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Review article

Systematic Review of the Role of Footwear Constructions in Running Biomechanics: Implications for Running-Related Injury and Performance

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Abstract
Although the role of shoe constructions on running injury and performance has been widely investigated, systematic reviews on the shoe construction effects on running biomechanics were rarely reported. Therefore, this review focuses on the relevant research studies examining the biomechanical effect of running shoe constructions on reducing running-related injury and optimising performance. Searches of five databases and Footwear Science from January 1994 to September 2018 for related biomechanical studies which investigated running footwear constructions yielded a total of 1260 articles. After duplications were removed and exclusion criteria applied to the titles, abstracts and full text, 63 studies remained and categorised into following constructions: (a) shoe lace, (b) midsole, (c) heel flare, (d) heel-toe drop, (e) minimalist shoes, (f) Masai Barefoot Technologies, (g) heel cup, (h) upper, and (i) bending stiffness. Some running shoe constructions positively affect athletic performance-related and injury-related variables: 1) increasing the stiffness of running shoes at the optimal range can benefit performance-related variables; 2) softer midsoles can reduce impact forces and loading rates; 3) thicker midsoles can provide better cushioning effects and attenuate shock during impacts but may also decrease plantar sensations of a foot; 4) minimalist shoes can improve running economy and increase the cross-sectional area and stiffness of Achilles tendon but it would increase the metatarsophalangeal and ankle joint loading compared to the conventional shoes. While shoe constructions can effectively influence running biomechanics, research on some constructions including shoe lace, heel flare, heel-toe drop, Masai Barefoot Technologies, heel cup, and upper requires further investigation before a viable scientific guideline can be made. Future research is also needed to develop standard testing protocols to determine the optimal stiffness, thickness, and heel–toe drop of running shoes to optimise performance-related variables and prevent running-related injuries.

Key words: Running shoes; cushioning; bending stiffness; impact force; comfort perception.

Introduction

Over the past 50 years, running shoes have experienced tremendous changes. That is, from very minimal to highly supportive and cushioned shoes, and then to very minimal and finally back to highly cushioned shoes (Krabak et al., 2017). Shoes with various functionality were released because of technological advancements (e.g., structural and material engineering) used in running shoe development, such as cushioned, stability and minimalist running shoes. Although cushioned midsoles can theoretically reduce the impact forces by influencing the stiffness of one's impact attenuation system and reducing the body's deceleration (Shorten and Mientjes, 2011), the reported injury rate and performance of running have not remarkably improved over the years (Nigg, 2001). Therefore, reducing injuries and improving performances by using running shoes have become a focus in both sport industries and academia.

Running shoes are designated to improve shoe comfort, enhance running-related performance and reduce the injury potentially. To identify the appropriate functionality of running shoes, previous research has examined different shoe constructions, which included shoelaces (Hong et al., 2011), midsole (TenBroek et al., 2014), heel flare (Stacoff et al., 2001), heel-toe drop (Malisoux et al., 2017), minimalist shoes (Fuller et al., 2015), Massai Barefoot Technology (MBT) ((Boyer and Andriacchi, 2009), heel cup (Li et al., 2018), shoe upper (Onodera et al., 2015), and bending stiffness (Stefanyshyn and Wannop, 2016). For one example, shoelace regulate the tightness of the shoe opening to allow a geometrical match between the foot and the shoe based on the individual's preference. Good fit is considered a prerequisite for shoe comfort (Ameersing et al., 2003). A shoelace system, heel counter or any other systems that can secure the foot within the footbed should be integrated in running shoes.

For another example, the midsole is an important shoe component for cushioning and shock absorption of running impacts. Midsole thickness is considered important to influence plantar sensations and alter foot strike pattern for shod and minimalist shoes running (Chambon et al., 2014). A wide range of heel-toe drops used in running shoes (e.g., 0 mm to 12 mm) has been shown to influence foot strike pattern and injury risk (Malisoux et al., 2016). Technically, minimalist shoe is defined as the footwear with high flexibility and low shoe mass, stack height and heel-toe drop (Esculier et al., 2015). The minimalist shoe index is the combined scores of shoe quality, sole height, heel-toe drop, motion control, and stabilisation techniques, flexibility, longitudinal flexibility and torsional flexibility (Esculier et al., 2015). Recently, forefoot bending stiffness has received more attention because it has the potential to influence both running-related injury and performance (Stefanyshyn and Wannop, 2016). Softer and thicker running shoes (Sterzing et al., 2013; Teoh et al., 2013) were claimed that reduced impact in order to reduce impact-related injuries. However, Theisen et al., (2014) found that there was no difference in running-related injury between softer and harder shoes. Such a relationship

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between biomechanics and injury not well established in the literature.

While different shoe constructions showed the remarkable changes in running biomechanical and performance-related variables, no consistent findings on running biomechanics can be found for most shoe constructions. For example, shoe cushioning properties are interplayed with multiple footwear constructions including midsole hardness, midsole thickness, heel-toe drop, and crash-pad. The efficacy of isolated footwear constructions on running performance requires further investigation. Furthermore, analysing the development trend of running shoes can provide valuable guidelines to understand the roles of various footwear constructions in lower extremity biomechanics. Therefore, the current review aimed to examine the effect of different footwear constructions on running biomechanics and review the development status of running shoes related to injury, performance and applied research.

Methods

Systematic review process

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for this systematic review (Alessandro et al., 2009). A standardised electronic literature search strategy was performed using the following keyword combinations: "*running shoes*" OR "*running footwear*" AND ("*upper*" OR "*shoe lace*" OR "*midsole*" OR "*minimal shoes*" OR "*minimalist*" OR "*stiffness*" OR "*bending stiffness*" OR "*heel flare*" OR "*heel cup*" OR "*friction*" OR "*traction*" OR "*Masai Barefoot Technologies*" OR "*MBT*") AND PUBYEAR from 1994 to September 2018 via the five databases (Elsevier, Ebsco, WoS, SAGE Knowledge e-book database, and PubMed Central) and *Footwear Science*. WKL and WJF agreed on the use of the search terms. Figure 1 summarises the search and selection processes. All articles were input into Endnote to eliminate duplicates. Then, the original research articles in peer-reviewed journals that investigated the effect of shoe constructions on biomechanical changes during running were included. The exclusion criteria included duplicates, orthotics, non-biomechanical related (i.e., only physiological-, biochemical-, and medical-related), non-running shoe related, non-English or non-full text articles.

