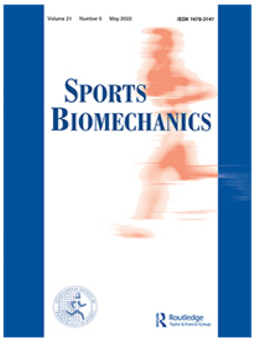

Sports Biomechanics

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rspb20

Effect of shoe modifications on biomechanical changes in basketball: A systematic review

Wing K. Lam, Wei H. Kan, Jingyi S. Chia & Pui W. Kong

SPORTS BIOMECHANICS
2022, VOL. 21, NO. 5, 577–603
https://doi.org/10.1080/14763141.2019.1656770

Effect of shoe modifications on biomechanical changes in basketball: A systematic review

Wing K. Lam[a,b], Wei H. Kan[b,c], Jingyi S. Chia[c] and Pui W. Kong[c]

[a]Department of Kinesiology, Shenyang Sport University, Shenyang, China; [b]Li Ning Sports Sciences Research Center, Li Ning (China) Sports Goods Co., Ltd., Beijing, China; [c]Physical Education and Sports Science Academic Group, National Institute of Education, Nanyang Technological University, Singapore, Singapore

ABSTRACT

Shoe modifications are suggested to reduce the risks of injuries and improve sports performance in basketball. This review aimed to critically evaluate the effect of different basketball shoe modifications on biomechanical changes in basketball movements. Searches of four major databases for biomechanics studies which evaluated footwear construction/material in basketball yielded 442 records. After duplicates were removed and exclusion/inclusion criteria applied to the titles and abstracts, 20 articles remained for further quality assessment. Two reviewers independently confirmed 17 articles (n = 340 participants), with 95.5% of agreement between judgements, which were included for review. The results were categorised based on the following shoe modifications: (a) cushioning, (b) midsole hardness, (c) collar height, (d) outsole traction component, (e) forefoot bending stiffness and (f) shoe mass that influence lower limb biomechanics. The included articles revealed that 1) better shoe cushioning or softer midsole is related to better impact attenuation in passive/unanticipated situations, 2) high shoe collars are effective to improve ankle stability in jumping and cutting tasks, 3) increased shoe traction and forefoot bending stiffness can improve basketball jump, sprint and/or cut performances and 4) lighter shoe mass results in better jump and/or cut performances when the shoe mass is known.

ARTICLE HISTORY
Received 3 March 2019
Accepted 13 August 2019

KEYWORDS
Cushioning; midsole hardness; collar height; outsole; shoe mass

Introduction

Basketball has continuously grown in popularity worldwide (Cantwell, 2004) and across all levels of participation, from recreational to professional level (Zvijac & Thompson, 1996). Game analysis has revealed that basketball players spend more than 20% of their playing time executing high-intensity movements (Ben Abdelkrim, El Faza, & El Ali, 2007; McInnes, Carlson, Jones, & McKenna, 1995) such as running/sprinting with acceleration and deceleration (sprint = 55 and run = 97 times), jumping (44 times) and various high-intensity basketball movements (94 times, Ben Abdelkrim et al., 2007). This places large external and internal loads on the lower extremities. The injury rate of high school basketball players has been reported as 1.94 per 1000 athlete exposure, with

CONTACT Wing K. Lam gilbertlam@li-ning.com.cn

the ankle/foot being the most commonly (39.7%) injured site (Borowski, Yard, Fields, & Comstock, 2008). In adults, basketball injuries were found to be most prevalent (31.6%) among all sports and recreational injuries presenting to a hospital emergency department (Padegimas, Stepan, Stoker, Polites, & Brophy, 2016). There is therefore a pertinent need to understand the injury mechanisms through biomechanical analysis and preventive strategies such as the use of appropriate footwear and foot orthoses to reduce the incidence of ankle/foot injuries (Lu & Chang, 2012).

Basketball shoes should be developed to minimise injuries whilst enhancing a player's performance (Lam, Park, Lee, & Cheung, 2015; Liu, Wu, & Lam, 2017). Bouché (2010) summarised the key functionalities for a general court shoe as follows: 1) ability to offset the excessive pronation during sideward movements, 2) adequate heel and forefoot cushioning for better shock attenuation and comfort, 3) moderate bending stiffness in the midfoot region but with torsional flexibility and 4) optimal traction to avoid foot interlocking and slippage. In the literature, many studies have investigated the biomechanical changes resulting from modifying specific shoe features with an overall goal of optimising the design of basketball footwear. For example, considering that lateral ankle sprains are one of the most common injuries among basketball players (Harmer, 2005; Randazzo, Nelson, & McKenzie, 2010), high-collar shoes can potentially be used to reduce excessive ankle supination/inversion and thus improve ankle stability during cutting and landing movements (Barrett et al., 1993; Frederick, 1995; Lam et al., 2015; Liu et al., 2017; Stacoff, Avramakis, Siegenthaler, & Stussi, 1998). It has also been suggested that shoes must provide a stable shank and lateral (side-to-side) stability to prevent the occurrence of fracture or re-injury of the fifth metatarsal (Losito, 2008), a common injury in basketball that is hard to recover from and potentially season-ending (DeLee, 1995; Zelko, Torg, & Rachun, 1979). However, high-collar shoes might restrict the functional range of movement at the ankle joint and thus lead to inferior agility and jump performances (Brizuela, Llana, Ferrandis, & Garcia-Belenguer, 1997; Robinson, Frederick, & Cooper, 1986), smaller peak plantarflexion moment and power in layup (Yang, Fang, Zhang, He, & Fu, 2017). Strategies for optimising individual aspect of shoe modification to minimise injury risk(s) and/or enhance sport performance as well as integrating various shoe modifications are integral parts of the science which go into the design of top-end basketball shoes. It is therefore necessary to summarise the findings of shoe modifications to provide scientific guidelines for basketball footwear development.

