	25	58.6 (10.9)	8 (32)	28.2 (3.9)	• KAM1 and KAAI were significantly reduced at 6 months when walking in the intervention footwear. • KAM1 was reduced in all participants at 6 months wearing the intervention footwear ($p < 0.001$). o KAM1 (%Bw x Ht) (SD): baseline 2.67 (0.76), 6 months 2.47 (0.75) • KAAI was reduced in 13 of the 18 subjects (72.2%) ($p < 0.09$). o KAAI (%Bw x Ht x s) (SD): baseline 1.06 (0.36), 6 months 0.99 (0.35) • No differences in walking speed ($p = 0.30$) was observed with the intervention footwear ($p < 0.30$) • Walking speed (m/s): baseline 1.20 (0.14), 6 months 1.22 (0.16)
[94]	Shakoor	2013	USA	Minimalist footwear	12-, and 24-weeks	Symptomatic knee OA (KL grade 2-3)	knee OA	16	57 (10)	9 (56.2)	NR	• Intervention footwear significantly reduced KAM by 18% and KAAI by 19% at 24 weeks ($p < 0.001$). o KAM (%BW x Ht) (SD): intervention 2.89 (1.11), own footwear 3.12 (1.10) o KAAI (%BW x Ht x s) (SD): intervention 1.17 (0.53), own footwear 1.26 (0.52) • No differences in KFM were observed at 24 weeks ($p = 0.496$). o KFM (%BW x Ht) (SD): intervention 1.54 (1.00), own footwear 1.73 (1.04) • Own footwear significantly reduced KAM by 11% ($p = 0.002$) and a KAAI by 13% ($P = 0.009$) at 24 weeks • Intervention footwear significantly reduced stride length compared to own footwear ($p < 0.01$). o Stride length (meter/height) (SD): intervention 0.74 (0.09), own footwear 0.77 (0.09) • Intervention footwear significantly increased cadence compared to own footwear ($p < 0.01$). No differences in walking speed were observed between footwear conditions ($p > 0.05$). o Cadence (steps/min) (SD): intervention 104 (9), own footwear 102 (6) o Walking speed (meter/second) (SD): intervention 1.10 (0.17), own footwear 1.12 (0.15)

[95]	Shakoor	2016	USA	Minimalist footwear	12-, and 24-weeks	Symptomatic medial knee OA (KL grade 2-3)	knee OA	28	59 (7)	21 (75)	NR	• Intervention footwear significantly reduced KAM at 24 weeks (p = 0.030). ○ KAM (%BW x Ht) (SD): intervention 2.73 (0.81), own footwear 2.88 (0.99) • Reductions in KAM was associated with foot supination/pronation at baseline (p = 0.024) and maximal medial arch angle at 24 weeks (p = 0.023).
OA, osteo arthritis; NR, not reported; KAM, knee adduction moment; KAM1, 1st peak knee adduction moment; KFM, knee flexion moment; KL, Kellgren-Lawrence; KAAI, knee adduction angular impulse, BW, body weight; Ht, height; SD, standard deviation; CI, confidence interval.												

Table 5.6 Study characteristics and findings for cross-sectional studies

	Author	Year	Country	Footwear Intervention(s)		Participant characteristics						Study findings
				Control	Intervention	Study population	Knee pathology	Sample size	Age (SD)	Female (%)	BMI	
[96]	Bagheri	2020	Iran	Conventional footwear	Rocker soled footwear	ACL reconstruction (4-11 months post-surgery)	ACL	10	24.5 (3.83)	0	24.3 (3.46)	• Intervention footwear significantly increased knee flexion angle from heel strike to 25% stance (p = 0.03). o Intervention footwear (12.99 ± 3.8 degrees) o Control footwear (11.32 ± 3.1 degrees) • No differences in knee flexion ankle at heel strike were observed between footwear conditions (p = 0.16) o Intervention footwear (6.77 ± 3.8 degrees) o Control footwear (5.56 ± 3.5 degrees) • No differences in peak knee flexion angle during the first half of stance were observed between footwear conditions (p = 0.51) o Intervention footwear (18.35 ± 3.5 degrees) o Control footwear (17.77 ± 3.5 degrees).
[97]	Bennell	2013	Australia	Conventional footwear	Variable stiffness footwear	Medial tibiofemoral knee OA (KL grade 2-4)	knee OA	30	63.3 (9.7)	17 (57)	28.6 (3.6)	• Intervention footwear significantly reduced peak KAM (p = 0.002) and KAAI (p < 0.001) compared to the control footwear o SD percentage change in peak KAM in the intervention footwear compared to the control footwear: -7.9 ± 8.9% (range -42.9% to 6.4%, p = 0.002) o SD percentage change in KAAI in the intervention footwear compared to the control footwear: -8.7 ± 11.2% (range -55.3% to 10.1%, p < 0.001) • No differences in KFM were observed between footwear conditions (p = 0.60).
[99]	Bonacci	2018	Australia	Standard running footwear	Minimalist footwear	Recreational runners with PFP, clinical diagnosis, pain >30/100	PFPS	15	32.6 (9.6)	12 (86.6)	23.3 (3.07)	• Intervention footwear at increased cadence significantly reduced peak PFJ stress, peak PFJRF, peak knee extensor moment and peak knee flexion compared to preferred cadence (p < 0.001). • Peak PFJ stress (MPa) (SD) o Control footwear at preferred cadence, 12.27 (2.92) o Control footwear at increased cadence, 10.37 (1.99) o Intervention footwear at preferred cadence, 10.39 (1.93) o Intervention footwear at increased cadence, 8.95 (2.23) • Peak PFJRF (N/kg) (SD) o Control footwear at preferred cadence, 43.14 (14.03) o Control footwear at increased cadence, 35.08 (9.08) o Intervention footwear at preferred cadence, 35.93 (10.56) o Intervention footwear at increased cadence, 30.03 (10.16) • Peak knee extensor moment (Nm/kg) (SD) o Control footwear at preferred cadence, 1.23 (0.29) o Control footwear at increased cadence, 1.08 (0.19) o Intervention footwear at preferred cadence, 1.08 (0.22) o Intervention footwear at increased cadence, 0.95 (0.95)