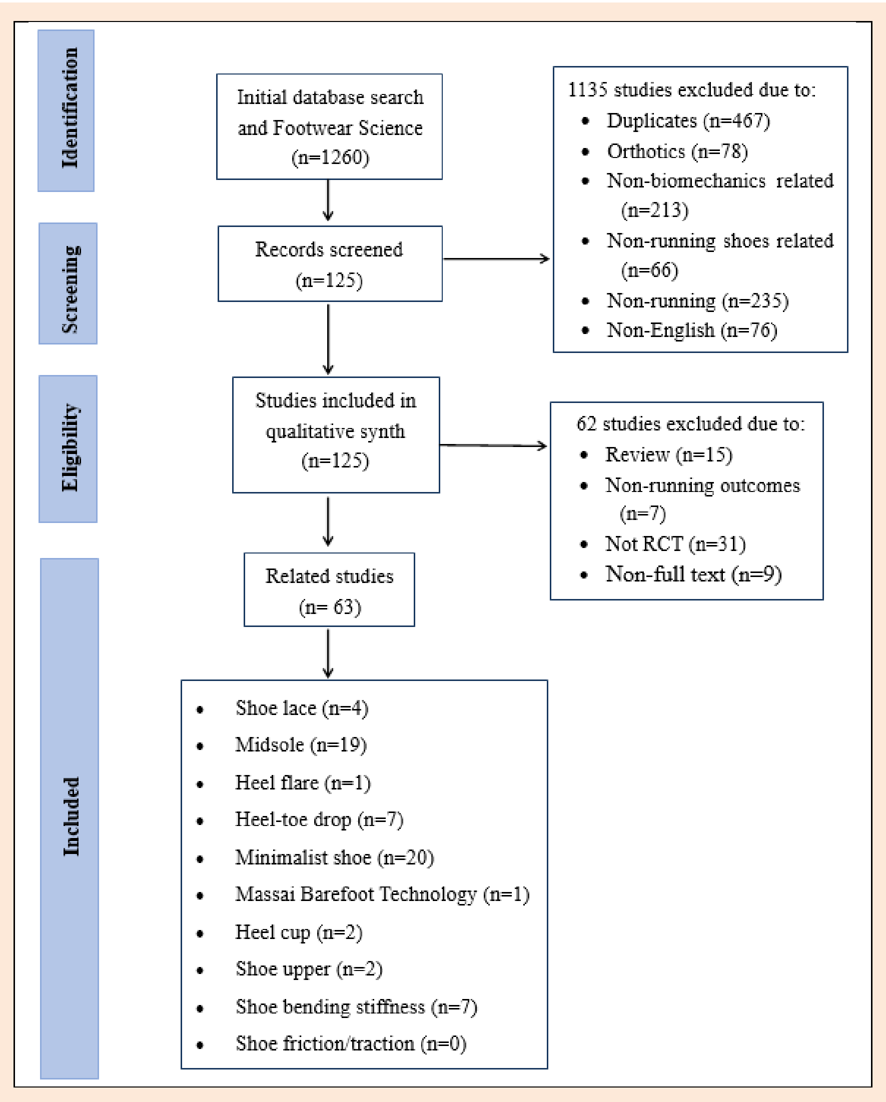

Figure 1. Search and screening procedure.

This systematic review included mainly laboratory-based biomechanical studies, a Physiotherapy Evidence Database (PEDro) scale (Macedo et al., 2010) was used to assess the quality of each included study. Studies with a PEDro score of less than 6 were deemed as low quality and were not included in the review. Two independent raters (authors XLS and XNZ) performed each step of the search and the PEDro quality assessment. When the steps or the quality scores differed between the raters, it would be discussed and consulted with the third rater (author WJF) to reach a final consensus.

The effects of different running shoe constructions on athletic performance-related and injuries variables were shown in Tables 1 to 9, respectively. The injury-related variables included cushioning, motion control, reduce sprain, lower pronation, lower plantar pressure in the braking phase. Meanwhile, the performance-related variables included energy consumption, running efficiency, kinematics, GRF, and plantar pressure in the propulsion phase (Wing et al., 2019).

Results

Overview of review data

The full search yielded 1260 articles (Figure 1). After excluding the articles which were duplicates, irrelevant and low PEDro scores (i.e., less than 6), a total of 63 articles were included into subsequent analysis.

Effects of shoelace

Four included articles (Table 1) investigated the effects of shoelace on running biomechanics. Three articles compared the effect of different shoelace patterns (6 eyelets-regular lacing, 6 eyelets-tight lacing, all 7 eyelets) on the biomechanics during overground running (Hagen and Feiler, 2011; Hagen and Hennig, 2009; Hagen et al., 2010). One article investigated different running mechanics between laced and elastic-covered running shoes (Hong et al., 2011). As shown in Table 1, 6 eyelets-regular lacing was the most unstable than other patterns, and showed higher loading rate and heel peak pressure than all 7 eyelets

Table 1. Summary of the studies on shoelace effect (n = 4).

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome		PEDro Score
					Performance related	Injury related	
Hong et al., (2011)	1. Laced running shoes (LS); 2. Elastic-covered running shoes (ES)	3.8	15, M, 20.3, rearfoot striker	Treadmill running	LS ↑ perceived forefoot cushioning, heel cup fitting, shoe heel width, shoe forefoot width & shoe length; LS ↓ max. rearfoot pronation; ES ↑ PP on 3rd, 4th & 5th MTH; → PP on other foot regions; ↔ contact area for all regions.	NA	6
Hagen and Hennig, (2009)	1. REG6 (6 eyelets-regular lacing) 2. WEAK6 (6 eyelets-very weak lacing) 3. TIGHT6 (6 eyelets-very tight lacing) 4. EYE12 (eyelets 1 and 2) 5. EYE135(eyelets 1,3,5) 6. ALL7 (all 7 eyelets)	3.3	20, M, 32, rearfoot striker	Overground running	Low lacing ↓ vGRF impact, PP on 3rd & 5th MTH than high lacing; ↔ maximum pronation.	EYE12↓ the peak vertical forces than REG6 and TIGHT6; TIGH 6, ALL7 and REGULA 6↓ loading rate & pronation velocities than EYE12, EYE135, and WEAK6; High lacing ↓ heel & lateral midfoot PP than tighter lacing; REG 6 ↑ loading rate & heel PP than ALL7.	6
Hagen et al., (2010)	1. All 7 eyelet (ALL) 2. 6 eyelets-tight lacing (TIGHT6) 3. 6 eyelets-regular lacing (REG6) 4. Skipping the 6th eyelet (A57)	3.3	14, M, 24, rearfoot striker	Overground running	TIGHT6, ALL & A57 ↑ perceived stability than REG6; A57, REG6 ↑ comfort than other; TIGHT6 is the most uncomfortable.	TIGHT6 ↑ PP on medial foot dorsum than other; ALL, A57 ↓ PP on tarsal bones.	6
Hagen et al., (2011)	1. All 7 eyelets (ALL) 2. 6 eyelets-tight lacing (TIGHT6) 3. 6 eyelets-regular lacing (REG6) 4. Skipping the 6th eyelet (A57)	Self-selected Speed	High level (21, M, NA, rearfoot striker); Low level (20, M, NA, rearfoot striker)	Overground running	Low level: A57 ↑ perceived stability & comfort than REG6; High level: A57 ↓ perceived comfort than other.	NA	6

Max = maximum, PP = peak pressure, vGRF = vertical ground reaction force, MTH = metatarsal head, NA = Not available patterns (Hagen and Hennig, 2009; Hagen et al., 2010). Additionally, 6 eyelets-tight lacing was considered as the most uncomfortable (Hagen et al., 2010).

Effects of shoe midsole

Nineteen included articles investigated the hardness (n = 13), thickness (n = 2), and material properties (n = 4) of the midsoles, which would influence lower extremity biomechanics that is related to injury or athletic performance (Table 2). The PEDro score was "8" for only one, all of the other articles were equal to "6. 4". Out of 13 studies (Stefanyshyn and Nigg, 2000; Willwacher et al., 2014; Maclean et al., 2009; Hardin et al., 2004) demonstrated that the increase in the stiffness/hardness of midsoles from Asker C40 to Asker C70 would be related to running performance as indicated by the reduced energy lost at metatarsophalangeal and maximum rearfoot eversion velocity, and increased positive work at metatarsophalangeal and peak ankle dorsiflexion velocity in running. However, 4 out of 13 studies (Hardin and Hamill, 2002; Nigg and Gerin-Lajoie, 2011; Teoh et al., 2013; Wakeling et al., 2002) showed no significant effects on peak tibial acceleration, running velocity, stride duration and all frequency spectral or time domain parameters of gastrocnemius medialis, biceps femoris and vastus medialis variables. Among the related studies, two included studies (Sterzing et al., 2013; Teoh et al., 2013) demonstrated soft midsoles could reduce impact forces and loading rates, thereby minimising the risk of impact-related injuries.

Two out of 19 articles found that thicker midsoles can provide better cushioning effects and attenuate shock during impacts but may also decrease plantar sensations of a foot (Robbins and Gouw, 1991).

Table 2. Summary of the studies on midsole effect (n = 19).