There are many possible ways of modifying shoe constructions/material in basketball footwear (e.g., cushioning, midsole hardness, thickness, forefoot bending stiffness, heel counter support, collar height). However, aside from the physical properties of the shoe, participants' personal playing experience and preferences may also influence the human-shoe interaction (Brauner, Zwinzscher, & Sterzing, 2012), making it very difficult to understand how basketball shoe modifications can influence injury risks and/or sporting performance. An evidence-based cohesive mechanism is therefore essential to provide insights for the applications and optimisation of basketball footwear. Hence, the present study aimed to systematically review and summarise the effect of different basketball shoe modifications on biomechanical changes. It is hypothesised that optimal shoe modifications would be identified for improving performance and/or reducing the risk of injury. Findings from this study may guide recommendations for how basketball shoe modifications can be optimised to reduce the risk of injuries and enhance performance in basketball players.

Methods

This review is reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A standardised electronic literature search strategy was performed using the following keyword combinations: *'basketball' [Abstract] AND 'shoe OR shoes OR footwear' [Abstract] AND 'biomechanics OR kinetics OR kinematics' [All Fields]* via the following databases from 2000 to September 2018: PubMed, ScienceDirect, EBSCO and Web of Science. The search terms were agreed on by WK and WL. In addition, the reference list of the articles identified and from other relevant articles (i.e., Footwear Science) were examined for additional relevant titles. Given the fast advancement in material science and design in the shoe industry, as reflected by new concepts and technology every season, older articles may not be as relevant as those shoe modifications that are unlikely available in the current market. Therefore, the search criteria included only research articles published starting from 2000 to ensure the high relevancy and updated context of information.

The search and study selection process is summarised in Figure 1. All articles were input into the Excel to eliminate duplicates. Then, original research articles in peer-reviewed journals that investigated any effect of basketball shoe modifications on biomechanical changes (i.e., force, plantar pressure, movement) were included. Only articles presenting absolute values (means and measures of variability) of the effects of different footwear features on the biomechanical parameters of participants at any age, sex, mass or level of performance were analysed. The exclusion criteria were duplicates, orthotics, non-basketball shoe related, non-English, or non-full text articles.

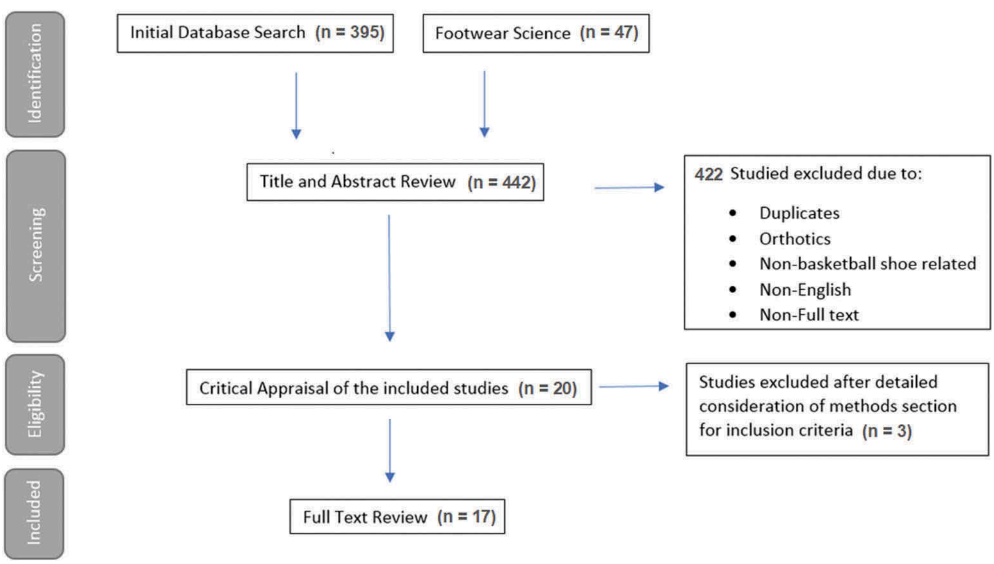

Figure 1. Systematic review process.

