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Review

Barefoot vs common footwear: A systematic review of the kinematic, kinetic and muscle activity differences during walking

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ABSTRACT

Habitual footwear use has been reported to influence foot structure with an acute exposure being shown to alter foot position and mechanics. The foot is highly specialised thus these changes in structure/position could influence functionality. This review aims to investigate the effect of footwear on gait, specifically focussing on studies that have assessed kinematics, kinetics and muscle activity between walking barefoot and in common footwear. In line with PRISMA and published guidelines, a literature search was completed across six databases comprising Medline, EMBASE, Scopus, AMED, Cochrane Library and Web of Science. Fifteen of 466 articles met the predetermined inclusion criteria and were included in the review. All articles were assessed for methodological quality using a modified assessment tool based on the STROBE statement for reporting observational studies and the CASP appraisal tool. Walking barefoot enables increased forefoot spreading under load and habitual barefoot walkers have anatomically wider feet. Spatial-temporal differences including, reduced step/stride length and increased cadence, are observed when barefoot. Flatter foot placement, increased knee flexion and a reduced peak vertical ground reaction force at initial contact are also reported. Habitual barefoot walkers exhibit lower peak plantar pressures and pressure impulses, whereas peak plantar pressures are increased in the habitually shod wearer walking barefoot. Footwear particularly affects the kinematics and kinetics of gait acutely and chronically. Little research has been completed in older age populations (50+ years) and thus further research is required to better understand the effect of footwear on walking across the lifespan.

1. Introduction

Humans are one of the few species who have mastered bipedal locomotion and their foot has evolved to be the basis for such a specialised gait. The human foot alone comprises 26 bones, 33 joints and 19 muscles [1]. The bones are arranged to form a medial longitudinal arch which makes it ideal for its function of supporting the weight of the body and spreading the forces experienced during gait [2]. Aside from the structure of the bones there is a complex array of muscles, both internal and external of the foot, which combine with the somesthetic system to control balance and movement [3]. Kennedy et al. [4] reported the presence of 104 cutaneous mechanoreceptors located in the foot sole. Furthermore receptor distribution was primarily where the foot is in contact with the ground, and when the foot was unloaded no background activity was found. In addition there are more fast adapting units than slow suggesting a high dynamic sensitivity [4]. Collectively these factors evidence the role of the human foot in balance and movement control but what is less clear is the impact of wearing shoes on the human foot and whether this may influence movement control and associated variables during walking gait.

Anthropological evidence suggests that footwear began to be worn approximately 40,000 years ago [5]. This is hypothesised based on the observations of a reduction in toe length at this time indicating a reduction in reliance on and loading of the lesser toes during locomotion [6]. Furthermore as footwear has evolved from simple open-toe sandals to more complex items of fashion, with their design being increasingly dependent on aesthetics, the potential impact on foot function has been overlooked. Pointed toe and closed toe shoes have become increasingly prominent in Western societies and the restriction of area within the toe box potentially contributes to, now deemed common, toe deformities such as hallux valgus, a valgus deformity on the first metatarso-phalangeal joint [7]. This is particularly a problem in advanced age with the over two thirds of the older population's feet being

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considerably wider than the footwear available [8]. Additionally research has reported that wearing high heels of 5 cm or higher over a minimum of a two-year period has significant effects to the muscle-tendon unit at the ankle [9,10]. Csapo and colleagues [9] found a significant reduction in the gastrocnemius medialis fascicle lengths and significantly greater Achilles' tendon stiffness in the high heels group, resulting in a more plantar flexed ankle position at rest and a reduced active range of motion. This demonstrates the modifiable nature of the foot-ankle complex and the importance of wearing appropriate footwear to maintain good foot health and function.

Research has also shown how certain footwear can directly influence function. A common feature of modern athletic footwear is that of increased sole thickness which is marketed as providing cushioning against harmful impacts. Recent research has demonstrated that wearing this type footwear evokes significantly increased activation in the Peroneus Longus suggesting greater interference to ankle stability [11]. Moreover, footwear has been shown to hinder the kinesthesia [12], with greater awareness of foot position observed in volunteers standing barefoot compared with wearing athletic footwear. Whilst these studies are limited to investigation in standing, the findings suggest the possibility that footwear could be interfering with the functional ability of the human foot and if this corresponds to changes in gait.

The aim of this review is to systematically review the research investigating kinematic, kinetic and muscle activity variables during walking barefoot and in normal footwear to help improve our understanding of how footwear influences gait pattern.

2. Methods

2.1. Study design and search strategy

Reporting in line with PRISMA guidelines (www.prisma-statement.org) and through consultation with subject specific and systematic review experts the literature review methodology was developed. The literature search was performed across a variety of databases (Medline, EMBASE, Web of Science, Cochrane Library, SCOPUS and AMED) encompassing publications within the years of 1980-January 2014. The search strategy employed across the electronic databases is presented below:

1. barefoot
2. walk*
3. exp Gait/
4. exp Locomotion
5. kinematic*
6. kinetic*
7. exp Electromyography
8. EMG
9. muscle activ*
10. 7 or 8 or 9
11. 5 or 6 or 10
12. 2 or 3 or 4
13. 1 and 12
14. 11 and 13

2.2. Study selection

One reviewer (SF), who had received training on database searching, completed all searches which were independently checked by a second author (LB). Differences of opinion were resolved through discussion or a third author. Citation checking and search of grey literature, including key conference proceedings within the last 3 years was also undertaken. Authors were subsequently contacted to determine if any relevant proceedings had since reached publication.

Inclusion criteria were determined a priori. Studies were required to assess gait characteristics between footwear in terms of spatial-temporal variables, kinematics, kinetics, and muscle activity and behaviour. Participants were to be healthy and able to ambulate independently such that their gait pattern was considered normal and would not influence comparisons between footwear conditions. They could be of any age group and either gender to observe any differences throughout age and include data from both males and females to draw comparisons from if possible. Overground walking and treadmill walking were both deemed acceptable in order to access all studies analysing barefoot walking gait characteristics. Studies of observational cross-sectional design were included to allow for review of the comparison between footwear conditions wear inclusive of socks, open-toe footwear such as sandals or flip-flops and slippers. Observational comparative studies were deemed suitable if they were comparing between habitually barefoot, who have grown up and continue to live without wearing shoes, and habitually shod, who wear shoes on a day-to-day basis, populations to determine changes which occur over long term use with or without shoes. Case-control studies were also included providing the control group fitted the participant criteria and data was available for conclusions to be drawn solely from this group with regard to footwear intervention. If both groups fitted the participant criteria, then providing that data was available these were included and comparisons were focussed on the separate group's response to the footwear intervention rather than the comparisons between groups.

Studies were excluded if the footwear included any interventions aside from the features included in the original footwear design such as separate insoles or orthotics. Any studies involving participants who required a walking aid to ambulate were also excluded along with participants who had a known previous or current gait disorder or condition that could influence their gait (unless the study also consists of a control group through which analysis can be drawn from). Studies were excluded if they used running, unless a walking test was also completed from which analysis could be solely focussed. Literature other than peer-reviewed journal articles and comparative studies were excluded from the review.

2.3. Data collection and items

Using a standardised form the lead reviewer independently extracted the data. Study characteristics included repeated measures designs between various footwear conditions and between subject comparisons in terms of habitual barefoot and habitual shod users. Included outcomes were any measures which assessed spatial-temporal, kinematic, kinetic or muscle activity/behaviour variables.