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome		PEDro Score
					Performance related	Injury related	
Baltich et al. (2015)	1. Asker C40 (Soft) 2. Asker C52 (Medium) 3. Asker C65 (Hard)	3.33 ± 0.15	93, M=47, F=46, rearfoot striker Group1:16-20yr Group2:21-35yr Group3:36-60yr Group4:61-75 yr	30-m over-ground running	Soft ↑ ankle stiffness than Medium & Hard; Female Soft ↑ knee stiffness than Medium&Hard; Male Soft ↑ knee stiffness than Medium	Soft ↑ vGRF impact peak than Medium & Hard	6
Chambon et al. (2014)	1. Barefoot (BF) 2. 0-mm midsole (MT0) 3. 2-mm midsole (MT2) 4. 4-mm midsole (MT4) 5. 8-mm midsole (MT8) 6. 16-mm midsole (MT16)	3.3	15, M, 23.9, rearfoot striker	Over-ground running	BF & MT0 ↓ stance-phase duration than MT16; BF ↑ initial plantarflexion than shoe condition; BF ↑ strike index than shoe condition; BF ↑ ankle dorsiflexion but ↓ knee flexion during stance; BF ↓ max knee joint moments than MT0 & MT4; ↔ hip & knee flexion angles at TD.	↔ peak GRF impact, peak tibial acceleration.	6
Dixon et al., (2015)	1. A neutral shoe with an average hardness of 52 Asker C (CON); 2. Medially-52 Asker C lateral -60 Asker C (LAT1); 3. Medially-52 Asker C lateral -70 Asker C (LAT2);	3	10, F, ＞50 years, NA	Over-ground running	LAT1 ↓adduction movement than CON	LAT2↑ max 1st loading rate & eversion movement than CON; ↔ peak knee abductor moment and peak rearfoot eversion.	6
Hardin & Hamill, (2002)	1. Shore A40 (Soft) 2. Shore A55 midsole (Medium) 3. Shore A70 midsole (Hard)	3.4	24, M, NA, rearfoot striker	Treadmill downhill running	↔ peak tibial acceleration.	NA	6
Hardin et al., (2004)	1. Shore A40 midsole (Soft) 2. Shore A70 midsole (Hard)	3.4	12, M, NA, rearfoot striker	Treadmill running	Hard midsole ↑ peak ankle dorsiflexion velocity.	NA	6

Yr = year, vGRF = vertical ground reaction force, MF = midfoot, RF = rearfoot, FF = forefoot, Max = maximum, MTP = metatarsophalangeal, VO_2 = oxygen consumption, EMG = electromyography, RMS = root mean square, RoM = range of motion, NA = Not available, TD= Touch down.

Table 2. Continued…

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome: Performance related	Outcome: Injury related	PEDro Score
Law et al. (2018)	1.1-mm midsole thickness (MT1) 2.5-mm midsole thickness (MT5) 3.9-mm midsole thickness (MT9) 4.21-mm midsole thickness (MT21) 5.25-mm midsole thickness (MT25) 29-mm midsole thickness (MT29);	Self-paced	15, M, 31.4, rearfoot striker	Treadmill running	Thinner midsole (MT1 & MT5) ↓ contact time than MT25 & MT29; ↔ footstrike angle, cadence & stride length.	Thinner midsole (MT1 & MT5) ↑ vertical loading rates than (MT25 & MT29).	6
Maclean, Davis, & Hamill, (2009)	1.Asker C70 midsole (Hard) 2.Asker C55 midsole (Medium) 3.Asker C40 (Soft)	4.0 ± 5%	12, F, 19-35, Rearfoot striker with iliotibial band or patellofemoral pain syndrome	Over-ground running	Hard shoe ↓ Max rearfoot eversion velocity.	NA	6
Nigg et al., (2011)	1.Asker C40 (Soft) 2.Asker C52 (Medium) 3.Asker C65 (Hard)	3.33 ± 0.17	54, M=36, F=18, 33.9, rearfoot striker	30-m over-ground running	↔ all frequency spectral or time domain parameters of gastrocnemius medialis, biceps femoris and vastus medialis.	NA	6
Oriwol et al., (2011)	7 dual-density shoe condition: Medial dual density midsole elements with 62 Asker C 1. M1 is the neutral shoe. 2. M2 – 36 mm 3. M3 – 52 mm 4. M4 – 58 mm 5. M5 – 79 mm 6. M6 – 89 mm 7. M7 – 104 mm	3.5 ± 0.1	16, M, 29.4, rearfoot striker	Over-ground running	↔ all rearfoot motion variables.	NA	6
Sterzing et al., (2013)	All shoe with Asker C50 MF 1.Soft-RF/Soft-FF (SS) 2.Medium-RF/Medium-FF (MM) 3.Hard-RF/Hard-FF (HH) 4.Soft-RF/Hard-FF (SH) 5.Hard-RF/Soft-FF (HS)	3.3 ± 0.1	28, M, 23.8, rearfoot striker	13-m over-ground running	Softer ↓ max plantarflexion & pronation velocity than stiffer shoes; MM ↓ sagittal footstrike angle than SH & HS; ↔ Contact time	SH, SS, & MM ↓ max 1st loading rate than HH, HS; SH ↓ max 2nd loading rate than MM, HH & HS; SS ↓ max 2nd loading rate than HH & HS; MM ↓ max 2nd loading rate than HH.	6
Sterzing et al. (2015)	1. Soft medial/Hard Lateral (SMH) 2.Medium medial/Medium lateral (MMM) 3.Hard medial/Soft lateral (HMS) 4.Very Hard medial/Very Soft lateral (VHMVS)	3.3 ±10%	24, M, 21.8, rearfoot striker	Over-ground running	SMH ↑ perceived softer at medial midsole than HMS; MMM ↑ perceived softer at medial midsole than HMS & VHMVS; SMH ↑ ground contact time than HMS & VHMVS; SMH ↑ max 1st loading rate MMM & VHMVS; VHMVS ↓ maximum inversion at touchdown than all other shoe condition; ↔Cushioning, stability & propulsion during push-off	VHMVS ↑ PP at medial region than SMH & MMM; VHMVS ↑ force-time integral at rearfoot than HMS & SMH; VHMVSC force-time integral at medical region than all other shoes; SMH ↓ force-time integral at centre than MMM & VHMVS; SMH ↑ force-time integral at lateral region than all other shoes	6

Yr = year, vGRF = vertical ground reaction force, MF = midfoot, RF = rearfoot, FF = forefoot, Max = maximum, MTP = metatarsophalangeal, VO_2 = oxygen consumption, EMG = electromyography, RMS = root mean square, RoM = range of motion, NA = Not available, TD= Touch down.

Table 2. Continued…

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome: Performance related	Outcome: Injury related	PEDro Score
Stefanyshyn et al., (2000)	1.Control shoe 2. Stiff midsole shoe (Stiff) 3.Very stiff midsole shoe (Very stiff)	4.0 ± 0.4	5, M, 32, rearfoot striker	Over-ground running	Stiff ↓ energy lost at MTP; ↔ energy generation & absorption at ankle, knee & hip; ↔ energy stored & reused at MTP.	NA	6
Teoh et al., (2013)	1. medial stiffness 1C, lateral stiffness 1.6C (VSS) 2. same medial & lateral stiffness 1C (CS)	self-selected speeds	M=16, F=14, 22.6,	Over-ground running	↔running speed	VSS ↓ the peak EKAM than CS; VSS ↓ the maximum medial GRF than CS ↑ in anterior GRF than CS.	6
Theisen et al., (2014)	1.Soft midsole shoe (Soft) 2.Hard midsole shoe (Hard)	2.61-2.69	247, M=136, F=111, 41.8, leisure-time distance runners	Over-ground running	NA	↔ running-related injury. ↔ Injury location, type, severity or category.	8
Willwacher et al. (2014)	1.Control (Control) 2.Medium stiffness (Medium) 3.High stiffness (High)	3.5 ±5%	19, M, 25.3, rearfoot striker	25m over-ground running	Medium & High ↑ overall Stance time & push-off time than Control; High ↓ Negative work & ↑ positive work at MTP than Control & Medium. ↔Effective contact time & braking time.	NA	6
Wakeling, & Nigg, (2002)	1.Shore C61 midsole (Hard) 2.Shore C41 midsole (Soft)	2.5-4.2	3, M, 26, NA 3, F, 23.3, NA	Over-ground running	↔EMG intensities varied in different shoe condition; ↔ running velocity, stride duration	NA	6
Wang et al. (2012)	1.Ethylene Vinyl Acetate (EVA) 2.Polyurethane -1 (PU1) 3.Polyurethane -2 (PU2)	NA	15, M, 21.2, rearfoot striker	Over-ground outdoor running	EVA & PU-1 ↓ peak forces than PU2 at all running distance; PU-1 ↓ peak forces at 200-30 km than 0 km; EVA ↑ energy return performance than PU1&PU2	NA	6
Wunsch et al., (2016)	1.Leaf spring-structured midsole (Leaf) 2.Standard foam (Foam)	2 mmol/l blood lactate speed	10, M, 33.1, long-distance rearfoot striker	Over-ground running	Leaf ↑ stride length but ↓ stride rate & oxygen consumption than foam; ↔ strike pattern	NA	6
Wunsch et al., (2017)	1.Leaf spring-structured midsole (Leaf) 2.Standard foam (Foam)	3.0 ± 0.2	9, M, 32.9, long-distance rearfoot striker	Indoor track	LEAF↓ energy absorption at hip joint as well as energy generation at ankle joint; LEAF↓ muscle forces of the soleus, gastrocnemius lateralis & gastrocnemius medialis	NA	6