												• Peak knee flexion angle (degree) (SD) o Control footwear at preferred cadence, 40.62 (7.60) o Control footwear at increased cadence. 37.03 (6.78) o Intervention footwear at preferred cadence, 38.03 (7.03) o Intervention footwear at increased cadence, 35.61 (6.70) • Intervention footwear at increased cadence significantly reduced PFJ stress and PFJRF by 29% ($p < 0.001$), PFJ stress by 15% ($p < 0.001$) and PFJRF by 17% ($p < 0.001$) compared to control footwear.
[98]	Bonacci	2020	Australia	Standard running footwear	Minimalist footwear	Recreational runners with PFP, clinical diagnosis, pain >30/100	PFPS	15	32.6 (9.6)	12 (80)	23.3 (3.07)	• No difference in preferred running cadence (steps per minute) was observed between footwear conditions ($p = 0.215$). o Preferred cadence in control footwear, 165.4(13.3) o Preferred cadence in intervention footwear, 168 (13.4) • There were significant differences in running cadence between conditions ($p < 0.001$). o Cadence in the control footwear + 10% cadence compared with the control footwear at preferred cadence, mean difference 15.8 ($p < 0.001$) o Cadence in the intervention footwear + 10% cadence compared with the intervention footwear at preferred cadence, mean difference, 13.3 ($p < 0.001$) • Minimalist footwear had no effect on kinematic variability ($p > 0.0037$)
[100]	Erhart	2008	USA	Conventional footwear	Variable stiffness footwear	Medial knee osteoarthritis symptoms	Knee OA	79	60.2 (9.8)	37 (46.8)	NR	• Intervention footwear significantly reduced peak KAM by 2.4% ($p < 0.01$) at slow walking speed and 6.2% ($p<0.001$) at fast walking speed, compared to control footwear. • Peak knee adduction moment, mean (SD) %Bw x Ht o Slow speed: intervention 2.67 (0.92), control 2.73 (0.91) o Normal speed: intervention 2.74 (0.95), control 2.87 (0.99) o Fast speed: intervention 3.07 (1.11), control 3.28 (1.17) • Peak KAM increased with walking speed in the intervention ($P = 0.02$) and control footwear ($p < 0.001$). • The magnitude of change in peak KAM ranged from a 20% reduction to a 7% increase with intervention footwear • Intervention footwear significantly reduced knee and hip abduction moments at all walking speeds ($p < 0.001$). • No differences were observed for the ankle inversion moment at any walking speed ($p > 0.05$) • Intervention footwear significantly increased the ankle eversion moment at normal and fast speeds ($p < 0.001$). • No differences in walking speed were observed between footwear conditions at any walking speed ($p > 0.05$) • Intervention footwear significantly increased toe-out angle at fast walking speed only ($p = 0.011$)
[101]	Ferrigno	2017	USA	Own footwear	Minimalist footwear	Symptomatic medial knee OA (KL 2 and 3)	knee OA	39	60.2 (8.7)	31 (79.4)	30.0 (4.2)	• Intervention footwear significantly reduced stride length compared to own footwear ($p = 0.014$) o Own footwear 1.31 (0.15), intervention footwear 1.29 (0.14) • Intervention footwear significantly reduced KAM1 by 5.4% ($p = 0.004$) and KAM2 by 3% ($p = 0.020$) compared to own footwear. o KAM1: own footwear 2.41 (0.95), intervention footwear 2.29 (0.99) ($p = 0.004$)

												○ KAM2: own footwear 2.71 (1.04), intervention footwear 2.63 (0.99) (p = 0.022)
[102]	Jang	2018	Korea	Conventional footwear	Laterally Wedged footwear	Medial knee OA (grade 1-4)	knee OA	93	61 (range 48-76)	93 (100)	24.8(range 18.5-30.0)	• Intervention footwear significantly reduced KAM1 compared to control footwear at all grades of knee OA (p = 0.001). ○ Grade 1 Peak KAM mean (Nm/kg) (SD): Intervention 0.32 (0.17), control footwear 0.35 (0.17) ○ Grade 2 Peak KAM mean (Nm/kg) (SD): Intervention 0.35 (0.15), control footwear 0.40 (0.16) ○ Grade 3 Peak KAM mean (Nm/kg) (SD): Intervention 0.39 (0.16), control footwear 0.45 (0.18) ○ Grade 4 Peak KAM mean (Nm/kg) (SD): Intervention 0.60 (0.16), control footwear 0.67 (0.15) • No differences in KAM2 were observed between footwear conditions (p = 0.087). • Post hoc analysis found control footwear significantly increased KAM1 compares to intervention footwear (grade 2: p = 0.014, grade 3: p = 0.010). • No differences in peak ankle eversion angle (p = 0.353) and peak eversion ankle angle between footwear conditions (p = 0.612) at KAM1.
[103]	Jenkyn	2011	USA	Conventional footwear	Variable stiffness footwear	Medial knee osteoarthritis symptoms	knee OA	32	58.7 (9.3)	12 (32.5)	NR	• Intervention footwear significantly reduced peak KAM by 6.6% (p=0.002) compared to control footwear. ○ KAM (%Bw x Ht) (SD): intervention 2.57 (1.00), control 2.76 (1.07) ○ KAM was reduced in 25/32 participants in the intervention group • No differences in total GRF and the medial-lateral component of GRF were observed between footwear conditions (p = 0.424). ○ Total GRF (%BW): intervention 837.61 (159.67), control 848.81 (169.45) • Intervention footwear significantly reduced the frontal plane level arm by 1.6% for the affected knee (p=0.02) compared to control footwear. ○ Lever arm (%Ht): intervention 4.34 (0.69), control 4.46 (0.76) ○ Lever arm was reduced 27/32 participants in the intervention group • Intervention footwear significantly shifted the COP medially by 3.8% (p=0.003) compared to control footwear. ○ Medial-lateral COP (cm): intervention -1.58 (0.48), control -1.53 (0.42)
[119]	Jones	2015	UK	Conventional footwear	Minimalist footwear	Medial knee OA (KL grade 2-3)	knee OA	70	60.3 (9.6)	27 (38.6)	30.5 (4.9)	• No differences in KAM1 (p = 0.38) and KAM2 (p = 0.34) were observed between footwear conditions. ○ KAM1 Nm/kg mean (SD): intervention 0.39 (0.16), control 0.39 (0.16) ○ KAM2 Nm/kg mean (SD): intervention 0.32 (0.14), control 0.33 (0.14) • No differences in KAAI (p = 0.09) and KFM (p = 0.611) were observed between footwear conditions. ○ KAAI Nm/kg*s mean (SD): intervention 0.15 (0.07), control 0.16 (0.07) ○ KFM Nm/kg mean (SD): intervention 0.60 (0.24), control 0.61 (0.24) • Intervention footwear significantly increased walking speed by 0.03m/s (p < 0.001) compared with to control footwear. ○ Walking speed m/s mean (SD): intervention 1.11 (0.34), control 1.08