As this systematic review included mainly laboratory-based biomechanical studies, the quality assessment was checked for each question included of a Physiotherapy Evidence Database (PEDro) scale. This scale objectively assesses the internal validity, which is essential when evaluating the treatment effects of basketball shoe modifications on biomechanical and perceptual changes, of each article. Two reviewers (WHK and JSC) independently assessed the quality of all included articles and the average percentage of agreement between judgements was 95.5% across 10 items (Table 1). When the quality scores differed between the assessors, consensus was reached through discussion and consultation with a third reviewer (PWK). Studies with the final consensus PEDro score of less than 6 were deemed as low quality and were not included in the review (Table 1).

Results

Data search and overview of included articles

The full search yielded 442 studies (Figure 1). After exclusion of duplicates, irrelevant titles and screening of abstract, 20 studies remained. Three studies were excluded after full assessment as the PEDro score was less than 6. Thus, 17 studies were examined in detail.

The shoe features, participant characteristics, test protocols, and outcome measures of each study were summarised accordingly to the type of shoe modification investigated (Table 1): cushioning (n = 6), midsole hardness (n = 3), collar height (n = 4), outsole traction (n = 2), forefoot bending stiffness (n = 2), and shoe mass (n = 2), of which one included article (Worobets & Wannop, 2015) examined three different shoe modifications (mass, traction and bending stiffness). The included studies involved different protocols for basketball-related movement tasks: jumping (n = 5), landing (n = 7), running (n = 6), shuffling (n = 2), agility (n = 1), cutting manoeuvre (n = 6), layup (n = 4), and basketball-related movement task (n = 2). The 17 included studies analysed involved a total of 340 participants (329 males and 11 females). Sixteen studies included only males while one study included only females. The mean sample size was 17.9 ± 5.8 (ranged from 11 to 32) and the mean age was 23.5 ± 1.7 years (ranged from 20 to 26 years). Fourteen studies included competitive athletes, three included recreational participants and the remaining three did not specify the playing level. Shoe sizes chosen for the studies were US 9.0 (n = 8), others (n = 3) or not indicated (n = 6). All articles excluded participants with lower extremity injuries: 6 months prior to testing (n = 13), no current injury (n = 2) or not indicated (n = 2).

Shoe cushioning effect

Six included articles (Table 2) investigated the effects of shoe cushioning on basketball landing (Fu et al., 2017; Fu, Liu, & Zhang, 2013; Wang, Zhang, & Fu, 2017; Wei et al., 2018), running (Lam et al., 2018) and lateral movements (Lam, Qu, Yang, & Cheung, 2017). Three of the articles compared the basketball shoes with non-basketball shoes (Fu et al., 2017, 2013; Wang et al., 2017), while the other two articles compared the basketball shoes with systematic increment of shoe cushioning scores (Lam et al., 2018; Wei et al., 2018) and one article compared basketball shoes with and without shear-cushioning structures at forefoot region (Lam et al., 2017).

Table 1. PEDro scores independently assessed by two reviewers.

Article	Q1 Random allocation of subjects		Q2 Allocation was concealed		Q3 Groups were similar at baseline		Q4 Blind to subjects		Q5 Blind to therapists		Q6 Blind to assessors		Q7 At least 1 key outcome from 85% of subjects		Q8 All subjects received treatment or control condition		Q9 Between group comparisons reported for at least 1 outcome		Q10 Provides at least 1 point of measure (effect size AND variability)		Total score (max = 10, article excluded when score < 6)			
	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	Final score	Outcome related to modification
Fleischmann, Mornieux, Gehring, and Gollhofer (2013)	1	1	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	5	6	5	Excluded
Fu et al.(2013)	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	6	6	6	Cushioning
Fu et al.(2014)	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	6	6	6	Collar height
Fu et al.(2017)	1	1	0	0	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	7	6	6	Cushioning
Graf and Stefanyshyn.(2013)	1	1	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	5	6	5	Excluded
Lam, Lee, et al. (2017)	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	6	6	6	Bending stiffness
Lam, Liebenberg, et al. (2018)	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	6	6	6	Cushioning
Lam, Ng, et al.(2017)	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	6	6	6	Midsole hardness
Lam, Qu, et al.(2017)	1	1	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	8	7	7	Cushioning
Leong et al.(2018)	1	1	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	8	7	7	Midsole hardness
Liu et al.(2017)	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	6	6	6	Collar height
Luo and Stefanyshyn. (2011)	1	1	0	0	1	1	0	0	0	0	0	0	1	1	0	1	1	1	1	1	5	6	6	Traction
Mohr et al.(2016)	1	1	0	0	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	7	6	6	Mass
Nin et al. (2016)	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	6	6	6	Midsole hardness
Wang et al.(2017)	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	6	6	6	Cushioning
Wei et al.(2018)	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	6	6	6	Cushioning

(*Continued*)

Table 1. (Continued).

Article	Q1 Random allocation of subjects		Q2 Allocation was concealed		Q3 Groups were similar at baseline		Q4 Blind to subjects		Q5 Blind to therapists		Q6 Blind to assessors		Q7 At least 1 key outcome from 85% of subjects		Q8 All subjects received treatment or control condition		Q9 Between group comparisons reported for at least 1 outcome		Q10 Provides at least 1 point of measure (effect size AND variability)		Total score (max = 10, article excluded when score < 6)			
	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	Final score	Outcome related to modification
Worobets et al.(2015)	1	1	0	0	1	1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	6	7	6	Traction, bending stiffness, mass
Yang et al.(2017)	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	6	6	6	Collar height
Yentes et al.(2014)	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	6	6	6	Collar height
Zhang et al.(2005)	1	1	0	0	0	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	5	6	5	Excluded
Score agreement	100%		90%		85%		85%		100%		100%		100%		95%		100%		100%				Overall agreement	95.5%

Note: R1 and R2—Scores assessed by reviewer 1 and reviewer 2, respectively. Final—Consensus score agreed by a third reviewer.