Yr = year, vGRF = vertical ground reaction force, MF = midfoot, RF = rearfoot, FF = forefoot, Max = maximum, MTP = metatarsophalangeal, VO_2 = oxygen consumption, EMG = electromyography, RMS = root mean square, RoM = range of motion, NA = Not available, TD= Touch down.

Effects of heel flare

Only one included article (Table 3, Figure 2) investigated the effects of heel flare construction (lateral heel flare of 25°, no lateral heel flare 0°, rounded heel) on running biomechanics. However, there were no significant differences in tibiocalcaneal and ankle kinematics (initial inversion, maximal eversion velocity) among heel flare conditions (Stacoff et al., 2001).

Table 3. Summary of the studies on heel flare effect (n = 1.)

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome: Performance related	Outcome: Injury related	PEDro Score
Stacoff et al., (2001)	1. Lateral heel flare of 25° (Flared) 2. No lateral heel flare 0° (Straight) 3. Rounded heel (Round).	2.5–3	5, M, 28.6, rearfoot striker	Over-ground running	↔ Tibiocalcaneal rotations & shoe eversion; ↔ Initial inversion, max eversion velocity, max & total eversion on bone, & total internal tibial rotation.	NA	6

NA = Not available

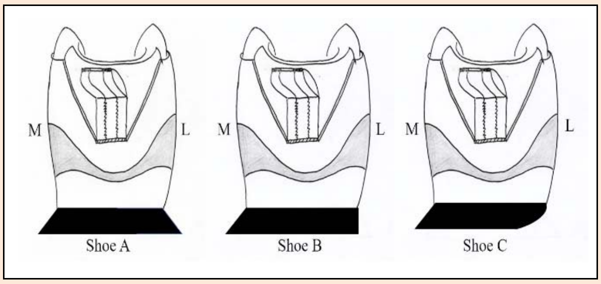

Figure 2. Three different heel flares.

Effects of heel–toe drop

Seven included articles (Table 4) investigated the effects of heel-toe drop on running. The PEDro scores of 5 articles were 6 and the other two were 7. As shown in Table 4, all these studies investigated different performance-related variables. Shoes with higher drops were found to be related to increase knee adduction (Malisoux et al., 2016), knee excursion, knee flexion at midstance, stance time (TenBroek et al., 2014) and reduce tibial acceleration, initial ankle plantarflexion, initial knee extension angle (TenBroek et al., 2014). For running mechanics, shoes with higher drops would increase net knee flexion moment in the push-off, but reduced net joint ankle flexion moment during braking phase (Besson et al., 2017). In a randomized controlled study (Malisoux et al., 2016), cox proportional hazards regression was used to compute the hazard rates in the exposure groups, using first-time injury as the primary outcome and concluded that there was no significant difference of overall injury risk among different heel-toe drops.

Table 4. Summary of the studies on heel-toe drop effect (n = 7).

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome		PEDro Score
					Performance related	Injury related	
Besson et al., (2017)	1. Heel–toe drop 10 mm (D10) 2. Heel–toe drop 6 mm (D6) 3. Heel–toe drop 0 mm (D0)	Preferred speed	14, F, 21.4, rearfoot striker	Overground running	D0 ↓ Foot ground angle, ankle dorsiflexion at initial & last 40% stance phase than D6 & D10; D0 ↑ AP GRF during first part of stance phase than D6 & D10; D0 ↑ push-off time but ↓ braking time than D6 & D10; D0 ↑ net joint ankle flexion moment during braking phase ↓ net knee flexion moment in the push-off phase compared to D6 & D10; ↔ knee & hip angles, & stance phase duration.	NA	6
Chambon et al. (2015)	1. Heel–toe drop 0 mm (D0) 2. Heel–toe drop 4 mm (D4) 3. Heel–toe drop 8 mm (D8) 4. Barefoot (BF)	Preferred Speed	12, M, 21.8, rearfoot striker	Treadmill & overground running	NA	Overground: D0 ↓ foot ground angle at touchdown than D8; BF↑ loading rate than D8; Treadmill: BF & D0 ↓ foot ground angles than D8; BF & D0 ↑ ankle flexion during stance phase than D8; BF ↓ knee flexion RoM than D4 & D8; BF ↓ peak & loading rate of vGRF than D8; ↔ initial ankle angle	6
Malisoux et al., (2017)	1. Heel–toe drop 10 mm (D10) 2. Heel–toe drop 6 mm (D6) 3. Heel–toe drop 0 mm (D0)	Preferred speed	59, M=42, F=17, rearfoot striker	Treadmill running	D6 & D10 ↑ knee adduction than D0; ↔ contact time, flight time, stride frequency, stride length, hip vertical displacement	NA	7
Malisoux et al. (2016)	1. Heel–toe drop 10 mm (D10) 2. Heel–toe drop 6 mm (D6) 3. Heel–toe drop 0 mm (D0)	2.64	553, M&F, D10=176; D6=190; D0=187; 38; rearfoot striker (occasional & regular)	Outdoor overground running	NA	D6 & D0 ↓ injury risk in occasional runners but ↑ injury risk in regular runners; ↔ overall injury risk for all participant	7

Max = maximum, RoM = range of motion, GRF = ground reaction force, AP = anterior-posterior direction, ML = medio-lateral direction, CoP = centre of pressure, NA = Not available.

Table 4. **Continued…**

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome		PEDro Score
					Performance related	Injury related	
Mits et al. (2015)	1. Heel–toe drop 12 mm (D12) 2. Heel–toe drop 8 mm (D8) 3. Heel–toe drop 4 mm (D4) 4. Heel–toe drop 0 mm (D0)	0.97±10%	14, M, 27, rearfoot striker	Overground running	D8, & D12 ↑ max AP CoP excursion than D4; D8 ↑ range of AP CoP than D0; ↔ ML CoP variables.	NA	6
TenBroek et al. (2014)	Forefoot–rearfoot offset: 1.3–3 mm offset (Thin) 2.9–14 mm offset (Medium) 3.12–24 mm offset (Thick)	3.0	10, M, 18-55, rearfoot striker	Treadmill running	Thin & Medium ↑ initial ankle plantarflexion than other; Thin↑ initial knee extension angle than other; Thick ↑ knee flexion at midstance than Medium; Thick ↑ knee excursion than Thin & Medium; Thick ↑ stance time than Thin & Medium.	NA	6
TenBroek et al., (2012)	Forefoot–rearfoot offset: 1. 3–3 mm offset (Thin) 2. 9–14 mm offset (Medium) 3. 12–24 mm offset (Thick) 4. Barefoot (BF)	3.0	10, M, 18-55, rearfoot striker	Treadmill running	Barefoot & Thin ↓ initial dorsiflexion than Medium & Thick; BF & Thin ↑ leg segment vertical at TD than Thick; Medium & Thick↑ knee flexion excursion than Thin & BF; Thin ↑ knee excursion than BF; Thin ↑eversion excursion than all other conditions; Thin ↑ stance time than Medium & Thick Barefoot & Thin ↑ peak tibial acceleration than other condition; Medium ↑ peak tibial acceleration than Thick	NA	6

Max = maximum, RoM = range of motion, GRF = ground reaction force, AP = anterior-posterior direction, ML = medio-lateral direction, CoP = centre of pressure, NA = Not available.