												(0.33)
[104]	Kean	2013	Australia	Conventional footwear	Variable stiffness footwear	Medial tibiofemoral knee OA (KL grade 2-4)	knee OA	30	63.3 (9.7)	17 (57)	28.6 (3.6)	• Intervention footwear significantly reduced peak KAM by 7.2% (p < 0.001) and KAM impulse by 7.9% (p < 0.01) o Peak KAM (Nm/(BW x HT)%): intervention 3.73 (1.30), control 4.02 (1.35) o KAAI (Nms/(BW x HT)%): intervention 1.17 (0.47), control 1.26 (0.48) • Intervention footwear significantly decreased the knee-GRF lever arm by 8.3% (p <0.001) and laterally shifted in the centre of pressure by 30.4% (p < 0.001) compared to control footwear o Mean knee-GRF lever arm (mm): intervention 35.97 (16.75), control 39.22 (16.97) o COP offset (mm): intervention -8.67 (4.32), control -6.65 (4.08) • No differences in frontal plane GRF magnitude (p = 0.60), medial GRF magnitude (p = 0.85), lateral trunk lean or stance duration (p = 0.15) were observed between footwear conditions. • No differences in hip–knee–ankle angle (p =0.05) were observed between footwear conditions • No differences in stance time (p = 0.00) and walking speed (p = 0.14) were observed between footwear conditions
[105]	Khan	2018	Pakistan	NA	Other footwear (party, casual, sandal)	Bilateral symptomatic medial knee OA (KL 1-2)	knee OA	25	55.48 (5.78)	0	NR	• Party footwear significantly increased KAM1 compared to casual footwear (p=0.03) and sandals (p = 0.04). o KAM1 (Nm/(BW x Ht)%) (SD); party 5.22 (1.1), casual 3.49 (0.74), sandal 4.41 (0.92) • Party footwear significantly increased KAM2 compared to casual footwear (p=0.03) and sandals (p = 0.02). o KAM2 (Nm/(BW x Ht)%) (SD): party 2.39 (0.90), casual 2.02 (0.77), sandal 2.23 (0.81) • Party footwear significantly increased KAAI compared to casual footwear (p = 0.03) and sandals (p = 0.04). o KAAI (Nms/ (BW x Ht)%) (SD): party 2.80 (0.41), casual 1.71 (0.28), sandal 2.11 (0.33)
[106]	Kutzner	2013	Germany	NA	Rocker soled footwear	Total knee joint replacement	knee OA	6	69 (4.7)	1 (16.6)	29.8 (3.09)	• Significant reductions knee joint forces were observed in rocker-soled footwear at late stance (p <0.0125). • No differences in medial compartment force at late stance were observed between footwear conditions.
[107]	Madden	2014	Australia	Conventional footwear	Rocker soled footwear	Knee OA (KL ≥2)	knee OA	30	61 (7.3)	15 (50)	28.3 (3.7)	• Intervention footwear significantly reduced peak KAM compared to control footwear (p < 0.001). o Peak KAM (Nm/BW x Ht%) (SD): intervention 3.76 (1.31), control 4.04 (1.33) • No differences in KAM impulse was observed between footwear conditions (p = 0.13). o KAAI (Nm/BW x Ht%) (SD): intervention 1.21 (0.52), control 1.24 (0.49)

												• No differences in KFM (p = 0.36) and walking speed (p = 0.06) were observed between footwear conditions. o Peak KFM (Nm/BW x Ht%) (SD): intervention 3.48 (1.95), control 3.53 (1.93) o Walking speed (m/s) (SD): intervention 3.3 (2.4), control 3.3 (2.2)
[108]	Madden	2017	Australia	Conventional footwear	Rocker soled footwear	Knee OA (KL ≥2)	knee OA	30	61 (7.3)	16 (50)	28.3 (3.7)	• Intervention footwear reduced KAM in 23/30 participants. Of those participants, changes in knee-GRF lever arm and frontal plane GRF magnitude at peak KAM were significant predictors (p < 0.001). o Peak KAM (Nm) (SD): intervention 48.6 (18.1), control 54.1 (19.3) o KAAI (Nms): intervention 15.0 (7.2), control 15.7 (7.2) o Knee-GRF lever arm (mm) at time of peak KAM: intervention 44.0 (18.0), control 46.4 (17.0) o Frontal plane GRF magnitude (N) at time of peak KAM: intervention 891.7 (150.3), control 902.9 (163.7)
[109]	Mauricio	2018	Germany	Own footwear	Laterally Wedged footwear	Medial knee OA (ACR criteria)	knee OA	52	59 (10)	30 (57.6)	27.5 (4.9)	• Intervention footwear significantly reduced peak KAM by 9% compared to control footwear (p < 0.005). o Peak KAM1 (Nm/kg) (SD): intervention 0.44 (0.34), control 0.55 (0.34) • Intervention footwear significantly reduced KAAI by 18% compared to control footwear (p < 0.005). o KAAI (Nm*s/kg) (SD): intervention 0.25 (0.12), control 0.28 (0.16) • Intervention footwear significantly increased KFM compared to control footwear (p > 0.005) o Peak KFM (Nm/kg) (SD): intervention 0.37 (0.35), control 0.35 (0.32) • Intervention footwear significantly reduced step length by 4%, double limb support by 12% and increased single limb support by 4% compared to control footwear (p < 0.005) o Step length (m) (SD): intervention 0.64 (0.11), control 0.68 (0.12) o Double support phase (%): intervention 12.30 (2.93), control 13.76 (3.11) o Single support phase (%): intervention 37.01 (2.72), control 35.70 (2.84)
[110]	Metcalf	2016	Australia	Neutral footwear	Variable stiffness footwear	Symptomatic medial knee OA	knee OA	32	61.3 (7.8)	19 (59.3)	NR	• Intervention footwear significantly reduced KAM1 by 4.9% (p < 0.001) and KAAI by 6.3% (p < 0.001) compared to control footwear. o KAM1 mean-difference (intervention-control): -0.22 Nm/Bw x Ht% (95% CI -0.31 to -0.14) o KAAI mean difference (intervention-control): -0.09 Nm*s/BW x Ht% (95% IC -0.11 to -0.07) • Intervention footwear significantly reduced peak inversion angle (p<0.001) compared to control footwear • Intervention footwear significantly increased peak eversion angle (p < 0.001), peak rearfoot eversion angle (p < 0.001) and frontal plane excursion (p = 0.003). • No differences in frontal plane excursion (p = 0.511), peak rearfoot inversions (p = 0.061) and forefoot-to-rearfoot angle at peak inversion (p=0.050) were observed between footwear conditions • No differences in gait velocity and stride length were observed between footwear conditions (p > 0.05).