Table 2. Summary of the studies on shoe cushioning effect (n = 6).

Reference	Shoe Conditions	Subject Info (Numbers, Sex, Age, Playing Level)	Testing Protocol	Outcome: Injury-related	Outcome: Performance-related	PEDro Score
Fu et al. (2013)	– Basketball (BB) – Minimally cushioned (MC)	12, M, 23.7(2.7), Competitive	Landing from heights of 30,45,60cm – Drop jump landing – Unanticipated drop jump landing	BB↓ peak GRF & LR in unanticipated drop jump landing ↔ Peak GRF & loading rate in drop jump landing ↔ ankle, knee & hip ROM during the landing phase	NA	6
Fu et al. (2017)	– Basketball (BB) – Minimally Cushioned (MC)	12, M, 23.7(2.7), Competitive	Drop landing from 60cm height – Self-selected drop jump landing – Unanticipated drop jump landing	BB ↓ peak force in unanticipated drop jump landing BB ↑ time to peak force in unanticipated drop jump landing ↔ peak force & time to peak force in self-selected drop jump landing	NA	6
Lam et al. (2017)	Basketball – with Shear Cushioning Structure (SCS) [rotational stiffness: clockwise 9.78 ± 0.14 Nm/° and anti-clockwise 9.17 ± 0.16 Nm/°] – without SCS (control) (rotational stiffness: clockwise 10.44 ± 0.06 Nm/° and anti-clockwise 9.78 ± 0.11 Nm/°)	15, M, 21.7(2.9), Competitive	– Lateral shuffling to the right – 45° cutting, with right foot on force plate and cutting towards a 45° left direction	↔ braking GRFs & braking impulses ↔ forefoot perception	– Lateral shuffling ↔ total foot contact time, horizontal GRFs & impulses – 45° cutting SCS ↑ horizontal propulsion impulse SCS ↑ perceived comfort of forefoot ↔ propulsion GRFs, completion time & total foot contact time	7
Lam et al. (2018)	Basketball – Best cushioned (9.8 g) – Better cushioned (11.3 g) – Regular cushioned (12.9 g)	18, M, 25.0(2.3), Competitive	Running at two different speeds – 3.0 m/s – 6.0 m/s	Best ↑ impact peak compared to Regular Best ↑ tibial shock compared to Better Better ↓ VALR and VILR compared to Regular & Best	NA	6

(*Continued*)

Table 2. (Continued).

Reference	Shoe Conditions	Subject Info (Numbers, Sex, Age, Playing Level)	Testing Protocol	Outcome		PEDro Score
				Injury-related	Performance-related	
Wang et al. (2017)	– Basketball (BB) – Minimally cushioned (MC)	12, M, 23.7(2.7), Competitive	Landing from heights of 30,45,60cm – Drop jump landing – Passive jump landing	BB ↓peak vertical force, VILR & post-activation of EMG_{rms} in passive landing ↔ peak vertical force, time to peak force & peak LR in contact phase of drop jump landing ↔ pre-activation of EMG_{rms} in both landing ↔ post-activation of EMG_{rms} in drop jump landing	NA	6
Wei et al. (2018)	Basketball – Best cushioned (9.8 g) – Better cushioned (11.3 g) – Regular cushioned (12.9 g)	19, M, 25.0(2.3), Competitive	Drop landing from different heights – 0.45m – 0.61m	Regular ↑ tibial shock compared to Better & Best Better ↑ ankle ROM compared to Best & Regular Regular ↑ VALR compared to Better & Best ↔ impact peak, heel comfort perception	NA	6

Note: GRF—Ground Reaction Force, ROM—Range of Motion, VALR—Vertical average loading rate, VILR—Vertical instantaneous loading rate, LR—Loading rate, EMG_{rms}—Normalised Electromyography amplitude, NA—Not available

When compared to the non-basketball shoes, players wearing basketball shoes experienced significantly smaller peak ground reaction force (GRF) and loading rates but longer time to peak impact force in the unanticipated drop landing (Fu et al., 2017, 2013) and passive landing (Wang et al., 2017), but no significant differences between basketball and non-basketball shoes were found in the self-selected drop landing task (Fu et al., 2017, 2013; Wang et al., 2017).

Wei and colleagues (2018) investigated basketball shoes with various mechanical impact scores in self-selected drop landing and found that participants wearing the highest impact shoes (regular-cushioned) experienced significantly greater tibial shock and mean loading rate compared with lowest (best-cushioned) and medium impact shoes (better-cushioned). In addition, a significant and larger ankle range of motion was determined in medium impact shoes compared with the lowest and highest impact shoes (Wei et al., 2018). In running tasks, basketball shoes with the lowest impact scores (best-cushioned) induced higher impact peak than those with highest impact scores (regular-cushioned) and higher tibial shock than medium impact scores (better-cushioned) (Lam et al., 2018). Basketball shoes with medium scores (better-cushioned) would lower maximum and average loading rates as compared with shoes of the highest and lowest scores (Lam et al., 2018).