2.4. Risk of bias across studies

To assess the methodological quality a bespoke critical appraisal tool was developed based upon the STROBE Checklist [3] for reporting observational studies and the CASP appraisal tool [1]. All articles were assessed on these questions which determine if all the required steps for successful scientific reporting were taken and if the relevant information is presented clearly in the scientific paper. A score of 1 was given for each question if the article satisfied the question and a 0 given if it failed to do so. A total score out of 20 was then given for each paper. The quality assessment of the selected studies was carried out by one reviewer (SF) and then repeated independently by a second author (LB). Any issues were discussed to achieve consensus of opinion.

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2.5. Synthesis of results

It was not appropriate to combine studies for meta-analysis, therefore the results were tabulated for semi quantitative comparison of spatial-temporal, kinematic, kinetic and muscle activity/behaviour variables.

3. Results

3.1. Search results

The database search was completed in January 2014 and resulted in 924 records (155 Medline, 236 EMBASE, 222 Web of Science, 58 AMED, 9 The Cochrane Library, 244 SCOPUS) and a further 7 records were included from hand searches of reference lists, conference proceedings and contacting relevant authors in the field. Following removal of duplicates there were 466 records remaining from which analysis of titles and abstracts was undertaken. Twenty one articles were selected for full text screening of which 15 were deemed to meet the inclusion criteria and were subsequently used in the analysis. See Fig. 1.

3.2. Methodological quality

In five articles [13–17] there was no description of the footwear characteristics and/or type of footwear worn in the trials. Seven articles [18–24] used a standardised shoe across participants or controlled for the type of footwear worn. Of the fourteen articles which consisted of footwear trial conditions eight [14,16,20–23,25,26] were administered in a random order to avoid carry over effects. Only one study reported details on the period of recruitment, exposure and data collection as well as the setting and location [13]. Four studies failed to report any demographic information of their participants [13,14,19,24]. Only two studies reported how they derived their sample size [21,23] whilst only 3 studies reported effect sizes to illustrate the magnitude of the effect [15,22,27]. The breakdown of the results of the critical appraisal for each article is displayed in Table 1.

3.3. Study characteristics

The included studies were conducted in a variety of areas. These included Australia [13,21,22], the USA [14,20,23,24], Taiwan [25], Germany [19], France [18], Brazil [15], Switzerland [26], Finland [16], Mexico [17], India [27] and Belgium [27]. Of the 15 included studies, 14 were within subject repeated measures design studies with one being a between subject comparison study [27] which comprised 3 subject groups: habitually barefoot, habitually minimally shod and habitually shod. The ages of participants in the studies ranged from 5 to 74 years old; however only two [15,25] of the fifteen studies assessed participants of 50 years of age or older. Five studies [13,14,17,19,21] investigated differences between footwear in children under the age of 13, with the remainder investigating the response of young-middle aged adults to barefoot walking. These data are summarised in Table 2.

3.4. Measurement approach

Two studies set a consistent gait speed with ten studies allowing for participants to self-select their velocity. Two studies monitored gait speed and then matched their gait speed on the treadmill and one study neither reported gait velocity nor acknowledged if it was self-selected or fixed. Fourteen of the fifteen studies analysed the differences between walking barefoot and wearing various types of footwear whereas the study by D'Août et al. [27] was novel in its approach of comparing habitually barefoot walkers with two different habitually shod populations. Of the fourteen studies analysing walking barefoot in comparison to walking in footwear three studies investigated athletic shoes, two explored flip-flops and sandals and one investigated the effects of just socks. Five studies compared the effects of more than one type of footwear to barefoot with five studies being unclear about the type of shoes used in the studies. Seven of the fourteen studies used a standardised shoe across participants and in the case of the study by Wirth et al. [26] the flexible shoe condition was standardised but the conventional shoes were not. Eight studies collected spatial-temporal data, six studies assessed kinetic variables, five studies reported kinematic data, three studies used electromyography to study muscle activity patterns and one study used ultrasound to explore muscle contractile behaviour.

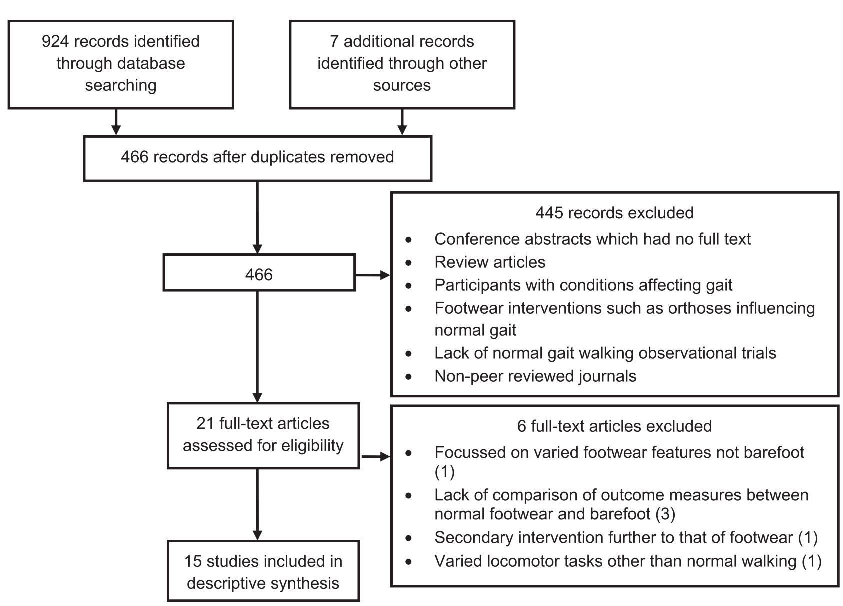

Fig. 1. Flowchart demonstrating the selection of articles through the review process.

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Table 1
Results of the methodological quality assessment following the critical appraisal tool developed based upon the STROBE Checklist for reporting observational studies and the CASP appraisal tool. The checklist offers a list of recommendations which should be included to ensure that all required steps for successful scientific reporting were taken and if the relevant information is presented clearly. A 1 in the table illustrates that this criteria was satisfied and a 0 demonstrates that this was missing.

	Tsai and Lin [25]	Lythgo et al. [13]	Morio et al. [18]	Wolf et al. [19]	Keenan et al. [20]	Oeffinger et al. [14]	D'Aout et al. [27]	Chard et al. [21]	Scott et al. [22]	Zhang et al. [23]	Sacco et al. [15]	Carl and Barrett [24]	Cronin and Finni [16]	Wirth et al. [26]	Moreno-Hernandez et al. [17]
Title and Abstract	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Introduction	11 = 2	11 = 2	11 = 2	11 = 2	11 = 2	11 = 2	11 = 2	11 = 2	11 = 2	11 = 2	11 = 2	11 = 2	11 = 2	11 = 2	11 = 2
Methods	10111101 = 6	11011001 = 5	10111001 = 5	10011001 = 4	10101101 = 5	10001101 = 4	10111-01 = 6	10111111 = 7	10111101 = 6	10101111 = 6	10111001 = 5	10001001 = 3	10111101 = 6	10111101 = 6	10111001 = 5
Results	011101 = 4	111001 = 4	011001 = 3	011100 = 3	011101 = 4	110000 = 2	110111 = 5	111101 = 5	011111 = 5	011101 = 4	111111 = 6	010101 = 3	111101 = 5	010101 = 3	111101 = 5
Discussion	111 = 3	111 = 3	111 = 3	101 = 2	111 = 3	111 = 3	111 = 3	111 = 3	111 = 3	111 = 3	111 = 3	111 = 3	111 = 3	111 = 3	101 = 2
Total Score	16/20	15/20	14/20	12/20	15/20	12/20	16/19	18/20	17/20	16/20	17/20	12/20	17/20	15/20	15/20