[111]	Paterson	2017	Australia	NA	Motion-control footwear (athletic, casual, dress), minimalist footwear (athletic, casual, dress)	Medial knee OA (KL ≥2), 4/10 pain	knee OA	28	63.7 (7.6)	13 (47)	29.5 (3.7)	• Minimalist footwear significantly reduced KAM ($p < 0.001$) and KAM impulse ($p < 0.001$) compared to motion control footwear in the athletic footwear category. o Peak KAM (Nm/BW x Ht%) (SD): minimalist footwear 0.25 (0.46), motion control footwear 0.48 (0.45) o KAAI (Nm.sec/(BW x HT)%) (SD): minimalist footwear 0.06 (0.09), motion control footwear 0.13 (0.09) • Casual footwear significantly increased KAM compared to athletic and dress ($p = 0.038$). o Peak KAM (Nm/BW x Ht%) (SD): casual minimalist footwear 0.38 (0.43), dress minimalist footwear 0.26 (0.56), athletic minimalist footwear 0.25 (0.46), casual stable supportive footwear 0.74 (0.48), dress stable supportive footwear 0.15 (0.11), athletic motion control footwear 0.48 (0.45) • Dress footwear category significantly increased KFM compared to the athletic footwear category ($p = 0.017$). o Peak KFM (Nm/BW x Ht%): casual minimalist footwear 0.15 (0.72), dress minimalist footwear 0.08 (0.77), athletic minimalist footwear 0.01 (0.75), casual stable supportive footwear 0.05 (0.75), dress stable supportive footwear 0.08 (1.07), athletic motion control footwear 0.48 (0.45)
[112]	Sacco	2012	Brazil	High heeled footwear	Minimalist footwear	Medial knee OA (KL grade 2-3)	knee OA	17	65 (6)	17 (100)	29.2 (3.3)	• Intervention footwear significantly reduced KAM1 by 21.4% ($p < 0.001$), KAM2 by 9.2% ($p < 0.001$) and knee adduction impulse by 16.3% ($p < 0.001$) compared to control footwear. o Peak KAM1 BW x Ht% (SD): intervention 3.45 (1.23), control 4.08 (1.28) o Peak KAM2 BW x Ht% (SD): intervention 2.49 (1.36), control 2.74 (1.46) o KAAI sX BW x Ht% (SD): intervention 139.07 (82.09), control 165.97 (92.29)
[113]	Shakoor	2008	USA	(A) Own footwear	Minimalist footwear	Symptomatic knee OA (KL grade 2-3)	knee OA	28 (A)	59 (9)	24 (85.7)	28.7 (5.1)	• Intervention footwear significantly reduced peak KAM by 8% ($p < 0.05$) and GRF by 3% ($p < 0.05$) compared to control footwear. o Peak KAM (%BW x H) (SD): Intervention 2.49 (0.80), control 2.71 (0.84) o GRF (%BW) (SD): Intervention 106 (46), control 109 (10) • No differences in KAAI were observed between footwear conditions ($p > 0.05$). o KAAI (%BW x H) (SD): intervention 0.87 (0.45), control 0.93 (0.46)
				(B) Motion control footwear				20 (B)	57 (9)	16 (80)	29.6 (4.7)	• Intervention footwear significantly reduced peak KAM by 13% ($p < 0.05$), KAAI by 10% ($p < 0.05$), GRF by 2% ($p < 0.05$) compared to control footwear. o Peak KAM (%BW x H) (SD): intervention 2.66 (0.69), control footwear 3.07 (0.75) o KAAI (%BW x H) (SD): intervention 0.96 (0.42), control footwear 1.07 (0.42) o GRF (%BW) (SD): intervention104 (9), control footwear 106 (9)

												• No differences in hip, knee, and ankle ROM were observed between footwear conditions (p > 0.05).
[114]	Shakoor	2010	USA	NA	Motion-control footwear, minimalist footwear, other footwear (clogs, flip-flops)	Symptomatic knee OA (KL grade 2-3)	knee OA	31	57(10)	10 (32.2)	29.3(4.8)	• Minimalist footwear and flip-flops significantly reduced KAM compared to motion-control footwear and clogs (p < 0.05). o Peak KAM (Nm/(BW x Ht%)) (SD): clog 3.1 (0.7), motion-control 3.0 (0.7), minimalist 2.8 (0.7), flip-flop 2.7 (0.8) • No differences in walking speed were observed between footwear conditions.
[115]	Starkey	2022	Australia	Minimalist footwear	Motion control footwear	Medial knee OA (KL grade ≥2)	knee OA	28	63.9 (4.8)	12 (42.8)	29.6 (3.4)	• Intervention footwear significantly reduced MTCF at 5–18% of stance, loading impulse (p < 0.001) and mean loading rate compared to control footwear (p = 0.001). o Loading stance joint contact impulse (SD): intervention 0.08 (0.02), control 0.10 (0.02) o Mean loading rate (SD): intervention 12.61 (3.28), control 14.03 (3.84) • Intervention footwear significantly increased peak KAM (p < 0.001) and higher stance KAAI (p = 0.001) compared to control footwear. o Peak KAM (SD): Intervention 0.52 (0.15), control 0.49 (0.15) o Overall stance KAAI (SD): Intervention 0.17 (0.05), control 0.15 (0.05) • No differences in KAM loading stance impulse (p = 0.36), mean KAM loading rate (p = 0.38), max KAM loading rate (p = 0.11) or walking speed (p = 0.68) were observed between footwear conditions. o Loading (8%-17%) stance KAAI (SD): intervention 0.04 (0.01), control 0.04 (0.15) o Max KAM loading rate (SD): intervention 6.71 (1.78), control 7.29 (2.44)
[116]	Steiner	2022	USA	Conventional footwear	Variable stiffness footwear	Knee OA with moderate pain	knee OA	14	65.7 (4.2)	10 (71.4)	25.3 (3.6)	• No differences in total, medial or lateral peak knee contact forces were observed between footwear conditions. o Total knee contact force (BW) (SD): intervention 2.8 (0.7), control 2.72 (0.68) (p = 0.29) o Peak medial knee contact force (BW) (SD): intervention 1.85 (0.46), control 1.78 (0.46) (p = 0.10) o Peak lateral knee contact force (BW) (SD): intervention 0.95 (0.27), control 0.95 (0.24) (p = 0.84) • No differences in walking speed, stride length and stride width were observed between footwear conditions o Walking speed (m/s) (SD): intervention 1.19 (0.07), control 1.19 (0.06) (p = 0.9) o Stride length (m) (SD): intervention 1.32 (0.14), control 1.35 (0.11) (p = 0.5) o Stride width (m) (SD): intervention 0.11 (0.02), control 0.11 (0.02) (p = 0.9) • No differences in summed muscle moment magnitudes to first peak medial contact forces (p = 0.17), lateral contact forces (p = 0.26) and knee flexion angle at first peak contact force (p = 0.12) between footwear conditions.