A recent article introduced a shear-cushioning structure to facilitate basketball cutting manoeuvres (Lam et al., 2017). The shear-cushioning structure is designed with a shear-cushioning interface which allows larger rotational deformation and thus reduces internal shear force on medial forefoot. This structure was shown to be associated with higher horizontal propulsion impulse and perceived forefoot comfort (Lam et al., 2017).

Midsole hardness effect

Three included articles investigated the effects of midsole hardness, varying Shore 38C to 60C, using GRF and/or plantar pressure analyses in various basketball-specific tasks (Table 3). Regarding GRF loading, harder midsoles induced a significant 12% increase in rearfoot peak GRF in the first step of layup than soft midsole (Nin, Lam, & Kong, 2016). Softer midsoles were showed to be associated with better forefoot comfort in all landing movements and higher forefoot GRF in shot-block task (Nin et al., 2016).

Regarding plantar pressure loading, softer midsoles were shown to be associated with the lower peak plantar pressures in midfoot/rearfoot regions (lateral forefoot, heel) during running and cutting tasks, lower peak plantar pressures at forefoot/toe regions (medial and lateral forefoot, second toe, and lateral toes) during running, sprinting and layup first step tasks, and lower pressure-time integrals in forefoot/toe regions (hallux, second toe, medial and lateral forefoot) during cutting and layup first step tasks (Lam, Ng, & Kong, 2017). Additionally, softer midsoles were related to the smaller initial footstrike angles (Lam et al., 2017) and higher medio-lateral centre of pressure excursion observed in the first step of a layup (Leong, Lam, Ng, & Kong, 2018).

Table 3. Summary of the studies on midsole hardness effects (n = 3).

Reference	Shoe Conditions	Subject Info (Numbers, Sex, Age, Playing Level)	Testing Protocol	Outcome: Injury-related	Outcome: Performance-related	PEDro Score
Lam et al. (2017)	– Soft (Shore 50C) – Hard (Shore 60C)	20, M, 24.8(1.5), Competitive	– Running: 3.3m/s for 15m – Sprinting: 7m – Cutting maximum-effort cut at 45° – Layup first step: right side of the basket	Soft ↓ peak pressure in the plantar regions for the following movements – Running: lateral midfoot, heel, medial & lateral forefoot – Cutting: lateral midfoot – Sprinting: medial forefoot & second toe – Layup: medial & lateral forefoot & lateral toes Soft ↓ PTI in the hallux region for cutting; second toes, medial & lateral forefoot regions for first step of layup ↔ initial footstrike angle at touchdown for all tested movements	NA	6
Leong et al. (2018)	– Soft (Shore 50C) – Hard (Shore 60C)	20, M, 24.8(1.5), Recreational	– Cutting: maximum-effort cut at 45° – Layup first step: right side of the basket	Soft ↑ ML CoP compared with Hard during layup ↔ ML CoP during cutting ↔ perceived stability for both forefoot & rearfoot in all tasks	NA	7
Nin et al. (2016)	– Soft (Shore 38C) – Medium (Shore 42C) – Hard (Shore 57C)	30, M, 21.8(2.8), Competitive	– Drop Landing: double leg landing from 42cm – Shot-blocking landing: two contralateral approach steps followed by a maximal reach vertical jump – Layup first step: two contralateral approach steps followed by a single-leg take-off	Hard ↑ rearfoot peak GRF & rearfoot stability compared to Soft during first step of layup Soft ↑ comfort perception ↔ peak vGRF or loading rates during layup or drop landing	Soft ↑ peak forefoot GRF compared to Hard during shot-block landing	6

Note: ML CoP—Centre of pressure in medial-lateral direction, GRF—Ground reaction force, vGRF—Vertical ground reaction force, PTI—Pressure-time integral, NA—Not available

Collar height effect

Four included articles (Table 4) examined the effects of collar height on drop jump landing onto tilted platforms (Fu, Fang, Liu, & Hou, 2014), jump manoeuvres (Liu et al., 2017; Yang et al., 2017), ankle functional test (Yang et al., 2017; Yentes, Kurz, & Stergiou, 2014), and cutting and agility tasks (Liu et al., 2017). In drop jump landing, high-collar shoes increased the onset time of tibialis anterior and peroneus brevis and longus, but reduced the pre-landing muscle activation of tibialis anterior and peroneus brevis in 15° inversion platform; high-collar shoes also reduced the pre-landing muscle activation of tibialis anterior and peroneus longus in combined 25° inversion + 20° plantarflexion platform condition (Fu et al., 2014). In cutting task, high-collar shoes were shown to be associated with shorter time to peak inversion angle together with smaller initial inversion angle, peak inversion velocity, and inversion range of motion than the low-collar shoes (Liu et al., 2017).