3.5. Spatial-temporal variables

Walking barefoot compared to shoes results in a reduced step and/or stride length [13,14,17,19,20,26]. This reduction is limited when walking in more flexible footwear [26] and reversed in older adults when walking in socks [25]. Walking barefoot was shown to correspond to an increase in cadence [13,17,19,26] and similarly this difference was limited in more flexible footwear [26]. The difference failed to reach significance in the study by Oeffinger et al. [14], but an increase was observed (134 steps/min barefoot, 126 steps/min in shoes). Other variables which showed significant differences from shoes to barefoot were that of percentage double support time decreasing [13], stance time decreasing [13,17,23] swing time increasing [17] and stride time decreasing [13,19]. Gait velocity differences between conditions was variable with some studies noting a decrease in velocity when barefoot [13,17,26] and some showing no significant differences [14,19,25]. Older adults (mean age 74.60 $\pm$ 7.21 years) were observed to reduce their gait velocity when walking in socks compared to barefoot [25]. The data is summarised in Table 3.

3.6. Kinematic variables

There are considerable kinematic differences observed in various studies particularly with respect to changes in foot motion. Forefoot width and forefoot spreading under load during walking is significantly increased when barefoot compared to shoes [19] and sandals [18] in populations used to walking in shoes. There are also significantly reduced medial longitudinal arch length changes in shoes compared to barefoot [19]. In addition, anatomically, habitual barefoot walkers have been shown to have considerably wider feet than their shod counterparts, and this is particularly prevalent in the forefoot region [27]. Walking barefoot also led to a change in the ankle angle at initial contact with a significant increase in plantarflexion corresponding to a flatter foot placement compared to athletic shoes, sandals and flip-flops [14,18,21,23]. Other variables of foot motion revealing differences between footwear are reduced eversion, adduction, external rotation and foot torsion when wearing shoes or sandals [14,18,19]. Aside from differences observed purely in the foot and ankle motion, footwear also appears to alter knee kinematics. An increase in knee flexion is observed at contact when walking barefoot [14,23] but a greater knee and ankle ROM exists throughout stance when wearing footwear [23]. The summary of kinematic variables is displayed in Table 4.

3.7. Kinetic variables

The kinetic variables described in the literature are quite varied and findings are at times contradictory between studies. For example, Oeffinger and colleagues [14] observed an increased hip extensor moment at terminal swing and decreased knee flexor moment at weight acceptance when walking barefoot compared to athletic shoes, whereas the opposite was observed in the study by Keenan and colleagues [20]. Keenan et al. [20] also reported a reduced hip flexor moment when walking barefoot which was supported by Zhang et al. [23]. Other variables which demonstrated significant differences between footwear conditions were a reduced initial peak vertical ground reaction force (GRF) [15,20] reduced drop in force between primary and secondary vertical impact peaks [15], reduced braking GRF [15,20] and reduced propulsive GRF [15] when walking barefoot. These correspond to a decreased ankle dorsiflexor moment in early stance [23] and reduced ankle plantar flexor moments in late stance [14] which were also reported during barefoot walking. On the other hand Keenan et al. [20] and Zhang et al. [23] observed an increase in

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Table 2
Summary of study characteristics of articles included in review.

	Sample size	Age	Outcome measures	Conditions	Test order randomised	Standardised shoes
Tsai and Lin (2013)	41 (21 young adults, 20 older adults)	22.52 ± 2.48 years and 74.60 ± 7.21 years	Spatial-temporal	Barefoot and socks	Yes	No
Lythgo et al. (2009)	898 children, 82 young adults	5–13 years and 19.62 ± 1.60 years	Spatial-temporal	Barefoot and athletic shoes	No	No
Morio et al. (2009)	10 young adults	25.4 ± 6.4 years	Kinematics–forefoot-rearfoot relative motion	Barefoot and 2 sandals (hard and soft sole)	No	Yes
Wolf et al. (2009)	18 children	8.2 ± 0.7 years	Kinematics–foot motion, spatial-temporal	Barefoot, conventional and flexible shoes	No	Yes
Keenan et al. (2011)	68 adults	34 ± 11 years	Kinetics, spatial-temporal	Barefoot and various athletic shoes	Yes	Yes
Oeffinger et al. (1999)	14 children	7–10 years	Kinematics, spatial-temporal, kinetics	Barefoot and athletic shoes	Yes	No
D'Aout et al. (2009)	255 adults (barefoot Indian (BI), shod Indian (SI) and shod western (W))	BI: 46.3 ± 14.9 years, SI: 34.3 ± 11.5 years and W: 33.9 ± 13.1 years	Kinetics – plantar pressures	Habitual barefoot vs Habitual Shod during barefoot walking	N/A	N/A
Chard et al. (2013)	13 children	10.3 ± 1.6 years	Kinematics	Barefoot and flip-flops	Yes	Yes
Scott et al. (2012)	28 young adults	21.2 ± 3.8 years	Electromyography	Barefoot, athletic and flexible shoe	Yes	Yes
Zhang et al. (2013)	10 young adults	25.8 ± 4.83 years	Kinematics, Kinetics, spatial-temporal	Barefoot, flip-flops, sandals and athletic shoes	Yes	Yes
Sacco et al. (2010)	21 healthy adults	50.9 ± 7.3 years	Kinetics, electromyography	Barefoot and Habitual Shoes	No	No
Carl and Barrett (2008)	10 young adults	24.6 years	Kinetics–plantar pressures	Barefoot (socks), flip-flops and athletic shoes	No	Yes
Cronin and Finni (2013)	10 adults	29 ± 4 years	Spatial-temporal, lower limb muscle fascicle behaviour	Barefoot and shoes (unknown type)	Yes	No
Wirth et al. (2011)	30 adults	31.4 ± 12.8 years	Electromyography, spatial-temporal	Barefoot, conventional shoes and flexible shoes	Yes	Conventional – No, Flexible – Yes
Moreno-Hernandez et al. (2010)	120 children	6–13 years	Spatial-temporal	Barefoot and school uniform shoes	No	No

propulsive force when barefoot compared to athletic shoes. A decreased knee varus moment [20] and greater ankle inversion moment at late stance [23] were also reported when walking barefoot. Aside from joint forces and moments, plantar pressure and Centre of Pressure (COP) displacement data was also reported. Peak plantar pressures were reported to be increased when walking barefoot compared to in athletic shoes and flip flops under the calcaneus and metatarsal heads but there was no difference observed under the hallux region [24]. Peak plantar pressures and pressure impulses were observed to be lowest in habitually barefoot walkers under the heel and metatarsal regions [27]. There were however lower relative peak plantar pressures witnessed under the toe and midfoot regions in the Western habitually shod group [27]. In terms of COP displacement, larger mediolateral but reduced anteroposterior displacements were observed when walking barefoot compared to flip-flops, sandals and athletic shoes [23]. Data is summarised in Table 5.