[117]	Tateuchi	2014	Japan	Minimalist footwear	Rocker soled footwear	Physician diagnosed medial knee OA	knee OA	17	63.6 (7.9)	17 (100)	23.0 (2.6)	• Intervention footwear significantly reduced knee flexion moment by 16.7% compared to control footwear ($p < 0.05$). ○ KFM1 (Nm/kgm) (SD): intervention 0.25 (0.14), control 0.30 (0.19) ($p = 0.047$) • No differences in KAM1, KAM2 and KAAI were observed between footwear conditions. ○ KAM1 (Nm/kgm) (SD): intervention 0.44 (0.09), control 0.45 (0.08) ($p = 0.549$) ○ KAM2 (Nm/kgm) (SD): intervention 0.35 (0.08), control 0.33 (0.09) ($p = 0.056$) ○ KAAI (Nms/kgm): intervention 0.18 (0.05), control 0.17 (0.05) ($p = 0.075$)
[16]	Thrombini-Souza	2011	Brazil	High heeled footwear	Minimalist footwear	Medial knee OA (KL 2, 3)	Medial knee OA	21	65 (5)	21 (100)	NR	• Intervention footwear significantly reduced peak KAM by 12% compared to control footwear ($p < 0.002$). ○ Peak KAM1 (Nm) (SD): intervention 2.58 (1.45), control 2.93 (1.43) ($p < 0.001$) ○ Peak KAM2 (Nm) (SD): intervention 1.92 (1.64), control 2.18 (1.59) ($p < 0.002$)
[118]	Walters	2019	UK	Conventional footwear	Laterally wedged footwear, motion control footwear	Post meniscectomy	Injury to the meniscus	7	29 (6.2)	5 (71.4)	NR	• No differences in KAM and KAAI were observed between footwear conditions ($p > 0.05$). ○ Differences in KAM (Nm/kg) (SD): laterally wedged -0.09 (0.08) motion control 0.06 (0.09), cushioned footwear 0.17 (0.09) ○ Differences in KAAI (Nm/kg s) (SD): laterally wedged -0.01 (0.03) motion control 0.02 (0.03), cushioned footwear 0.02 (0.06) ○ Differences in KFM (Nm/kg) (SD): laterally wedged -0.02 (0.03), motion control 0.02 (0.03), cushioned footwear 0.07 (0.10)

ACL, anterior cruciate ligament; PFJ, patellofemoral joint; PFP, patellofemoral pain; PFPS, patellofemoral pain syndrome; PFJRF, patellofemoral joint reaction force; COP, centre of pressure; GRF, ground reaction force; OA, osteo arthritis; NR, not reported; KAM, knee adduction moment; KAM1, 1st peak knee adduction moment; KAM2, 2nd peak knee adduction moment; KFM, knee flexion moment; KL, Kellgren-Lawrence; KAAI, knee adduction angular impulse, BW, body weight; Ht, height; SD, standard deviation; CI, confidence interval.

5.5 Footwear interventions

Footwear interventions included minimalist footwear [16, 88-92, 94, 95, 98, 99, 101, 111-114, 119], laterally wedged footwear [102, 109, 118], variable stiffness footwear [85-87, 93, 97, 100, 103, 104, 110, 116], motion-control footwear [111, 113, 115, 118], cushioned footwear [98, 99, 118] and rocker-soled footwear [96, 106-108, 117].

5.5.1 Minimalist footwear

Minimalist footwear was classified as having heel thickness less than 20 mm, offset (heel height less forefoot height) less than 7 mm, minimal sagittal sole rigidity, shoe mass less than 200 g and absence of motion control properties [88, 90-92, 94, 95, 100, 101, 112-114, 119]. Additionally, some footwear included grooves strategically placed at major flexion points of the foot [90, 92, 95, 101, 113, 119]. Minimalist footwear was used as an intervention for people with PFPS [98, 99] and knee OA [16, 88-92, 95, 101, 112, 113, 119].

5.5.2 Laterally wedged footwear

Laterally wedged footwear was classified as having a modified full-length midsole wedged laterally at 6-10 degrees embedded into the midsole. Laterally wedged footwear was used as an intervention for people with medial knee OA [102, 109] and people with meniscus injury [118].

5.5.3 Variable stiffness footwear

Variable stiffness footwear was classified as footwear with a midsole 1.3-1.5 times stiffer on the lateral aspect compared to the medial aspect. Asker C durometer values for the medial midsole were 55±2, with values for the lateral midsole 70-76±2. Additionally, some variable stiffness footwear was laterally-wedged with an angulation of 4-6 degrees [87, 97, 104, 110]. Variable stiffness footwear was used as an for intervention of people with medial knee OA [85-87, 93, 97, 100, 103, 104, 110, 116].

5.5.4 Motion-control footwear

Motion-control footwear was classified as having a heel thickness greater than 25 mm, offset greater than 10 mm, a midsole with a higher density medially compared to laterally, with a weight greater than 300 g. Motion-control footwear was used as an intervention for people with knee OA [111, 113, 115] and meniscus injury [118].

5.5.5 Cushioned footwear

Cushioned footwear was classified as having additional midsole cushioning in the heel or forefoot with uniform stiffness of the midsole. Additionally, cushioned footwear had a heel height of 30 mm, offset of 10 mm and weighed between 300-345 g. Cushioned footwear was used as an intervention for people with PFPS [98, 99] and people with meniscus injury [118].

5.5.6 Rocker-soled footwear

Rocker-soled footwear was classified as having a rounded sole in the anterior-posterior direction [106]. The heel height ranged from 45-60mm, forefoot height ranged from 30-35 mm [96]. The toe-rocker apex was centred 65% of the footwear length and angled at 15 degrees with 20 degree heel curve [108]. The weight of rocker soled footwear ranged from 370-650g [91, 117]. Rocker-soled footwear was used as an intervention for people with medial knee OA [91, 106, 108, 117] and ACL injury [96].

5.5.6 Conventional footwear

Conventional footwear was classified as having no specific motion-control or cushioning properties in the midsole [85-87, 90, 96, 97, 100, 102-104, 107, 110, 115, 119].