In layup jump, high-collar shoes were associated with reduced peak plantarflexion moment and power (Yang et al., 2017). In weight-bearing dorsiflexion test, smaller peak ankle dorsiflexion ($p = 0.041$) and sagittal ankle range of motion ($p = 0.034$) were determined in high-collar shoes compared with low-collar shoes (Yang et al., 2017). However, there was no significant collar height effect determined in maximum jump (Liu et al., 2017; Yang et al., 2017), agility (Liu et al., 2017), and ankle functional performances (Yentes et al., 2014).

Outsole traction effect

Two included articles (Table 5) examined the effects of outsole traction properties in various basketball maximum-effort performance of linear and curved sprints, jump and cutting drills (Luo & Stefanyshyn, 2011; Worobets & Wannop, 2015). Luo and Stefanyshyn (2011) revealed that greater amounts of traction (both peak and average) were utilised for peak sprint performance and overall ground reaction impulse generation, but no additional performance enhancement was observed when the utilised traction increased beyond a threshold of 0.82. Likewise, poor traction shoes (80%, traction coefficient = 0.78) were found to be associated with poorer sprint, jump and cut performances than the standard traction shoes (100%, traction coefficient = 0.97) and better traction shoes (120% traction, traction coefficient = 1.2); the better traction shoes (120%, traction coefficient = 1.2) had better cutting drills than the standard traction shoes (100%, traction coefficient = 0.97); no significant differences were determined in jumping and sprint performances among the three tested shoe conditions (Worebets & Wannop, 2015).

Forefoot bending stiffness effect

Two included articles (Table 6) investigated the effects of forefoot bending stiffness (Lam, Lee, Lee, Ma, & Kong, 2018; Worobets & Wannop, 2015) in sprinting, cutting drills, and vertical jump tasks. It was revealed that higher forefoot bending stiffness in a shoe was associated with the better sprint/cutting (Lam et al., 2018; Worobets & Wannop, 2015) and vertical jump performances (Lam et al., 2018). While Lam et al. (2018) found that stiffer shoes (Medial+Lateral plate) induced significantly higher jump height than control shoes, Worobets and Wannop (2015) did not report any improvements in jump

Table 4. Summary of the studies on collar height effects (n = 4).

Reference	Shoe Conditions	Subject Info (Numbers, Sex, Age, Playing Level)	Testing Protocol	Outcome: Injury-related	Outcome: Performance-related	PEDro Score
Fu et al. (2014)	High-low collar difference = 6 cm – High collar – Low collar	13, M, 21.3 (1.2), NI	Self-initiated drop landing onto a tilted platform with – 15° inversion – 30° inversion – 25° inversion + 10° plantarflexion – 25° inversion + 20° plantarflexion	High Collar ↑ onset times of TA, PB & PL, but ↓ EMG_{pre} of TA & PB while landing in the 15° inversion condition High Collar ↓ EMG_{pre} of PL & TA for the combined 25° inversion + 20° plantarflexion condition ↔ maximum ankle inversion angle, ankle inversion RoM & maximum ankle inversion angular velocity during contact for all conditions ↔ onset time of TA, PB & PL muscles for all conditions	NA	**6**
Liu et al. (2017)	High-low collar difference = 5.7 cm – High Collar + Regular Counter (H-R) – High Collar + Stiffer Counter (H-SR) – High Collar + Stiffest Counter (H-ST) – Low Collar + Regular Counter (L-R) – Low Collar + Stiffer Counter (L-SR) – Low Collar + Stiffest Counter (L-ST)	15, M, 20.9 (1.0), Competitive	– Jump and reach task: two contralateral approach steps followed by a maximal reach vertical jump – Agility task: sequence of backward shuffling, acceleration, deceleration, lateral shuffling and counter movement vertical jump movements – Cutting manoeuvre: right-footed landing on the force platform & a change in direction of 45° towards the left	High Collar ↓ initial inversion angle, time to peak inversion angle, peak inversion velocity & total range of inversion for cutting Stiffer Counter ↑ time to peak inversion compared to Regular Counter for cutting	Collar height & Heel counter ↔ maximum jumping height & agility completion time	6

(*Continued*)

Table 4. (Continued).

				Outcome		
Reference	Shoe Conditions	Subject Info (Numbers, Sex, Age, Playing Level)	Testing Protocol	Injury-related	Performance-related	PEDro Score
Yang et al. (2017)	High-low collar difference = 4.3cm – High collar – Low Collar	12, M, 23.7 (0.6), Competitive	– Drop landing jump: landing from 60cm height on separate force plates and immediately jump – Layup jump: step on force plate with the second contralateral step, and subsequently jumped up – Weight-bearing dorsiflexion: squat by gradually flexing ankles until they could no longer subjectively squat or heel off	High collar ↓ peak plantarflexion moment & power for Layup jump High collar ↓ ankle dorsiflexion angle & ankle RoM for Weight-bearing dorsiflexion ↔ any ankle kinematics for drop landing jump & Layup jump tasks	↔ jump height	**6**
Yentes et al. (2014)	– Own high-top basketball – Barefoot	11, F, 20.4 (3.2), Competitive	Functional ankle test – Inversion – Eversion	↔ peak torque, time to peak torque & eversion-to-inversion percent strength ratio	NA	6

Note: TA—Tibialis anterior, PB—Peroneus brevis, PL—Peroneus longus, EMG_{pre}—Pre-landing muscle activity, RoM—Range of motion, NA—Not available, NI—Not indicated in the article

Table 5. Summary of the studies on outsole traction effects (n = 2).