Effects of minimalist shoe

Twenty included articles (Table 5) investigated the effects of minimalist shoe on running. The PEDro scores of 18 articles were 6 and the other two were 7. Three included studies showed that minimalist shoes would improve running economy (Fuller et al., 2017b; Michael et al., 2014; Warne et al., 2014) and other three included studies indicated that minimalist shoes would increase the cross-sectional area, stiffness and impulse of Achilles tendon compared with the conventional shoes (Histen et al., 2017; Joseph et al., 2017; Sinclair and Sant, 2016). Furthermore, participants wearing minimalist shoes promote midfoot and/or forefoot running, with smaller footstrike angles (Fuller et al., 2016; Moore et al., 2014), more anteriorly shift of center of pressure (Bergstra et al., 2015), greater metatarsophalangeal and ankle loading but smaller knee loading (Firminger and Edwards, 2016), compared to conventional shoes.

Table 5. **Summary of the studies on minimalist shoe effect (n = 20).**

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome		PEDro Score
					Performance related	Injury related	
Bergstra et al., (2015)	1. Minimalist shoe (MS) 2. Standard running shoes (SS)	MS=3.38; SS=3.41	18, F, AGE, rearfoot striker	Overground running	MS ↓ stance time than Control; ↔ shoe comfort & landing strategy	MS ↑ peak & mean pressure in medial, central & lateral forefoot during the entire contact phase than SS	6

AT = Achilles tendons, MVIC = maximal voluntary isometric contraction, VE = pulmonary ventilation, EMG = electromyography, VO_2 = oxygen consumption, RoM = range of motion, MTP = metatarsophalangeal, NA = not available.

Table 5. Continued…

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome		PEDro Score
					Performance related	Injury related	
Bonacci et al., (2013)	1. Barefoot (BF); 2. Minimalist shoe (MS); 3. Racing flat shoe (Race); 4. Athlete's regular shoe (RS)	4.48 ±5%	22, M=8, F=14, 29.2, highly trained runners	Overground running	BF ↓ knee flexion during midstance, peak internal knee extension, knee abduction moments negative work done, & initial dorsiflexion than shod condition; BF ↑ peak ankle power generation & positive work done than MS & Race	NA	6
Campitelli et al., (2016)	1. Vibram minimalist shoe (MS) 2. Conventional shoe (CS)	NA	25-M; 16-F; 20-33, rearfoot striker	24-week training programme	MS ↑ thickness of abductor hallucis muscle; ↔ thickness of abductor hallucis muscle.	NA	7
Firminger & Edwards, (2016)	1. Minimalist shoe (MS) 2. Control shoe (Control)	Preferred speed	15, M, 26.2, rearfoot striker	Overground running	MS ↑ MTP eccentric work but ↓ MTP concentric work; MS ↑ peak plantarflexion moment, angular impulse, cumulative impulse & eccentric work; MS ↓ peak knee moment, angular impulse & cumulative impulse; ↔ peak MTP moment, angular impulse & cumulative impulse; ↔ knee concentric & eccentric work; ↔ concentric work at ankle	MS ↑ MTP & ankle loading; MS ↓ knee loading	6
Fredericks et al., (2015)	1. Barefoot (BF) 2. Minimalist shoe (MS) 3. Personal shoe (PS) 4. Standard shoe (CS)	2.5 3.0 3.5 4.0	26, M=13, F=13, 26.5,	Treadmill running	For rearfoot strike BF ↑ plantarflexion at toe-off than all other shoes; MS ↑ plantarflexion at toe-off than CS; For non-rearfoot strike MS & BF ↑ plantarflexion toe-off than PS; For all foot strike type PS ↑ step length than BF & MS; ↔foot strike knee angle or toe-off knee angle.	NA	6
Fuller et al., (2017)	1. Conventional shoe (CS) 2. Minimalist shoe (MS)	NA	61, M, 27, rearfoot strikers	Gradually increased shoe wearing time over 26-week running	NA	11 of 30 runners sustained an injury in CS; 16 of 31 runners in MS; MS ↑ knee & calf pain than CS	7
Fuller et a., (2016)	1. Conventional shoe (CS) 2. Minimalist shoe (MS)	5.0	26, M, 30.0, rearfoot striker with no experience of minimalist shoe	Overground running	MS ↓ initial ankle angle but ↑ strike index; MS ↑ negative & positive work at ankle; MS ↓ negative & positive work at knee; ↔ foot strike pattern	NA	6
Goss et al., (2013)	1. Minimalist shoe (MS) 2. Traditional training shoe (TTS) 3. Not training shoe (Control)	NA	47, F, 24, rearfoot striker	Athletic training	MS & TTS ↑ MPJ moments in 0°MPJ dorsal flexion than Control; MS ↑ toe flexor muscles strength in 25° MPJ dorsal flexion than TTS	NA	6

AT = Achilles tendons, MVIC = maximal voluntary isometric contraction, VE = pulmonary ventilation, EMG = electromyography, VO_2 = oxygen consumption, RoM = range of motion, MTP = metatarsophalangeal, NA = not available.

Table 5. Continued…

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome: Performance related	Outcome: Injury related	PEDro Score
Histen et al., (2017)	1. Minimalist shoe (MS) 2. Conventional shoe (CS)	NA	23, M (11 traditional runners, 12 minimalist) 8, F (6 traditional runner 2 minimalist runner); traditional runner: rearfoot striker Minimalist runner: forefoot/midfoot strike	NA	Minimalist ↑cross sectional area of AT, stiffness, Young's modulus, ATs stress during MVIC of plantar flexor muscles	NA	6
Joseph et al., (2017)	Minimalist shoe	NA	F =15; M=7; AGE, traditionally shod runner	Transitioned to minimalist shoe running- 12 weeks	Male ↑ force, cross sectional area, stiffness & Young's modulus of AT than women; Male ↓ elongation of AT than women	NA	6
Kahle et al., (2016)	1. Conventional shoe (CS) 2. Minimalist shoe (MS)	Ran at 70% VO2max	12, M, NA, recreational rearfoot striker	Treadmill running	↔VO2, heart rate, VE, EMG of gastrocnemius & tibialis anterior	NA	6
MaxRobert et al., (2013)	1. Minimalist shoe (MS) 2. Barefoot (BF) 3. Neutral running shoe (NS)	3.3 ± 5%	14, M, AGE, 7 Rearfoot & 7 Forefoot striker	Overground running	BF & MS ↑ peak propulsive GRF than NS; BF& MS ↓ peak ankle dorsiflexion, peak knee flexion, knee flexion RoM than NS; MS ↑ plantar flexor moment than BF & NS; MS ↓ peak ankle power than BF & NS; BF & MS ↓ peak knee extension moment than NS; BF & MS ↓ initial peak eccentric knee power than NS	BF & MS ↑ loading rates than NS in Rearfoot group	6
Mccallion et al., (2014)	1. Barefoot (BF) 2. Minimalist shoe (MS) 3. Conventional shoe (CS)	3.61 ± 0.28; 4.47 ± 0.36	14, M, 25, rearfoot striker	Treadmill running	MS ↑ stride duration & flight time than BF; CS ↑ contact time than BF & MS; BF ↑ stride frequency than CS &MS.	NA	6
Moody et al., (2018)	1. Mizuno Wave Rider (Mizuno) 2. Saucony Kinvara (Saucony) 3. Altra The One (Altra) 4. Vibram El-X/Entrada (Vibram) 5. Barefoot running (Barefoot)	3.3	F=4; 25.2; rearfoot striker M=6; 26.8, rearfoot striker	Treadmill running	Mizuno ↑ ground time & vertical oscillation but ↓ stride rate than Barefoot; ↔ max knee flexion during stance and swing, hip flexion & extension, ankle angle at touchdown & toe-off	NA	6
Moore et al., (2014)	1. Barefoot (BF) 2. Minimalist shoe (MS) 3. Conventional shoe (CS)	3.8	10, M=9, F=1, 21.0, rearfoot striker	Overground running; 7-week minimalist footwear transition	CS ↑ number of rearfoot strike trials than other condition; MS ↑ number of midfoot & forefoot strike trials than other shoes; CS↑ latest occurrence of peak impact force; BF ↓ ground contact time than others.	BF & MS ↑ loading rate than CS; ↔ magnitude of peak impact force	6
Sinclair et al., (2016)	1. Barefoot (BF) 2. Crossfit shoe (Cross) 3. Minimalist shoe (MS) 4. Conventional shoe (CS)	4.0 ± 5%	13, M, 27.81, rearfoot striker	Overground running	BF & MS ↑ peak Achilles tendon force than CS; BF & MS ↑ Achilles tendon impulse than CS; BF & MS ↑ Time to peak Achilles tendon force than CS; BF, Cross & MS ↑Achilles tendon load rate than CS.	NA	6