3.8. Muscle activity and behaviour

Three studies used electromyography measures to determine differences in muscle activity patterns during walking in footwear and barefoot. The variables of interest included mean peak amplitude (reported in mV [22] or % of MVC [26]), time to peak amplitude (reported in terms of % of gait cycle [15,22]) and maximum peak amplitude (reported as % of MVC [26]). Scott et al. [22] stated that tibialis anterior (TA) displayed a significantly reduced mean peak amplitude from shoes (0.12 mV) to barefoot (0.09 mV) ($p < 0.001$), an increase in peroneus longus (PL) mean peak amplitude (0.17 mV barefoot, 0.13 mV flexible shoe, 0.14 mV stability shoe) ($p < 0.05$) and no difference in the medial gastrocnemius (MG) (0.06 mV for all three footwear). However the time to peak amplitude occurred later in the TA (6.02–5.53%) ($p = 0.008$) and PL (50.11–47.55%) ($p = 0.004$) barefoot compared to the flexible shoe and stability shoe respectively and occurred earlier in the MG compared to the stability shoe (41.58–43.80%) ($p < 0.001$) [22]. Conversely, Sacco et al. [15] demonstrated that although not significant ($p = 0.06$) there was a trend towards the peak amplitude in the TA occurring later in shoes (CG: 5.46–6.52% DG: 5.61–6.58%). Sacco et al. [15] also reported that the Vastus Lateralis time to peak amplitude occurred significantly ($p = 0.002$) earlier when barefoot (CG: 10.76–15.47% DG: 14.14–15.35%). It is worth noting however that these statistics comprise both the control and diabetic group data and there is no statistical test reported stating whether these groups are similar. A slightly higher mean amplitude was observed in various back muscles (Lumbar Iliocostalis $p = 0.015$, Sternocleidomastoideus $p = 0.008$) and neck extensor muscles ($p = 0.003$) when barefoot compared to conventional shoes [26]. The same tendency was observed in the Lumbar Longissimus, the Lumbar Multifidi and Trapezius Pars Descendens; however these did not reach statistical significance. In comparison to the flexible shoe condition mean amplitude was only significantly higher barefoot in the Sternocleidiomastoideus ($p = 0.01$) [26]. Wirth et al. [26] also reported that the maximum amplitude in the Neck Extensor muscles exhibited a significantly higher ($p = 0.02$) amplitude barefoot than in conventional shoes. These differences although significant are relatively marginal in absolute terms with the mean activity ranging from a change of 0.23–0.47% of the maximum voluntary contraction. With no effect sizes being reported it is difficult to comment on the strength of the difference. Cronin and Finni [16] found no significant differences in soleus or medial gastrocnemius fascicle length or velocity changes

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Table 3
Summary of the spatial-temporal variables. Results are displayed as group means followed by standard deviations in parentheses () or standard error measurement in brackets [].

	Study	Conditions	Results
Velocity Sig. slower when barefoot	Lythgo et al. [13]	Barefoot or Athletic Shoes	Mean reduction of 8 cm/s barefoot
	Wirth et al. [26]	Barefoot (BF), Normal Shoes (NS)	BF: 0.04 m/s slower than NS ($p = 0.001$)
	Moreno-Hernandez et al. [17]	Barefoot (BF), School Shoes (SS)	BF: 113.32 cm/s (19.52), SS:118.69 cm/s (18.13) ($p < 0.001$)
Sig. slower in socks	Tsai and Lin [25]	Old in socks (S) or barefoot (BF)	Old: BF: 92.51 cm/s (19.18), S:80.76 cm/s (23.12) * ($p < 0.05$)
No Sig. difference between footwear	Wolf et al. [19]	Barefoot (BF), normal shoes (NS) or flexible shoes (FS)	BF:1.29 m/s [0.14], NS:1.28 m/s [0.13], FS:1.31 m/s [0.15] ($p = 0.679$)
	Oeffinger et al. [14]	Barefoot (BF), athletic shoes (AS)	BF: 139.11 cm/s (16.87), AS: 143.42 cm/s (14.61) ($p = 0.512$)
	Wirth et al. [26]	Barefoot (BF), Flexible Shoes (FS)	BF: 0.01 m/s slower than FS ($p = 0.25$)
	Tsai and Lin [25]	Young in socks (S) or barefoot (BF)	Young: BF: 101.32 cm/s (14.26), S: 101.12 cm/s (13.86)
Step length Sig. shorter when barefoot	Lythgo et al. [13]	Barefoot or Athletic Shoes	Mean reduction of 5.5 cm barefoot
	Wirth et al. [26]	Barefoot (BF), Normal Shoes (NS), Flexible Shoes (FS)	BF: 0.03 less than NS, BF: 0.01 less than FS ($p < 0.001$) (m)
	Moreno-Hernandez et al. [17]	Barefoot (BF), School Shoes (SS)	BF: 56.35 (6.74), SS: 60.05 (6.92) ($p < 0.001$) (cm)
Stride length Sig. shorter when barefoot	Lythgo et al. [13]	Barefoot or Athletic Shoes	Mean reduction of 11.1 cm barefoot
	Wolf et al. [19]	Barefoot (BF), normal shoes (NS) or flexible shoes (FS)	BF: 1.17 m* [0.10], NS: 1.24 m [0.09], FS:1.23 mm [0.11] ($p = 0.001$)
	Keenan et al. [20]	Barefoot (BF), athletic shoes (AS)	BF:2.15 m (0.32), AS:2.29 m (0.29) ($p < 0.001$)
	Oeffinger et al. [14]	Barefoot (BF), athletic shoes (AS)	BF:125.40 cm (13.55), AS:137.18 cm (11.49) ($p = 0.032$)
	Tsai and Lin [25]	Young and Old, in socks (S) or barefoot (BF)	Young: BF: 67.63 (6.31), S: 66.99 (5.96), Old: BF: 67.80 (9.30), S: 62.87 (12.06)* ($p < 0.05$) (%height)
Cadence Sig. faster when barefoot	Lythgo et al. [13]	Barefoot or Athletic Shoes	Mean increase of 3.9 steps/min barefoot
	Wolf et al. [19]	Barefoot (BF), normal shoes (NS) or flexible shoes (FS)	BF: 132.2 [8.9], NS: 123.5 [7.6], FS: 127.6 [7.56] ($p = 0.001$)
	Wirth et al. [26]	Barefoot (BF), Normal Shoes (NS), Flexible Shoes (FS)	BF: 2.93 steps/min more than NS, BF: 1.45 steps/min more than FS ($p < 0.001$)
	Moreno-Hernandez et al. [17]	Barefoot (BF), School Shoes (SS)	BF: 122.48 steps/min (13.83), SS: 118.97 steps/min (14.35) ($p < 0.001$)
Double Support time Sig. reduced when barefoot	Lythgo et al. [13]	Barefoot or Athletic Shoes	Mean reduction of 1.6% of gait cycle when barefoot
Stance time Sig. reduced when barefoot	Lythgo et al. [13]	Barefoot or Athletic Shoes	Mean reduction of 0.8% barefoot
	Zhang et al. [23]	Barefoot (BF), flip-flops (FF), sandals (S) and athletic shoes (AS)	BF:0.70 s* (0.02), FF:0.73 s (0.02), S:0.74 s (0.02), AS:0.77 s# (0.03) ($p = 0.0001$) *sig. less than FF, S and AS, #sig. more than FF and S
	Moreno-Hernandez et al. [17]	Barefoot (BF), School Shoes (SS)	BF: 56.30%gait cycle (1.62), SS: 57.04%gait cycle (3.03) ($p = 0.007$)
Swing time Sig. increased when barefoot	Moreno-Hernandez et al. [17]	Barefoot (BF), School Shoes (SS)	BF: 43.71%gait cycle (1.62), SS: 42.97%gait cycle (3.04) ($p = 0.006$)
Stride time Sig. reduced when barefoot	Lythgo et al. [13]	Barefoot or Athletic Shoes	Mean reduction of 25 ms barefoot
	Wolf et al. [19]	Barefoot (BF), normal shoes (NS) or flexible shoes (FS)	BF: 0.91 s [0.06], NS: 0.98 s [0.06], FS: 0.94 s [0.06] ($p < 0.001$)

between footwear despite seeing significant differences in the spatial-temporal characteristics of gait.