Reference	Shoe Conditions	Subject Info (Numbers, Sex, Age, Playing Level)	Testing Protocol	Outcome: Injury-related	Outcome: Performance-related	PEDro Score
Luo and Stefanyshyn (2011)	4 outsole traction coefficients – MT0.26 – MT0.54 – MT0.82 – MT1.13	32, M, 24.5(5.4), Competitive	– Curved sprints: in a circle of 2.3m radius – Linear acceleration: in 3m line	NA	-Curved sprint: ↓ Stance time from MT0.2 to MT0.5 to MT0.8 ↑ Weighted average $\mu_{utilised}$, average centripetal GRF & impulse from MT0.2 to MT0.5 to MT0.8 then ↔ in MT1.1 ↓ Average body lean angle & average GRF angle from MT0.2 to MT0.5 to MT0.8, then ↔ for MT1.1 -Linear Acceleration: ↓ Stance time but ↑ average horizontal GRF & net GRF impulse from MT0.2 to MT0.5, then ↔ between MT0.5 & MT1.1 ↑ Weighted average $\mu_{utilised}$ from MT0.2 to MT0.5 to MT0.8 then ↔ for MT1.1 ↓ Average body lean angle & average GRF angle from MT0.2 to MT0.5, then ↔ for MT0.8 & MT1.1	6
Worobets and Wannop (2015)	3 outsole traction coefficients – 0.78 (80% traction) – 0.97 (100% traction) – 1.18 (120% traction)	20, M, NA, Recreational	– 10m sprint – Vertical jump and reach test with one footed take-off – Cutting drill around a pylon course	NA	–80% condition ↑ sprint time, ↓ jump height &↑ time to complete the cutting drill compared to reference & 120% conditions 120% condition ↓ time to complete the cutting drill compared to 100% condition 120% condition ↔ sprint time & jump height compared to 100% condition	6

Note: $\mu_{utilised}$—Utilised traction, GRF—Ground reaction force, MT—Traction coefficient of medical tape, NA—Not available

Table 6. Summary of the studies on forefoot bending stiffness effects (n = 2).

Reference	Shoe Conditions	Subject Info (Numbers, Sex, Age, Playing Level)	Testing Protocol	Outcome: Injury-related	Outcome: Performance-related	PEDro Score
Lam, Lee, et al. (2018)	Basketball shoes with 3 forefoot plate conditions – Medial (0.277 Nm/°) – Medial+Lateral (0.376 Nm/°) – No Plate Control (0.261 Nm/°)	17, M, 24.5(1.5), Competitive	– Running vertical jump – 5m sprint	NA	– Running vertical jump Medial+Lateral condition↑ jump height compared with Control condition but ↔ between Medial & Control conditions ↔ ankle or MTPJ kinematic, moment or power variables among shoe conditions – 5m sprint Medial condition ↑ peak plantarflexion velocity at the MTPJ compared with medial + lateral plates condition but ↔ compared with Control condition ↔ ankle or MTPJ kinematic, moment or power variables among shoe conditions	6
Worobets and Wannop (2015)	3 forefoot bending stiffness – 0.22Nm/° (80% stiffness) – 0.28Nm/° (100% stiffness) – 0.33Nm/° (120% stiffness)	20, M, NA, Recreational	– 10m sprint – Vertical jump and reach test with running approach and one footed take-off – Cutting drill around a pylon course	NA	120% condition ↓ sprint time & cutting drill time compared to 80% condition All conditions ↔ jump height	6

Note: NA—Not available, MTPJ—Metatarsophalangeal joint performance wearing stiffer shoes (single-plate). The inconsistent findings could further support the importance of how inserted location and bending stiffness of forefoot plate interacted with sports performances.

Shoe mass effect

Two included articles (Table 7) examined the effects of shoe mass on various performance tasks including vertical jump, shuffle cut, sprint and cutting drills (Mohr, Trudeau, Nigg, & Nigg, 2016; Worobets & Wannop, 2015). Experimental shoes were built either by adding individual masses to the shoe upper between lateral malleolus and fifth metatarsal (Worobets & Wannop, 2015) or by strapping a plastic bag around shoe heel region (Mohr et al., 2016). One included article revealed no shoe mass effect on jump, sprint and cutting performances (Worobets & Wannop, 2015). The other article examined the effects of shoe mass on performance with participants either aware or blinded to the shoe mass (Mohr et al., 2016). Findings showed that the shoes with lighter shoe mass leads to significant better jump (i.e., vertical displacement) and shuffle cut performances (i.e., horizontal shuffle velocity) than medium shoe and heavy shoe only when the participants were informed about the shoe mass differences of the tested shoes. No significant differences were found in the group blinded to the shoe mass (Mohr et al., 2016).