5.5.7 Other footwear

Other footwear was used to classify footwear used as a control condition that did not fall into the previously described categories. High-heeled footwear were classified as a having a heel height between 40-50 mm, used as control to compare with intervention footwear for people with knee OA [16, 92, 112]. Party footwear has a heel height of 2 mm [105]. Sandals were classified as having a rubber soled footwear with a leather upper and back strap [105]. Clogs has stiff sole and 50 mm heel height and 182-363 g weight [114]. Flip-flops were classified as flexible footwear with a 15 mm heel height and weighing 91 g [114]. Party footwear, sandals, clogs, and flip-flops were used in studies of people with knee OA.

5.6 Knee OA

5.6.1 Minimalist footwear

The long-term effect of minimalist footwear studies reported an 18-39% reduction in the knee adduction moment (KAM) compared to non-minimalist footwear at 24-weeks [88-90, 92]. Minimalist footwear studies reported a 20% reduction in KAM ($p = 0.002$) compared to identical-appearing conventional footwear [90, 92]. Another study reported an 18% reduction in first peak KAM (KAM1) ($p = 0.043$), and 29% reduction in knee adduction angular impulse (KAAI) ($p = 0.041$) in minimalist footwear compared to the participant's own footwear [89]. There was a strong correlation between the reduction in the KAM and frontal plane torsional stiffness at 24-weeks in minimalist footwear group compared to conventional footwear [90]. In prospective observational studies [94, 95], minimalist footwear was associated with a 20% reduction in KAM and a 19% reduction in the KAAI ($P < 0.001$) when compared to participant's own footwear at 24-weeks [94]. Minimalist footwear resulted in a shorter stride ($p < 0.01$) and greater cadence ($p < 0.01$) compared to participants own footwear [94].

In cross-sectional studies, minimalist footwear was associated with reductions in KAM by 27% during the midstance ($p < 0.001$) compared to high-heeled footwear [16]. Minimalist footwear also reduced peak KAM1 and the second peak KAM (KAM2) by 12% ($p = 0.002$) during stair descent compared to high-heeled shoes [112]. Another cross-sectional study found that minimalist footwear showed reduced stride length ($p = 0.014$), KAM1 by 5% ($p = 0.004$) and KAM2 by 3% ($p = 0.020$) when compared to participant's own footwear [101]. When compared to motion-control footwear, minimalist footwear reduce KAM1 by 13% ($p < 0.05$), KAAI by 10% ($p < 0.05$) and ground reaction forces by 2% ($p < 0.05$) [113]. Another cross-sectional study found motion-control, conventional footwear and high-heeled footwear resulted in a higher KAM ($P < 0.001$) and KAAI ($P < 0.001$) compared to minimalist footwear [111]. Minimalist footwear had a lower peak KAM ($p < 0.001$) and a lower stance KAAI ($p = 0.001$) when compared to motion-control footwear. However post-hoc testing demonstrated that compared to motion control footwear, minimalist footwear had a higher medial tibiofemoral contact force (MTCF) at 5-18% of stance ($p = 0.001$), higher muscle contribution to MTCF at 11–18% of stance, and higher external contribution to MTCF at 5–15% of stance [115]. Contrary to these findings, one cross-sectional study reported minimalist footwear did not produce a significant reduction in KAM1 compared to conventional footwear ($p = 0.38$) [119].

5.6.2 Laterally wedged footwear

In one cross-sectional study, laterally wedged footwear resulted in a 9% decrease in KAM and 18% decrease in KAAI, when compared to the participant's own footwear ($p < 0.001$) [109]. Laterally wedged footwear increased the knee flexion moment (KFM) compared to the participant's own footwear ($p < 0.001$) [109]. In another cross-sectional study, laterally wedged footwear reduced KAM1 by 13% compared to conventional footwear without lateral wedging ($p = 0.01$) [102]. No differences in hip abduction moments were observed between footwear conditions [102].

5.6.3 Variable stiffness footwear

Ten studies [85-87, 93, 97, 100, 103, 104, 110, 116] compared variable stiffness footwear to conventional footwear. In one RCT, variable stiffness footwear significantly reduced the peak KAM by 4% ($p = 0.001$) at baseline, 7% ($p < 0.001$) at 6-months when compared to conventional footwear [85]. Another RCT reporting findings at 6-months found that variable stiffness footwear significantly reduced peak KAM by 4% ($p = 0.02$) and KAAI by 3% ($p < 0.001$) compared to the conventional footwear [87]. Another RCT, reported that variable stiffness footwear reduced KAM by 6% ($p < 0.001$) compared to the conventional footwear at 12-months [86]. In one prospective observational study, significant reductions in KAM1 and KAAI were seen with variable stiffness footwear at 6-months compared to conventional footwear ($P < 0.05$) [93]. For participants wearing variable stiffness footwear KAM1 was reduced in all participants, while KAAI reduced in 72% of participants [93]. Walking speed did not change between footwear conditions ($p = 0.30$) [93]. Contrary to this, another cross-sectional study reported 18% of people saw an increase in KAM with variable stiffness footwear [100]. When walking in variable stiffness footwear, greater reductions in KAM1 were associated with increasing walking speed by 2% ($P < 0.01$) at slow walking speed, and

6% ($p < 0.001$) at fast walking speed [100]. Another cross-sectional study reported that variable stiffness footwear reduced KAM1 by 59% ($p < 0.001$) and KAAI by 6% ($p < 0.001$) when compared to conventional footwear [110], however, no changes in KFM were observed [97]. In contrast to these findings, another study reported no differences in KAM1 ($p = 0.06$), KAM2 ($p = 0.2$) and knee joint total ($p = 0.29$), medial ($p = 0.7$) and lateral contact force ($p = 1.0$) when wearing variable stiffness footwear compared to conventional footwear [116]. Walking with variable stiffness footwear shifted centre of pressure medially by 4% ($p = 0.003$), and reduced the frontal plane lever arm 2% ($p = 0.02$) [103]. Footwear containing both lateral-wedging and variable stiffness was associated with a 7-8% reduction in lever arm length [104] compared to a 2% reduction in variable stiffness footwear [103]. Ankle biomechanics of variable stiffness footwear were reported that peak inversion angle was reduced ($p < 0.001$), peak eversion angle was increased ($p < 0.001$), with no differences in frontal plane excursion ($p = 0.511$) compared to conventional footwear [110].