4. Discussion

The aim of this systematic review was to explore the research on walking barefoot to help understand the effect that wearing footwear has on gait kinematics, kinetics and muscular activity. It was also possible to compare different footwear types and how closely they link to walking barefoot in terms of the variables of interest.

A marked discrepancy in the results of some studies is observed with respect to changes in gait velocity between footwear conditions, with some studies reporting a reduction in velocity when barefoot and some reporting no significant difference. This is potentially explained by the familiarity or variability of the footwear used. A standardised shoe was employed in the studies finding no significant differences, whereas in the studies that noted a decrease in gait velocity when barefoot participants used their own habitual shoes. This suggests that the familiarity of the shoes worn by participants potentially has a significant impact on gait parameters such as gait velocity and thus future studies investigating such parameters should take this into consideration when designing their methodology.

Results were more conclusive regarding step and/or stride length differences with many studies observing a clear reduction when walking barefoot. Some authors suggest this could be due to a pendulum lengthening effect such that the extra weight of the shoe leads to greater inertial load during the swing phase and a corresponding increase in step length [14]. This reduction in stride length was shown to be limited in more flexible shoes. The weights of these were not reported. However, based on the descriptions of the footwear and the type of footwear they were compared against, it can be assumed that these were significantly lighter, supporting the pendulum-lengthening suggestion. On the other hand, the change in stride length may not be purely due to increased weight

Table 4
Summary of the kinematic variables. Results are displayed as group means followed by standard deviations in parentheses () or standard error measurement in brackets [].

	Study	Conditions	Results
Forefoot Width/Spreading Sig. increase in forefoot spreading when walking barefoot	Wolf et al. [19]	Barefoot (BF), normal shoes (NS) or flexible shoes (FS)	BF: 9.7% (3.1), NS: 4.3% (1.4), FS: 5.9% (1.4) ($p < 0.001$) (%change from standing)
	Morio et al. [18]	Barefoot (BF), Hard Sandal (HS), Soft Sandal (SS)	Metatarsal heads BF: 1.1°(0.8), SS: 0.9°(1.3), HS: 1.6°(1.7) (change from standing calibration SS: −2.5°(1.8), HS: −3.5°(1.8)) Metatarsal bases BF: 0.8°(1.0), SS: 1.1°(1.1), HS: 1.7°(1.4) (change from standing calibration SS: −0.7° (0.9), HS: −2.4°(1.4))
Habitual barefoot walkers have sig. wider feet	D'Aout et al. [27]	Habitually barefoot Indian (BI) vs habitually shod Indian (SI) vs Western Shod (WS)	BI: approx. 37%, SI: approx. 35.5%, WS: approx. 33.5% ($p = 0.000$) (%footwidth/length) Foot area normalised to stature squared = WS: 15.5% smaller than both Indian groups ($p = 0.000$)
Ankle Angle at initial contact (sagittal plane) Sig. more plantarflexed when barefoot	Morio et al. [18]	Barefoot (BF), Hard Sandal (HS), Soft Sandal (SS)	BF: 4.8°(2.1), SS: 5.5°(1.5), HS: 6.8°(2.3) ($p < 0.05$) (dorsiflexion excursion)
	Oeffinger et al. [14]	Barefoot (BF), athletic shoes (AS)	A decrease of 3° in ankle plantarflexion in AS ($p < 0.05$)
	Chard et al. [21]	Barefoot (BF) and flip-flops (FF)	BF: 1.1°(8.3) FF: 12.0°(12.2) ($p = 0.005$)
	Zhang et al. [23]	Barefoot (BF), flip-flops (FF), sandals (S) and athletic shoes (AS)	BF: −3.9°(3.9) FF: 0.4°(5.0) S: −0.1°(4.5) AS: 3.7°(3.8) ($p = 0.001$)
Foot Angle at Contact (sagittal plane) Sig. more plantarflexed when barefoot	Zhang et al. [23]	Barefoot (BF), flip-flops (FF), sandals (S) and athletic shoes (AS)	BF: 19.2°(3.4), FF: 25.5°(3.9) S: 24.9°(3.6), AS: 29.5°(4.5) ($p < 0.001$) (angle between foot and ground)
Foot Eversion Sig. more when barefoot	Morio et al. [18]	Barefoot (BF), Hard Sandal (HS), Soft Sandal (SS)	BF: 9.5°(2.9), SS: 8.2°(2.8), HS: 7.9°(2.7) ($p < 0.05$)
Foot Adduction Sig. more when barefoot	Morio et al. [18]	Barefoot (BF), Hard Sandal (HS), Soft Sandal (SS)	BF: 11.5°(1.8), SS: 9.8°(2.0), HS:8.3°(1.6) ($p < 0.05$)
Foot External rotation Sig. more when barefoot	Wolf et al. [19]	Barefoot (BF), normal shoes (NS) or flexible shoes (FS)	BF: 20.9% [3.9], NS: 18.7% [4.3], FS: 19.4% [4.7] ($p < 0.001$) (% change from standing)
Foot torsion Sig. more when barefoot	Wolf et al. [19]	Barefoot (BF), normal shoes (NS) or flexible shoes (FS)	BF: 9.8°[3.0], NS: 4.7°[1.6], FS: 5.2°[2.0] ($p < 0.001$) (forefoot-hindfoot relative motion in transverse plane)
Medial Longitudinal Arch Sig. greater change in length when barefoot	Wolf et al. [19]	Barefoot (BF), normal shoes (NS) or flexible shoes (FS)	BF: 9.9% [2.5], NS: 5.9% [1.5], FS: 6.0% [1.8] ($p < 0.001$) (% change from standing)
Knee Flexion at initial contact Sig. more flexion when barefoot	Zhang et al. [23]	Barefoot (BF), flip-flops (FF), sandals (S) and athletic shoes (AS)	BF: −8.0°(3.9) FF: −6.3°(3.7) S: −6.3°(3.9) AS: −5.2°(3.4) ($p = 0.001$) (negative value means greater flexion)
Knee ROM throughout stance Sig. reduced when barefoot	Zhang et al. [23]	Barefoot (BF), flip-flops (FF), sandals (S) and athletic shoes (AS)	BF: 39.9°(5.3) FF: 44.2°(4.7) S: 45.8°(4.8), AS: 46.7°(4.4) ($p < 0.001$)
Ankle plantarflexion ROM in late stance Sig. reduced when barefoot	Zhang et al. [23]	Barefoot (BF), flip-flops (FF), sandals (S) and athletic shoes (AS)	BF: 8.0°(1.9), FF: 8.7°(1.4), S: 9.4°(1.7), AS: 11.8°(2.9) ($p = 0.001$)