AT = Achilles tendons, MVIC = maximal voluntary isometric contraction, VE = pulmonary ventilation, EMG = electromyography, VO_2 = oxygen consumption, RoM = range of motion, MTP = metatarsophalangeal, NA = not available.

Table 5. Continued…

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome: Performance related	Outcome: Injury related	PEDro Score
Sinclair et al., (2016)	1. Minimalist (MS) 2. Maximalist (Max) 3. Conventional shoe (CS)	4.0 ± 5%	20, M, 24.24, rearfoot striker	Overground running	CS & Max ↑ peak knee flexion; knee RoM, peak contact loading (force, pressure, average & instantaneous loading rates, impulse, force per mile) & step length than MS. MS ↑ initial plantarflexion & number of steps per mile.	CS & Max ↑ peak patellofemoral force & pressure than MS;	6
Sinclair et al., (2016)	1. Barefoot (BF) 2. Minimalist shoe (MS), 3. Conventional shoe (CS) 4. Cross-fit (CF)	4.0 ± 5%	12, M, 23.1, rearfoot striker	Overground running	BF ↓ time to peak AT force than CF	BF & MS ↑ peak AT force, the time to peak AT load than CS; CS ↓ average load rate, instantaneous AT load rate of AT than all other conditions; BF & MS ↑ AT impulse than CS;	6
Willy & Davis, (2014)	1. Minimalist shoe (MS) 2. Conventional shoe (CS)	3.35	14, M, 24.8, rearfoot striker	Treadmill running	↔ Step length, step rate; MS↑ knee flexion, dorsiflexion angle at footstrike	MS ↑ Vertical impact peak & average vertical loading rate	6
Warne et al., (2014)	1. Conventional shoe (CS) 2. Minimalist shoe (MS)	3.06	10, F, 21, rearfoot striker	Treadmill running; 4-week minimalist footwear transition	NA	MS ↑ max force & pressure than CS.	6

AT = Achilles tendons, MVIC = maximal voluntary isometric contraction, VE = pulmonary ventilation, EMG = electromyography, VO_2 = oxygen consumption, RoM = range of motion, MTP = metatarsophalangeal, NA = not available.

Massai Barefoot Technology (MBT)

Only one included article (Table 6) investigated the effects of MBT on running kinematics and kinetics with a PEDro score of 6. Specifically, running in MBT shoes was related to larger dorsiflexion at initial contact and mid-stance, reduced peak ankle moments and power, and smaller medial and anterior GRF peak than the conventional shoes (Boyer and Andriacchi, 2009).

Effects of heel cup

Two included articles (Table 7) investigated the effects of heel cup on running tasks. Both PEDro scores were 6. Li and colleagues (2018) investigated the effect of 3D printed and customised heel cup on plantar pressure, stress, and pain score variables. Their results showed that heel cup reduced peak plantar pressure, stress on plantar fascia and calcaneus bone and self-reported pain significantly after wearing heel cups for 4 weeks. Another article reported that plastic heel cup increased heel pad thickness than rubber heel cup and that rubber and plastic heel cup increased shock absorption of heel than no heel cup condition (Wang et al., 1994).

Effects of shoe upper

Two included articles (Table 8) investigated the effects of shoe upper on running biomechanics. Both PEDro scores were equal to 6. These articles investigated the influence of different shoe upper constructions on the plantar pressure distribution (Onodera et al., 2015), joint angle in sagittal, frontal, and transversal planes, and ground reaction force (Onodera et al., 2017). Structured shoe upper increased contact time and peak pressure at midsole than minimalistic shoe upper (Onodera et al., 2015).

Table 6. Summary of the studies on Massai Barefoot Technology (MBT) effect (n = 1).

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome: Performance related	Outcome: Injury related	PEDro Score
Boyer & Andriacchi, (2009)	1.Conventional flat shoe (CS) 2.Rounded sole MBT (MBT)	Preferred Speed	11=F, 28.9, NA 8=M,32.6, NA	Over-ground running	MBT ↑ ankle dorsi-flexion at heel-strike & mid-stance than CS; MBT ↓ peak ankle plantar & dorsi-flexion moments, peak ankle joint power than CS.	MBT ↓ 1st medial & anterior GRF peaks than CS.	6

GRF = ground reaction force

Table 7. Summary of the studies on heel cup effect (n = 2).

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome: Performance related	Outcome: Injury related	PEDro Score
Li et al., (2018)	1. Heel cup (HC) 2. Non-heel cup (N-HC)	NA	16, F=6, M=10, NA	jogging	HC ↓ load on plantar fascia & calcaneus bone after wearing heel cups for 4 weeks	HC ↓ self-reported pain than N-HC.	6
Wang et al., (1994)	1. Rubber heel cup 1 (Rub-1) 2. Rubber heel cup 2 (Rub-2) 3. Plastic heel cup (Plastic) 4. No-heel cup	2.78	16, NA, AGE, volunteers without heel pain & 6 with heel pain	Treadmill	Plastic ↑ heel pad thickness than rubber heel cup; Rubber & Plastic ↑ shock absorption of heel than no heel cups	NA	6

NA = not available

Table 8. Summary of the studies on shoe upper effect (n=2).

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome: Performance related	Outcome: Injury related	PEDro Score
Onodera et al., (2015)	1. Structured upper (Structure) 2. Minimalistic upper (Minimal)	2.64-2.91	20, M, 33.3, rearfoot striker	Overground running	Structure ↑ contact time for total midfoot & lateral forefoot than Minimal; ↔ contact area	Minimal ↑ PP in total area, rearfoot & medial forefoot than Structure; Minimal ↓ PP at midfoot than Structure	6
Onodera et al., (2017)	1. Structured upper (Structure). 2. Minimalist upper (Minimal). 3. Low Resilience cushioning material (Low) 4. High Resilience cushioning material (High)	2.64-2.92	27, M, 36.0, Rearfoot striker	Overground running	Accuracy higher than 85% was achieved by considering only 25 variables to differentiate upper structures; a mean accuracy of 93.4% with 25 variables, & 95.6% with 150 variables.	NA	6

NA = not available

Effects of shoe bending stiffness

Seven included articles (Table 9) investigated shoe bending stiffness on running. All the PEDro scores were equal to 6. In performance perspective, 5 out of the 7 included studies (Hoogkamer et al., 2018; Stefanyshyn and Nigg, 2000; Roy and Stefanyshyn, 2006; Stefanyshyn and Fusco, 2004; Madden et al., 2015) showed that increasing bending stiffness could improve running performance and economy, as indicated by the reduction of energetic cost, maximum VO_2, energy lost at metatarsophalangeal joint, and sprint time in stiffer shoes. One of the included studies (Madden et al., 2015) found that there was no difference in running economy among tested shoe conditions. The other two studies (Oh and Park, 2017; Willwacher et al., 2013) showed that stiffer shoes reduced stance time, negative work and flexion of metatarsophalangeal joint, and increased GRF lever arms for all joints.

Table 9. Summary of the studies on bending stiffness effect (n = 7).