5.6.4 Motion-control footwear

Three studies used motion-control footwear as an intervention for knee OA [111, 113, 115]. Wearing motion-control footwear resulted in a 13% increase in KAM ($p < 0.05$) and 10% increase in KAAI ($p < 0.05$) compared to minimalist footwear [113]. No differences in KFM ($p < 0.133$) were seen between motion-control and minimalist footwear [111]. Similar increases in KAM with motion-control footwear were reported in other two cross-sectional studies compared to minimalist footwear [111, 115]. Contrary to these findings, one cross-sectional study found motion-control footwear was associated with reduced MTCF during loading stance (at 5-18% of stance), lower loading impulse ($p < 0.001$), lower mean loading rate ($p = 0.01$) and lower maximal loading rate ($p = 0.01$) when compared to minimalist footwear [115].

5.6.5 Rocker-soled footwear

Four studies used rocker-soled footwear as an intervention for knee OA [106-108, 117]. There was a 7% reduction in peak KAM with rocker soled footwear compared to conventional footwear ($p < 0.001$) [107]. However, the individual response to rocker-soled footwear was variable (-28.3-9.6%) with 23% participants displaying increases in peak KAM [107]. In those who decreased KAM with rocker-soled footwear, changes in knee-GRF lever arm and the magnitude of frontal plan of GRF at peak KAM, were significant predictors in the change in peak KAM ($p < 0.001$) [108]. In contrast to this study, another study found no differences in KAM1, KAM2, KAAI, KFM2 and GRF with rocker-soled footwear compared to minimalist footwear. However, first peak of KFM (KFM1) showed a significant reduction of 17% while wearing the rocker-soled footwear as compared to minimalist footwear [117]. One study found a 9% reduction ($P < 0.5$) in tibiofemoral contact forces when wearing rocker-soled shoes compared to barefoot walking [106].

5.7 PFPS

Two cross-sectional studies used minimalist footwear as an intervention for PFPS [98, 99]. When running at preferred cadence, minimalist footwear reduced patellofemoral joint stress by 15% and patellofemoral joint reaction force by 17% ($P < 0.001$) compared to cushioned footwear. When running with a 10% increase in cadence, minimalist footwear reduced patellofemoral joint stress and patellofemoral joint reaction force by 29% ($p < 0.001$) compared to cushioned footwear [99]. When running at preferred cadence, minimalist footwear reduced peak knee extensor by 13% ($p < 0.001$) and peak knee flexion angle by 3 degrees ($P < 0.001$) compared to cushioned footwear [99]. When running in minimalist footwear greater variability in hip internal/external rotation moments ($p < 0.001$), knee adduction/abduction moments ($p < 0.001$) and knee internal/external moment ($p < 0.001$) compared to cushioned footwear [98].

5.8 ACL reconstruction

One cross-sectional study used rocker soled footwear as an intervention for people with ACL reconstruction [96]. Rocker-soled footwear significantly increased the knee flexion angle from heel strike to 25% stance ($p = 0.03$) compared to conventional footwear. No differences were seen in knee flexion angle at heel strike ($p = 0.16$) of first peak knee flexion angle ($p = 0.51$) in rocker-soled footwear.

5.9 Meniscus injury

One cross-sectional study compared laterally wedged footwear, motion-control footwear, cushioned footwear to conventional footwear. There were no significant differences in KAM, KAAI and KFM between the four footwear conditions ($p > 0.05$) [118].

Chapter 6 : Discussion

6.1 Introduction

This chapter presents the discussion of the systemic literature review. Firstly, the findings of the review will be discussed. The strengths and limitations will then be examined. Lastly, the implications for clinical practice and future directions will be explored.

6.2 Findings

The aim of this systemic review was to identify and evaluate the evidence for the effectiveness of footwear on lower limb biomechanics in people with knee pathology. The findings of the review support that footwear is associated with changes to biomechanics at the knee. Despite the broad search strategy, the search only identified studies investigating knee OA, PFPS, ACL injury and meniscus injury. This may reflect the epidemiology of knee pathology, where knee OA affects 40% of people aged 60 years [6], PFPS affects up to 15% of runners [9] and the annual incidence of ACL and meniscus injuries being 60-70 per 100,000 people [120]. While PFPS, ACL and meniscus injuries are more commonly seen in sporting populations, these knee pathologies can progress to more long-term conditions such as OA [121].

Reducing load on the knee joint is a key management strategy for people with knee pathology [122]. Most studies used KAM as a surrogate measure for tibiofemoral joint loading, with higher KAM values indicative of greater compressive forces at the medial aspect of the knee. Despite this, the links KAM and medial knee compression are inconclusive [106]. Importantly, the use of the external KAM to infer internal joint loading is limited as it does not account for the contribution of muscular forces acting about the knee joint [115, 116].

Internal forces can be measured directly using in-vivo instrumented knee implants, however, this is highly invasive thus have low participant recruitment rate [106]. Recent modelling techniques utilising internal and external forces have been used to calculate MTCF, which may be a more appropriate measure of knee loading. Additionally, there is wide variability in KAM between participants in response to footwear interventions, ranging from 40% reductions in KAM to 15% increases in KAM [86, 97, 100, 107].

6.2.1 Knee OA

Footwear was found to influence key biomechanical variables at the knee joint in people with knee OA. Footwear increases KAM compared to barefoot which is in agreement with most articles in this review [16, 94, 95, 97, 102, 105, 107, 112-114, 119]. Although barefoot walking is associated with reduced KAM, this may not be a practical strategy to adopt in daily life. In older adults, walking barefoot is associated with increased risk of falls [123]. Of the footwear types identified in this review, minimalist footwear was associated with the greater reductions in KAM compared to motion-control footwear [111, 113, 115], high-heeled footwear [16, 112] and participant's own footwear [88, 89]. This may be due to the design of minimalist footwear which aims to mimic barefoot walking through having a lower sole height, increased midsole flexibility and an absence of motion-control properties [101, 113]. Despite these biomechanical improvements seen with minimalist footwear, a recent RCT of people with knee OA compared flat-flexible footwear to motion-control footwear found greater improvements in pain with motion-control footwear [115, 124]. This suggests that rather than reducing KAM, motion-control footwear offers other biomechanical benefits such as reducing MTCF and loading rate/impulse at the knee [124]. This suggests that motion-control footwear may be a more appropriate intervention for people with knee OA.

Variable stiffness [85-87, 93] and laterally wedged footwear [102, 109] were also found to reduce KAM, through the reduction of the frontal plane lever arm from the knee to the ground [103]. With both interventions, there was variability in the people that responded with a reduction in KAM, which may be due to differences in disease severity, lower limb alignment, gait patterns and lower limb biomechanics [97].