as Tsai and Lin [25] observed a reduction in the stride length from barefoot to socks in older adults. This suggests that in this population a mechanism other than that of distal weight influenced their gait performance to bring about a change in their stride length. Interestingly, no difference was observed in younger adults suggesting that wearing only socks influences those with reduced gait performance to a greater extent. It could be proposed therefore that the observed changes in stride length are as a result of a change in gait concerned with gait stability as opposed to purely an inertial difference. A significant increase in ankle plantarflexion was observed when walking barefoot in a number of studies resulting in a flatter foot placement at contact [14,18,21,23] which also corresponds to a delayed and reduced mean peak amplitude of the Tibialis Anterior (TA) [22]. The removal of shoes often leads to a reduction in the contact surface area which may increase the risk of a slip. Therefore this increase in plantarflexion when barefoot could be explained as a method of increasing the surface area of the foot at contact. Further to reducing the risk of a slip, increasing the surface contact area appears to have a considerable effect on plantar pressures and impulses. D'Août and colleagues [27] compared habitual barefoot walkers, who have never worn shoes, with habitually shod subjects, who wear shoes on a daily basis outdoors, and also incorporated an intermediate group of habitually minimally shod users who normally wear open-toed footwear such as flip-flops or sandals but walked mostly barefoot as a child in accordance with native habits. They used plantar pressure plates to analyse the long term effects that footwear use has on foot function and foot shape during repeated barefoot walking trials. They observed that the habitual barefoot walkers, displaying an anatomically larger plantar foot area, had significantly reduced peak plantar pressures at the heel and metatarsal regions compared to the habitually shod populations. This suggests that due to a larger plantar surface area the habitually barefoot walkers are able to distribute the pressures more evenly across the foot. Additional to the anatomical differences in foot area, the habitual barefoot walkers were also observed to adopt a flatter initial foot placement thus further allowing for distribution of pressures across a larger area. D'Août et al. [27] also state that a flatter foot placement allows for the pressures to be distributed over a longer period of time, reducing the pressure impulse, instead of being applied quickly at one point at initial contact and then relatively low pressures following this as observed in shod populations. Clearly these findings from the participants in the study by D'Aout et al. [27] suggest that this is as a result of habitual lack of footwear. However, it must be noted that there are other differences besides the lack or presence of footwear between these populations. The habitually shod population have grown up in a Westernised environment compared to the native

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Table 5
Summary of the kinetic variables. Results are displayed as group means followed by standard deviations in parentheses () or standard error measurement in brackets [].

	Study	Conditions	Results
Hip Extensor Moment Sig. reduced when barefoot	Keenan et al. [20]	Barefoot (BF), 2x athletic shoes (AS)	BF: 0.48 Nm/kgm (0.13) AS: 0.51 Nm/kgm (0.14) ($p < 0.003$)
Hip Flexor Moment Sig. reduced when barefoot	Keenan et al. [20]	Barefoot (BF), 2x athletic shoes (AS)	BF: 0.35 Nm/kgm (0.14) AS: 0.50 Nm/kgm (0.15) ($p < 0.003$)
	Zhang et al. [23]	Barefoot (BF), flip-flops (FF), sandals (S) and athletic shoes (AS)	BF: 0.63 (0.09), FF: 0.66 (0.10), S: 0.67 (0.11), AS: 0.66 (0.11) ($p = 0.007$) (Nm/kg)
Knee Flexor Moment Sig. increased when barefoot	Keenan et al. [20]	Barefoot (BF), 2x athletic shoes (AS)	BF:0.11 Nm/kgm (0.09) AS1:0.07 Nm/kgm (0.09) AS2:0.05 Nm/kgm (0.08) ($p < 0.003$)
Ankle Dorsiflexor moment – early stance Sig. reduced when barefoot	Zhang et al. [23]	Barefoot (BF), flip-flops (FF), sandals (S) and athletic shoes (AS)	BF: 0.11 (0.04), FF: 0.11 (0.04), S: 0.13 (0.04), AS: 0.16 (0.04) ($p = 0.008$) (Nm/kg)
Initial Peak vGRF Sig. reduced when barefoot	Keenan et al. [20]	Barefoot (BF), 2x athletic shoes (AS)	BF: 109.94% BW (7.53) AS: 112.37% BW (7.26) ($p < 0.003$)
	Sacco et al. [15]	Barefoot (BF) and Shoes (SH)	BF: 1.04 (0.09) SH: 1.09 (0.09) ($p < 0.001$) (times BW)
Braking GRF Sig. reduced when barefoot	Keenan et al. [20]	Barefoot (BF), 2x athletic shoes (AS)	BF: 17.59% BW (3.84) AS1: 18.73% BW (4.08) AS2: 18.80% BW (3.99) ($p < 0.003$)
	Sacco et al. [15]	Barefoot (BF) and Shoes (SH)	BF: −0.131(0.02) SH: −0.142 (0.04) ($p < 0.001$) (times BW)
Propulsive GRF Sig. increased barefoot	Keenan et al. [20]	Barefoot (BF), 2x athletic shoes (AS)	BF: 20.09% BW (3.43) AS1: 18.42% BW (3.22) AS2: 19.17% BW (3.05) ($p < 0.003$)
Sig. decreased barefoot	Sacco et al. [15]	Barefoot (BF) and Shoes (SH)	BF: 0.155 (0.02) SH: 0.178 (0.02) ($p < 0.001$) (times BW)
Knee Varus Moment Sig. decreased barefoot	Keenan et al. [20]	Barefoot (BF), 2x athletic shoes (AS)	BF: 0.31 Nm/kgm (0.06) AS: 0.34 Nm/kgm (0.07) ($p < 0.003$)
Ankle Inversion Moment – late stance Sig. increased barefoot	Zhang et al. [23]	Barefoot (BF), flip-flops (FF), sandals (S) and athletic shoes (AS)	BF: 0.29 (0.23), FF: 0.26 (0.22), S: 0.26 (0.22), AS: 0.17 (0.10) ($p = 0.026$) (Nm/kg)
Peak Plantar Pressure Sig. greater barefoot (in habitually shod subjects)	Carl and Barrett [24]	Barefoot, Flip-flops, athletic shoes	Barefoot > Flip-flops > Shoes (no values) under metatarsals and calcaneus
Sig. reduced in habitual barefoot walkers compared to habitual shod walkers	D'Aout et al. [27]	Habitually Barefoot Indian (BI) vs Shod Indian (SI) vs Western Shod (WS)	BI < SI < WS under heel and metatarsals (no values)
COP displacement (Medio-lateral) (cm) Sig. greater barefoot	Zhang et al. [23]	Barefoot (BF), flip-flops (FF), sandals (S) and athletic shoes (AS)	BF: 5.5 (1.4), FF: 4.7 (1.2), S: 4.5 (1.1), AS: 4.0 (1.0) ($p = 0.009$)
COP displacement (Antero-posterior) (cm) Sig. reduced barefoot	Zhang et al. [23]	Barefoot (BF), flip-flops (FF), sandals (S) and athletic shoes (AS)	BF: 21.1 (1.3), FF: 26.2 (2.1), S: 26.8 (1.6), AS: 26.8 (2.2) ($p = 0.0001$)