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome: Performance related	Outcome: Injury related	PEDro Score
Hoogkamer et al., (2018)	1. New prototype shoe (NP) 2. Nike racing shoe (Nike) 3. Adidas racing shoe (Adidas)	3.89, 4.44 & 5.0	18, M, 23.7, rearfoot striker	Overground running	NP ↓ energetic cost than other two shoes	NA	6
Madden et al., (2015)	1. Control shoe (Control) 2. 185% Stiffer shoe (Stiff)	Began at 2.2 m/s, with Speed increasing by 0.2 m/s every two min	18, M, 28.0, rearfoot striker	200 m indoor track running	Stiff ↓ peak MTP bending & peak plantarflexion velocity; ↔ running economy; 10 of 18 athletes improved their running economy across bending stiffness	NA	6

Min = Minute, MTP = metatarsophalangeal, VO_2 = oxygen consumption, EMG = electromyography, RMS = root mean square, RoM = range of motion, NA = Not available.

Table 9. Continued…

Reference	Shoe Conditions	Tested running Speed (m/s)	Subject Info (Numbers, Sex, Age, Landing type)	Testing Protocol	Outcome		PEDro Score
					Performance related	Injury related	
Oh & Park, (2017)	1. Stiffness 1.5 2. Stiffness 10 3. Stiffness 24.5 4. Stiffness 32.1 5. Stiffness 42.1	Under the anaerobic threshold	19, NA, 24.7, rearfoot striker	Treadmill running	Stiffer ↑ stance time & push-off time; Stiffer↓ MTP flexion but ↑ GRP moment arm from ankle; Stiffer↓ mean MTPJ angular impulse.	NA	6
Roy & Stefan-yshyn, (2006)	Bending stiffness: 1.18 N•mm (Control) 2.38 N•mm (Stiff) 3.45N•mm (Stiffest)	Submaximal running speed	13, NA, 27.0, rearfoot striker	Treadmill running	Stiff ↓ max & rate of VO2 than Control; Stiffest ↑ peak ankle moments than Stiff & Control; Stiffest ↑ mean energy absorbed at ankle joint than Control; Stiff ↓ 1% metabolic energy than Control; ↔ MTP, knee & hip moments, & EMG RMS.	NA	6
Stefan-yshyn & Fusco, (2004)	1.Standard shoe (Control) 2.Stiffness 42 (S42) 3.Stiffness 90 (S90) 4.Stiffness 120 (S120)	Maximal effort	34, M =30, F= 4, AGE, rear-foot striker	20m sprint	Stiffer shoes (S42, S90, S120) ↓ sprint times than Control.	NA	6
Stefan-yshyn & Nigg, (2000)	1.Stiffness 0.04 (Control) 2.Stiffness 0.25 (Medium) 3.Stiffness 0.38 (Stiff)-1	4.0±0.4	5, M, 32.0, rearfoot striker	Overground running	Stiff shoe ↓energy lost at MTP than Medium & Control; Medium & Stiff ↓ energy absorbed at MTP than Control; ↔ energy generation & absorption at ankle, knee & hip.	NA	6
Willwacher et al., (2013)	1.Shoe 0.65-0.76 (Control) 2.Shoe 5.29-7.11 (Medium-S) 3.Shoe 16.16-17.10 (High-S)	3.5 m/s ± 5%.	19, M, 25.3, rearfoot striker	Overground running	Medium-S & High-S ↑ GRF lever arms for all joints than Control; Medium-S ↓ mean ankle joint moments than Control & High-S; High-S ↓ MTP negative work but ↑ positive work than Control and Medium-S; Medium-S & High-S ↑ stance time & push-off time than Control; Control ↑ MTP RoM & maximum dorsiflexion than Medium-S & High-S.	NA	6

Min = Minute, MTP = metatarsophalangeal, VO_2 = oxygen consumption, EMG = electromyography, RMS = root mean square, RoM = range of motion, NA = Not available.

Discussion

This study summarised the effect of various footwear constructions on running biomechanics that is related to performance and injury potentials. The main results were: 1) increasing the stiffness of running shoes at the optimal range can benefit performance. Some included studies showed stiffer shoe would reduce energetic cost (Hoogkamer et al., 2018), maximum VO_2, energy lost at metatarsophalangeal joint (Roy and Stefanyshyn, 2006; Stefanyshyn and Nigg, 2000), and sprint time (Stefanyshyn and Fusco, 2004); 2) softer midsoles can reduce the impact forces and loading rates (Sterzing et al., 2013; Teoh et al., 2013); 3) thicker midsoles could provide better cushioning effects and attenuate shock during impacts but might also decrease plantar sensations of a foot (Robbins and Gouw, 1991); 4) minimalist shoes can improve running economy (Fuller et al., 2017b; Michael et al., 2014; Warne et al., 2014; Ridge et al., 2013), increase the cross-sectional area and stiffness of Achilles tendon but it would increase the metatarsophalangeal and ankle joint loading compared to the conventional shoes (Histen et al., 2017; Joseph et al., 2017; Sinclair and Sant, 2016); 5) the shoe constructions included shoe lace, heel flare, heel-toe drop, Masai Barefoot Technologies, heel cup, and shoe upper did not show clear influence on biomechanics (Hong et al., 2011; Stacoff et al., 2001; Malisoux et al., 2017; Boyer and Andriacchi, 2009; Li et al., 2018; Onodera et al., 2015).

Effects of shoelace

Amongst the included articles, Hagen and Hennig (2009) typically examined the influence of the number of laced eyelets used (e.g. 1, 2, 3, 6 and 7) and lacing tightness (e.g. weak, regular and strong) on foot biomechanics in running. The tightest (strong) and highest lacing (i.e., seven-eyelet) conditions reduced loading rates and pronation velocities of rearfoot motion. The lowest peak pressures at the heel and lateral midfoot regions were observed in the high lacing pattern than in the lower lacing patterns. They (Hagen et al., 2010) also found that the shoe comfort and stability perception scores were related to the runners' level and experience. In contrast with the regular six-eyelet lacing pattern (REG 6), low-level runners perceived A57 (the laces were pulled from the outside from the fifth to the seventh eyelet) with better stability and comfort perception. However, high-level runners demonstrated poor comfort perception in A57 condition. Future studies should investigate the practicability of various shoe lacings (Figure 3) in runners with different arch height, muscle level (Lieber, 2018), and running experience (Clermont et al., 2019).

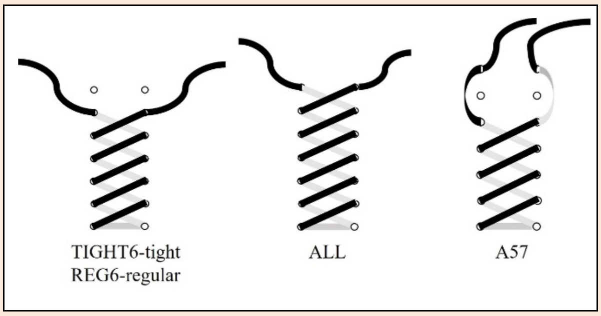

Figure 3. Three different shoe lacing patterns.

Effects of shoe midsole

For midsole hardness, the increase of midsole hardness from Asker C40 to Asker C70 would reduce the impact peak (Baltich et al., 2015), minimize energy loss (Stefanyshyn and Nigg, 2000) and increase the contact time (Willwacher et al., 2013); whereas other studies found that the impact peak increased (Chambon et al., 2014) while contact time did not change (Sterzing et al., 2013) across different midsole hardness. These inconsistent results may be due to the different tested speeds (3.3 ± 0.1 m/s vs. 3.5 ± 0.18 m/s) (Willwacher et al., 2013), hardness (0.6-17.10 N/mm vs. 40-65 Asker C vs. 47.1-62.8 Asker C) (Baltich et al., 2015) across the included studies.