Rocker-soled footwear was also found to reduce KAM [107] and KFM [117]. These changes may be due to the reduced knee range of motion observed throughout stance, resulting in reduced knee loading [125]. Importantly, the individual response to rocker-soled shoes was variable with nearly a quarter of the people experiencing an increase in peak KAM [107]. Having a valgus alignment of the knee was associated with reduced KAM with rocker-soled shoes [108]. This may limit the use of rocker-soled footwear in this population as a varus alignment of the knee is associated with incident knee OA [126]. Currently there is no data on their effect on balance in people with knee OA. Wearing rocker-soled footwear has is associated with greater postural instability in people with lower-back pain [127]. This may be an important consideration as people with knee OA demonstrate greater postural sway and reduced dynamic balance compared to controls [128].

6.2.2 Patellofemoral pain syndrome

Minimalist footwear was shown to reduce PFJ stress in people with PFPS. The mechanism of PFJ stress reduction may be due to the reduced knee flexion seen when running in minimalist footwear [99]. These changes may be important because excessive PFJ stress can exacerbate PFPS due to increases in subchondral bone metabolic activity [129]. The reduction in knee flexion seen may also be due to adopting a midfoot and forefoot strike pattern, which is often seen when running in minimalist footwear. [54, 59]. Further reductions in knee flexion were seen with increases in cadence, suggesting that a combination of minimalist footwear and increases to cadence is beneficial for people with PFPS.

Minimalist footwear was also associated with increased movement variability at the hip and knee [98]. Reductions in movement variability have been suggested as a mechanism for overuse injuries [130]. The variability in lower limb movement may be beneficial for people with PFPS with changes in loading patterns resulting in differences in the distribution of forces at the knee [98]. These changes were only measured during five minutes of running, so it is unclear what the long-term implications of this increase in variability are. Additionally, it is unclear if these changes are also linked with reductions in PFJ stress and patient-reported outcomes.

6.2.3 ACL injury

Rocker-soled footwear was shown to increase knee flexion in people following ACL-reconstruction surgery [96]. These changes are important as reduced knee flexion is commonly observed in people with ACL injuries compared to healthy controls [131], with increased knee flexion being associated with reduced ACL loading [132]. Additionally, exercise prescription and gait training are the most commonly used interventions to improve knee joint range of motion and functional mobility in people with ACL injuries [133]. Thus, rocker-soled footwear may act as an adjunct tool to modify gait patterns in the sagittal plane for people with ACL injuries during the rehabilitation period post-surgery.

6.2.4 Meniscus injury

No differences were found between laterally wedged, cushioned footwear, however, laterally wedged footwear was the only intervention to reduce KAM in people with meniscus injuries post-surgery [118]. People that have undergone meniscectomy experience a higher peak KAM and are at greater risk of developing tibiofemoral knee OA compared to healthy controls [134]. Cushioned and stability footwear were found to increase EKAM [118] which may be a result of the varus alignment seen in people post-meniscectomy [134].

6.3 Strengths and limitations

Strengths of this study include the broad search strategy and use of the PRISMA guidelines. This review is not without limitations. The majority of studies included participants with knee OA, with limited studies of other knee pathologies. Differences in the reporting of the duration of symptoms, severity of pain and disease severity across studies made it difficult to make recommendations for different clinical subgroups. Studies in PFPS, ACL and meniscus injuries reported on the immediate effects of footwear on lower limb biomechanics, and it is not known if these changes are retained over time. The reporting on footwear characteristics varied between studies making it difficult to determine if the benefits associated with footwear were due to specific characteristics or the footwear itself. As the aim of this review was focused on biomechanics, it is unclear how these changes translate to improvements in patient-reported outcomes.

6.4 Implications for clinical practice

The widest range of footwear interventions investigated were those for people with knee OA, with KAM the most investigated biomechanical outcome. If the goal is to reduce KAM, minimalist footwear appears to result in the greatest reduction in KAM, however, this footwear might not be appropriate for all people. Recent studies have suggested that motion-control footwear may be more appropriate for people with moderate to severe radiographic knee OA [124]. Other interventions such as laterally wedged and variable stiffness footwear can also reduce KAM, however, are not as readily available commercially so access to these may be problematic.

Running in minimalist footwear resulted in reductions in knee flexion for people with PFPS. As reduced knee flexion is associated with reduced loading at the patellofemoral joint, this may be a positive change for people with PFPS. Care should be taken when recommending this category of footwear to people as the transition to minimalist footwear can increase the risk of developing other lower limb injuries [135]. As reductions in knee flexion are also seen with an increase in cadence, suggests that a combination of footwear and gait retraining should be considered for people with PFPS.

Rocker-soled footwear intervention has the potential to be used as a tool in the rehabilitation of people following ACL-reconstruction due to its ability to increase knee flexion. As ACL injuries typically occur during activities involving jumping and rapid-changes in direction, rocker-soled footwear might not be an appropriate intervention during the return-to-sport period as their effect on lower limb biomechanics during these specific activities is not known. For people with meniscus injuries, the limited number of studies and small sample size makes it difficult to make recommendations for the most appropriate footwear in this population.

6.5 Future directions

There was variation in the response to footwear interventions with differences in the duration of symptoms, disease severity and lower limb biomechanics possible reasons for this. Examination of different clinical sub-groups may help to identify people most likely to respond positively to specific footwear interventions. Additionally, being able to identify people that might respond negatively to a specific type of footwear may help clinicians with the selection of footwear. Comparing biomechanical outcomes to patient-reported outcomes is important to help guide the most appropriate choice of footwear for people with knee pathology. As a reduction in KAM does not guarantee a reduction in loading, the assessment of multiple outcomes such as KAM, KAAI, KFM and MTCF should be considered to the gain the best insight into knee joint loading. In conditions such as PFPS, ACL and MCL injuries, future studies should look to evaluate biomechanical outcomes longitudinally to determine if the changes found are maintained over time. The acceptability of footwear is an important factor in adherence to wearing the footwear and that future studies should investigate how to make footwear interventions more usable for people with different types of foot and lower limb pathologies.

Chapter 7 : Conclusion

This systematic review has identified footwear interventions for people with knee OA, PFPS, ACL injury and meniscus injury that were associated with changes to lower limb biomechanics. Minimalist footwear resulted in the greatest reduction in KAM and motion-control footwear the greatest reduction in MTCF for people with knee OA. Minimalist footwear reduced knee flexion in people with PFPS. Rocker-soled footwear increased knee flexion in people following ACL-reconstruction. Evidence for the use of footwear in meniscus injuries is inconclusive.

Chapter 8 : References

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