rural environment of the habitual barefoot walkers. They are therefore clearly not of the same population and thus comparisons drawn between them must be taken with caution. Other factors such as walking surface (roughness and compliance), stature or age, which were different between the groups, could also account for a portion of the variance observed other than that of simply the lack of footwear worn. However the authors are aware of this issue and discuss it in their paper whilst highlighting the need for similar population groups as a suggestion for future work. Nonetheless, it is interesting to see a similar change in foot kinematics being observed in shod populations following a brief switch to walking barefooted thus suggesting it may be an inherent response. Even so, it must be stated that for those who are accustomed to wearing shoes, walking barefoot results in increased plantar pressures at the heel and metatarsal regions compared to walking in shoes or flip-flops [24]. Of note however is the observed reduction in the initial vertical peak ground reaction force witnessed in habitually shod participants walking barefoot [20,15]. Furthermore there was a reduced drop between vertical GRF peaks, suggesting that forces were distributed throughout the stance period more when barefoot as opposed to a greater initial impulse followed by a reduction in force prior to a secondary steep rise to the second peak GRF. This is similar to that suggested by D'Août et al. [27] from the plantar pressure data in the habitually barefoot participants. This indicates that acute and long term exposure to barefoot walking changes the kinematics and associated kinetics such that forces are spread more evenly over time. This is also consistent with barefoot running literature whereby a smooth force profile is observed when running barefoot. An abundance of research [28–31] has observed that in barefoot runners there is the absence of, or a distinct reduction in, the impact force transient contrasting that of when running in shoes. It is explained by a more plantarflexed foot strike when running barefoot which enables better use of the Windlass mechanism and absorption of load by the lower limb musculature. This reduction in force peaks and with the force being spread more evenly over time also appears to have an impact on the joint moments experienced by participants with differences being reported between footwear. A reduction in the hip extensor, hip flexor and knee varus moments in the early stance phase were observed when walking barefoot [20,23] which was contrasted by an increase in the knee flexor moment [20]. The authors suggest that these differences in joint moments are likely to be the result of the reduction in stride length; however, they are relevant to the onset and progression of osteoarthritis. Increased knee varus moments are particularly important in terms of medial compartment knee osteoarthritis and thus the reduction observed during barefoot walking could be potentially significant. The authors explain that this is likely due to the raised heel and medial arch support present within the shoes which have both previously been shown to increase knee varus moments [32]. This could potentially have relevance in the recommendations of athletic shoes with a raised heel and arch support to individuals particularly at a greater risk of developing osteoarthritis.

It has been noted previously that gait varies with age, thus caution must be taken when generalising the results across age groups without primary research being undertaken in older populations. It is apparent that some of the findings from this review, particularly surrounding those aspects concerned with the progression of deleterious joint conditions as well as balance and fall risk, are most relevant to the older population. However a notable finding from the review was that very little research has been completed in older age populations. Of the 15 articles in the review only 2 included participants over the age of 50 with the majority focussed on young or middle aged adults. Thus it seems necessary for research to be replicated in this population and assess if the same responses to barefoot walking are experienced.

Research into footwear use in children is also of great interest as footwear can have a lasting impact on the developing foot. With this in mind a number of articles reported data suggesting that footwear could potentially be restricting the natural motion of the foot thus affecting its development. Morio et al. [18] and Wolf et al. [19] both reported a significant increase in the forefoot width and forefoot spreading under load barefoot compared to walking in shoes [19] and sandals [18]. This demonstrates that the shoes are somewhat limiting the motion of the foot in the forefoot region and not allowing it to spread under the load and utilise its structure. In addition to potentially affecting the load bearing mechanisms of the foot, long term use of these footwear could be affecting the anatomical structure of the foot and observing the feet in older adults supports this. Research by Chaiwanichsiri et al. [33] indicates the prevalence of foot problems in older adults. They report that 87% of cases suffer from at least one form of foot deformity with 45.5% exhibiting hallux valgus and in these subjects 10% of men and 20% of women also had overriding toes and 87% had callus formations as a result. This prevalence of foot problems is supported by Menz et al. [34] who also stated that 87% of cases registered at least one foot problem and indicate that foot problems are significantly associated with reduced gait performance and their risk of falling. Insufficient room in the forefoot region of shoes could somewhat explain the occurrence of these conditions, and the data from the habitual barefoot walkers in the D'Août et al. [27] study exhibiting significantly wider feet and forefoot spreading also supports this. Thus, ensuring that footwear does not impact negatively upon foot development is of vital importance to reduce the prevalence of foot problems and to allow the foot to function as it would naturally. Another difference of note between walking barefoot and in shoes was that of changes in terms of medial longitudinal arch function. Wolf et al. [19] indicated that significantly reduced changes in length were observed when walking in shoes compared to barefoot thus suggesting that shoes inhibit the windlass mechanism. This is explained by that under load at contact the arch is under pressure to flatten thus tension is created along the plantar fascia to maintain the structure. This tension then recoils at push off causing the arch to rise; reducing the distance between heel and metatarsals. The reduction in the length changes of the arch in footwear indicates that this mechanism is somewhat inhibited. Longitudinal arch differences were also observed between habitual barefoot and habitual shod populations [27]. The habitually Western shod population generally had higher arches but significantly greater variability from very low to very high arches whereas the barefoot and minimally shod groups had lower arches but very little variation. This suggests that varied footwear use causes changes within the foot's structure and can lead to the extremes in arch height which are commonly associated with foot problems. Excessively high arches reduce the area of support and Chaiwanichsiri et al. [33] noted that patients with pes planus, denoted as the lack of a medial longitudinal arch, had a reduced risk of falling. The authors suggest that the greater area of support could be the reason for this. Clearly this is an extreme condition of a lower arch and comes with associated problems, such as the lack of an effective windlass mechanism and over pronation. However as highlighted in the habitual barefoot population having lower arches than their shod counterparts [27], aspects of modern footwear design such as arch supports could be forcing our feet into unnatural positions not allowing for normal foot function and resulting in weakness. This could explain the higher variability and prevalence of arch related foot problems in the shod populations and further research into ensuring footwear is designed such that it does not affect foot development and function is necessary.

It must be stated however that removing shoes and walking outside purely barefoot is likely not feasible to most populations. Shoes do offer a protective surface against the likelihood of cuts, abrasions and infections from mechanical insult and debris [31,35]. As research has suggested that flexible, lighter, minimalist footwear is more similar than normal footwear in kinematics and kinetics to that of when barefoot running [31] and walking [19,26], footwear design should focus on finding the balance between ensuring that the foot will be protected by the shoe whilst allowing for natural foot motion and structure to be maintained.

There are certain limitations of this review namely that of a wide range of variables being reported within the studies thus the subsequent lack of the ability to complete a quantitative meta-analysis. Additionally by limiting the sample population to that of healthy with no gait impairments we were unable to observe any effects of barefoot walking in patients with disorders which could have disrupted their gait and thus our findings cannot be applied to these patient groups.