Only a few longitudinal studies examined the relationship between midsole and running injuries. Theisen et al. (2014) randomly assigned soft (Asker 64C) and hard (Asker 57C) midsole shoes to 247 runners to wear for five months. The same injury rates were found between soft and hard midsole shoes used in training. However, Dixon et al. (2015) found that shoes with hard lateral stiffness (Asker 70C) had larger peak knee abduction moment and peak loading rates than softer midsoles (i.e., 52 and 60 Asker) during running, suggesting the increase the risk of running-related injuries (Dixon et al., 2015).

With regard to the material used, EVA and PU were widely used in footwear industry and related studies (Brückner et al., 2010). PU material exhibited lower relative changes of damping parameters than EVA and thus recommended as the alternative use of midsole material in running, even though PU material showed better durability than EVA (Brückner et al., 2010). From the running economy perspective, Wang et al. (2012) found that EVA shoes had higher capability of energy return than PU shoes at all running distances (e.g. 50 km, between 200 to 300 km and 500 km). A larger percentage of energy return could be related to improved running economy (Thomson et al., 2010). Future studies should investigate whether the varying hardness of the midsole would be related to the risk of injuries to provide sports scientists, coaches, and footwear manufacturers an insight into running shoe developments for injury prevention.

Effects of minimalist shoe

Minimalist shoes were suggested to improve running economy by changing a runner's strike and performance-related variables (Fuller et al., 2015). Most included studies have found that minimalist shoes showed remarkable differences in lower extremity biomechanics when compared with traditional running shoes (Table 5). In addition, the effect of minimalist shoes on the changes and adaptations in Achilles tendon became a popular research topic. One included article reported that participants who wore minimalist shoes developed greater cross-sectional area, stiffness and Young's modulus of Achilles tendon than those who used the conventional running shoes (Joseph et al., 2017). A consensus has been reached on running with minimalist shoes can improve running economy. For example, Warne et al., (2014) found that four-week habituation to simulated barefoot running would improve running economy (VO_{2max}) compared with shod running. Similarly, Fuller et al. (2017a) randomly assigned 61 runners gradually increased the amount of running when wearing either minimalist (n=31) or conventional (n=30) shoes during a six-week training program and found that minimalist shoes during training improved running economy compared to training in conventional shoes.

Although the concept and functionality of running shoes have dramatically evolved in recent years, the injury rate remains high and is still the focus in running research. A prospective cohort study demonstrated that running in minimalist footwear appears to increase the likelihood of experiencing pain and injury at the shin and calf (Michael et al., 2014).

Increased forefoot plantar pressure in minimalist shoes with minimal cushioning is one of the main causes of forefoot stress fracture. Bergstra et al.'s study (2015) minimalist shoes induced higher peak pressures on the medial, middle and lateral sides of the forefoot and maximum mean pressures, which were associated with metatarsophalangeal joints fractures than traditional running shoes. Another study (Ridge et al., 2013) examined the stress fracture injury risks by measuring the presence of bone marrow edema in the foot after runners transitioned to minimalist shoes (i.e., Vibram FiveFinger) throughout a 10-wk transition period. Their results indicated the Vibram group experienced a significantly greater incidence of bone marrow edema after the training period than the traditional shoes. From these studies, it confirmed that minimalist shoes may increase the injury risk. For runners with habitual conventional shoes, transition to minimalist shoes should progressively take time and training process.

Effects of shoe upper

To date, only a few included articles investigated the effect of shoe upper on performance-related and injuries-related variables (Table 8). The reason may be due to the large variety of upper materials used, the lack of mainstream upper materials and the difficulty of experimental control. Shoe upper has stronger influence over fit and comfort, which would alter the kinematic and kinetic strategies of runners. It was demonstrated that firmer foot contact within a shoe would result in lower loading rates due to a better coupling of foot-footwear (Hagen and Hennig, 2009). For example, Onodera et al. (2015) found that participants who wore shoes with minimalist upper would experience higher peak pressures in total area, rearfoot and medial forefoot regions but lower peak pressure at midfoot region; whereas those who wore shoes with structured upper demonstrated longer contact time for total area midfoot and lateral forefoot regions (Onodera et al., 2015). It is argued that the structured upper shoes would provide greater maneuverability and robustness, resulting in a uniformly distributed foot pressure and reduced foot plantar loading (Onodera et al., 2015). From the anthropometry perspective, better shoe upper fit and/or comfort can make the runner's foot coupled better with the sole (Onodera et al., 2017). Furthermore, various running speeds may have different requirements for the tightness of the shoe upper. However, the effects of shoe upper on comfort and running biomechanics included plantar pressures would require further investigation.

Effects of shoe bending stiffness

A review study summarized that shoe bending stiffness was related to changes in lower limb joint kinematics and kinetics as well as athletic performance (Stefanyshyn and Wannop, 2016). Forefoot bending stiffness of a shoe can be increased by inserting a forefoot plate (Madden et al., 2015) or using harder midsole (Willwacher et al., 2014). This has the potential to enhance sports performance in forward acceleration, jumping and agility tasks (Wannop and Stefanyshyn, 2016). Increasing the bending stiffness within a certain range could benefit runners. However, excessively increased bending stiffness may induce discomfort or hinder the performance benefits (Roy and Stefanyshyn, 2006). Furthermore, some included articles suggested that the reduction in metatarsophalangeal flexion would minimise the magnitude of negative joint power generation, which was beneficial to athletic performance (Stefanyshyn and Fusco, 2004). 5 out of the 7 included studies (Hoogkamer et al., 2018; Stefanyshyn and Nigg, 2000; Roy and Stefanyshyn, 2006; Stefanyshyn and Fusco, 2004; Madden et al., 2015) in Table 10 showed that increasing bending stiffness improved running performance and economy. Specifically, stiffer shoes would reduce energetic cost (Hoogkamer et al., 2018), maximum VO_2 (Roy and Stefanyshyn, 2006), energy lost at metatarsophalangeal joint (Stefanyshyn and Nigg, 2000), and sprint time (Stefanyshyn and Fusco, 2004).

In injury-related perspective, no longitudinal injury studies have been reported for the relationship between bending stiffness and running injury. The optimal bending stiffness of a shoe is currently unknown due to different stiffness measurement across studies, future research should develop standard testing protocols to identify the optimal ranges of forefoot stiffness used in various running level (elite, intermediate and novice), type of foot strikes (rearfoot, midfoot and forefoot) and running conditions (10k, half-marathon and full marathon).

Effects of heel flare, heel-toe drop, Massai Barefoot Technology (MBT), and heel cup

The outcomes related to heel flare, heel-toe drop, MBT, and heel cup were associated with insufficient studies to make strong conclusions and therefore require further investigation. Besides, the findings for heel cup appear to be the most promising across. In general, heel cups can serve as an effective treatment for heel pain because it can provide external support to the heel fat pad, maintain the heel pad thickness, and reduce the heel peak pressure and pain (Li et al., 2018).

Conclusion

Over the past decades, most of the included articles focused on midsole and minimalist constructions. Studies with running shoe constructions confirmed the beneficial effects on athletic performance and running injury: 1) increasing the forefoot bending stiffness of running at the optimal range can benefit performance-related variables; 2) softer midsoles can reduce impact forces and loading rates; 3) thicker midsoles can provide remarkable cushioning effects and attenuate shock during impacts but may decrease plantar sensations at touchdown; 4) minimalist shoes would improve running performance-related including economy and build the cross-sectional area and stiffness of Achilles tendon, but also induce greater loading of the ankle, metatarsophalangeal joint and Achilles tendon compared with the conventional shoes. Notably, progressive training and adaptation seems necessary and recommended when using minimalist shoes. Although research on heel flare, shoelace and heel cup were limited, these constructions showed some potentials to influence running stability. The role and interaction of these shoe constructions would require further investigations. Future research should also develop standard testing protocols to help to establish the scientific guidelines of optimal stiffness, thickness and heel-toe drop across various running shoe studies in the future.

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Key points

- Increasing the forefoot bending stiffness of running at the optimal range can benefit performance-related variables.
- Softer or thicker midsoles can provide remarkable cushioning effects but may decrease plantar sensations at touchdown.
- Minimalist shoes can improve running economy and build the cross-sectional area and stiffness of Achilles tendon but also induce greater loading of the ankle and metatarsophalangeal joint.

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