5. Conclusions

We have systematically reviewed studies investigating differences in gait variables between walking barefoot and in shoes and highlighted how habitually shod populations react acutely to barefoot walking and how habitual barefoot walkers vary to those who wear shoes on a daily basis. Long term use of footwear has been shown to result in anatomical and functional changes including reduced foot width and forefoot spreading under load probably due to the constraints of the shoe structure. Walking in footwear is associated with an increase in stride length and greater dorsiflexion at foot-ground contact. Lighter and more flexible footwear appears to elicit reduced differences in gait kinematics to walking barefoot. A reduced initial vertical impact force and more even distribution of pressure across the foot is experienced when walking barefoot which is likely to be as a result of a larger contact surface area achieved via a flatter foot placement. Little research on barefoot walking has been completed in adults approaching older age where foot problems and gait deficiencies are most prevalent and thus investigation into this population is required to determine the impact of barefoot walking across the lifespan.

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Conflict of interest statement

The authors have no conflicts of interest to declare.

References

[1] Theodore D. Anatomy of the moving body: a basic course in bones, muscles, and joints. 2nd ed. Berkeley, CA: North Atlantic Books; 2008. 280.
[2] McKeon P, Hertel J, Bramble D, Davis I. The foot core system: a new paradigm for understanding intrinsic foot muscle function. Br J Sports Med 2015; 49(290).
[3] Kavounoudias A, Roll R, Roll J-P. Foot sole and ankle muscle inputs contribute jointly to human erect posture regulation. J Physiol (Lond) 2001;532(3):869–78.
[4] Kennedy PM, Inglis JT. Distribution and behaviour of glabrous cutaneous receptors in the human foot sole. J Physiol (Lond) 2002;538(3):995–1002.
[5] Trinkaus E, Shang H. Anatomical evidence for the antiquity of human footwear: Tianyuan and Sunghir. J Archaeol Sci 2008;35(7):1928–33.
[6] Trinkaus E. Anatomical evidence for the antiquity of human footwear use. J Archaeol Sci 2005;32(10):1515–26.
[7] Al-Abdulwahab S, Al-Dosry RD. Hallux valgus and preferred shoe types among young healthy Saudi Arabian females. Ann Saudi Med 2000;20(3–4):319–21.
[8] Chantelau E, Gede A. Foot dimensions of elderly people with and without diabetes mellitus – a data basis for shoe design. Gerontology 2002;48(4):241–4.
[9] Csapo R, Maganaris CN, Seynnes OR, Narici MV. On muscle, tendon and high heels. J Exp Biol 2010;213(Pt 15):2582–8.
[10] Cronin NJ, Barrett RS, Carty CP. Long-term use of high-heeled shoes alters the neuromechanics of human walking. J Appl Physiol 2012;112(6):1054–8.
[11] Ramanathan AK, Parish EJ, Arnold GP, Drew TS, Wang W, Abboud RJ. The influence of shoe sole's varying thickness on lower limb muscle activity. Foot Ankle Surg 2011;17(4):218–23.
[12] Robbins S, Waked E, McClaran J. Proprioception and stability: foot position awareness as a function of age and footwear. Age Ageing 1995;24:67–72.
[13] Lythgo N, Wilson C, Galea M. Basic gait and symmetry measures for primary school-aged children and young adults whilst walking barefoot and with shoes. Gait Posture 2009;30(4):502–6.
[14] Oeffinger D, Brauch B, Cranfill S, Hisle C, Wynn C, Hicks R, et al. Comparison of gait with and without shoes in children. Gait Posture 1999;9(2):95–100.
[15] Sacco IC, Akashi PM, Hennig EM. A comparison of lower limb EMG and ground reaction forces between barefoot and shod gait in participants with diabetic neuropathic and healthy controls. BMC Musculoskelet Disord 2010;11:24.
[16] Cronin NJ, Finni T. Treadmill versus overground and barefoot versus shod comparisons of triceps surae fascicle behaviour in human walking and running. Gait Posture 2013;38(3):528–33.
[17] Moreno-Hernandez A, Rodriguez-Reyes G, Quinones-Uriostegui I, Nunez-Carrera L, Perez-SanPablo AI. Temporal and spatial gait parameters analysis in non-pathological Mexican children. Gait Posture 2010;32(1):78–81.
[18] Morio C, Lake MJ, Gueguen N, Rao G, Baly L. The influence of footwear on foot motion during walking and running. J Biomech 2009;42(13):2081–8.
[19] Wolf S, Simon J, Patikas D, Schuster W, Armbrust P, Doederlein L. Foot motion in children shoes – a comparison of barefoot walking with shod walking in conventional and flexible shoes. Gait Posture 2008;27(1):51–9.
[20] Keenan GS, Franz JR, Dicharry J, Della Croce U, Kerrigan DC. Lower limb joint kinetics in walking: the role of industry recommended footwear. Gait Posture 2011;33(3):350–5.
[21] Chard A, Greene A, Hunt A, Vanwanseele B, Smith R. Effect of thong style flip-flops on children's barefoot walking and jogging kinematics. J Foot Ankle Res 2013;6.
[22] Scott LA, Murley GS, Wickham JB. The influence of footwear on the electromyographic activity of selected lower limb muscles during walking. J Electromyogr Kinesiol 2012;22(6):1010–6.
[23] Zhang X, Paquette MR, Zhang S1. A comparison of gait biomechanics of flip-flops, sandals, barefoot and shoes. J Foot Ankle Res 2013;6(1):45.
[24] Carl TJ, Barrett SL. Computerized analysis of plantar pressure variation in flip-flops, athletic shoes and bare feet. J Am Podiatr Med Assoc 2008;98(5):374–8.
[25] Tsai Y-J, Lin S-I. Older adults adopted more cautious gait patterns when walking in socks than barefoot. Gait Posture 2013;37(1):88–92.
[26] Wirth B, Hauser F, Mueller R. Back and neck muscle activity in healthy adults during barefoot walking and walking in conventional and flexible shoes. Footwear Sci 2011;3(3):159–67.
[27] D'Aout K, Pataky TC, De Clercq D, Aerts P. The effects of habitual footwear use: foot shape and function in native barefoot walkers. Footwear Sci 2009;1(2): 81–94.
[28] Lieberman DE, Venkadesan M, Werbel WA, Daoud AI, D'andrea S, Davis IS, et al. Foot strike patterns and collision forces in habitually barefoot versus shod runners. Nature 2010;463(7280):531–5.
[29] Divert C, Mornieux G, Baur H, Mayer F, Belli A. Mechanical comparison of barefoot and shod running. Int J Sports Med 2005;26(7):593–8.
[30] De Wit B, De Clercq D, Aerts P. Biomechanical analysis of the stance phase during barefoot and shod running. J Biomech 2000;33(3):269–78.
[31] Squadrone R, Gallozzi C. Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. J Sports Med Phys Fit 2009;49(1):6–13.
[32] Kerrigan DC, Johansson JL, Bryant MG, Boxer JA, Della Croce U, Riley PO. Moderate-heeled shoes and knee joint torques relevant to the development and progression of knee osteoarthritis. Arch Phys Med Rehabil 2005;86(5): 871–5.
[33] Chaiwanichsiri D, Janchai S, Tantisiriwat N. Foot disorders and falls in older persons. Gerontology 2009;55(3):296–302.
[34] Menz HB, Lord SR. The contribution of foot problems to mobility impairment and falls in community-dwelling older people. J Am Geriatr Soc 2001;49: 1651–6.
[35] Menant JC, Steele JR, Menz HB, Munro BJ, Lord SR. Optimizing footwear for older people at risk of falls. J Rehabil Res Dev 2008;45(8):1167–81.

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