Discussion and implications

Basketball is one of the popular sports worldwide. Basketball players are required to perform various high-intensity movements in a basketball game (Ben Abdelkrim et al., 2007). Basketball shoes are built to reduce injuries while enhancing a player's performance in various basketball movements. This systematic review attempts to collate all available evidence to identify how various types of footwear construction/properties would impact the biomechanical outcomes associated with injuries and performance in basketball-related movements.

Shoe cushioning/midsole hardness effect

Impact forces are the primary consideration when designing and developing basketball shoes as players would experience sudden high impact forces that cannot be reduced by soft tissues in a very short time interval (Nigg, 2010). Both shoe cushioning and/or midsole hardness are key features of the shoes that would alter impact forces. Midsole hardness of basketball shoes can influence their functional characteristics, subsequently altering loading pattern, perception, and lower limb biomechanics of basketball players (Lam et al., 2017; Leong et al., 2018; Nin et al., 2016). Cushioning properties of a shoe are suggested to be an important factor of foot comfort (Nigg, 2010). Peak loading rates, tibial shock and plantar pressures are common test variables to assess the shoe cushioning and midsole hardness in basketball shoes (Tables 2 & 3). When compared to non-basketball shoes (i.e., minimally cushioned shoes), basketball shoes showed superior cushioning performance (i.e., lower peak GRF and/or loading rates) in passive landing (Wang et al., 2017) and unanticipated drop landing (Fu et al., 2017, 2013), but

Table 7. Summary of the studies on shoe mass effects (n = 2).

Reference	Shoe Conditions	Subject Info (Numbers, Sex, Age, Playing Level)	Testing Protocol	Outcome: Injury-related	Outcome: Performance-related	PEDro Score
Mohr et al. (2016)	Identical shoes with three custom-made fabric bags of different mass – Light (352g) – Medium (510g) – Heavy (637g)	22, M, 26(3), Recreational	– Countermovement jump – Shuffle-cut: lateral shuffle in 1 direction followed by a side-cut movement and a lateral shuffle in the opposite direction	NA	– Aware group (informed shoe mass) Light ↑ vertical displacement & horizontal shuffle velocity compared with Medium & Heavy conditions – Blind group (not informed shoe mass) ↔ vertical displacement, horizontal shuffle velocity & the perceived mean weight ratings among shoe conditions	6
Worobets and Wannop (2015)	3 shoes with varied shoe mass – 0.33kg (80% mass) – 0.41kg (100% mass) – 0.50kg (120% mass)	20, M, NA, Recreational	– 10m sprint – Vertical jump and reach test with running approach and one footed take-off – Cutting drill around a pylon course	NA	All conditions ↔ jump height, sprint time & cutting drill time	6

Note: NA—Not available

no significant differences in the self-selected drop conditions (Fu et al., 2017, 2013; Wang et al., 2017). These contradicting findings could be explained by the smaller muscle pre-firing activation (Kim et al., 2014) but greater GRF and joint loadings in the unanticipated/passive movements (Besier, Lloyd, & Ackland, 2003; Lam et al., 2015). These distinct findings in self-selected and unanticipated landing provide some insightful information to sports coaches and players about the functional benefits in the actual game situations which are often non-anticipatory in nature.

Most of the included articles revealed that shoes with better cushioning or softer midsoles were related to better impact attenuation (i.e., lower peak GRF, loading rate and/or plantar pressure) in unanticipated/passive landings (Fu et al., 2017, 2013; Wang et al., 2017), running (Lam et al., 2018, 2017), lateral movements and layups (Lam et al., 2017). However, it should be noted that there may be an optimal band of shoe cushioning regarding impact loading and tibial shock (Lam et al., 2018; Wei et al., 2018) and that softer midsoles would also influence the stability in layup (Leong et al., 2018). Some included articles (Lam et al., 2018; Nin et al., 2016; Wei et al., 2018) revealed that the impact load experienced by participant did not systematically change with mechanical shoe cushioning properties, which is in line with a previous study on running (Nigg, 2010). The lack of systematic findings between shoe cushioning and impact loading might be related to bottomed out of the midsoles (Nin et al., 2016; Shorten & Mientjes, 2011) and/or individual adaptation to the footwear condition (Paquette, Zhang, & Baumgartner, 2013).

In addition, Lam et al. (2017) introduced a shoe with built-in shear-cushioning structure at the medial forefoot region, which was based upon previous studies on in-shoe pressure and shear forces in basketball movements (Cong, Lam, Cheung, & Zhang, 2014). This modification was designed with larger material and structural deformation during the braking phase of lateral movements, thereby reducing internal shear forces on the foot. The finding of their study revealed that the shear-cushioning structure was related to higher rotational deformation, better forefoot perception, and high horizontal impulse in 45-degree cutting (Lam et al., 2017). A plausible working mechanism for higher impulse would be that the structural design might allow larger rotational deformation for accumulating/storing energy during braking and releasing energy during propulsion (Lam et al., 2017). This suggests the possibilities for a footwear rotational shear-cushioning structure without compromising cutting performance, which could be applicable in the future development of basketball footwear.

Collar height effect

The function of a high-shoe collar is expected to reduce excessive ankle supination and thus improve ankle stability during cutting and landing movements (Frederick, 1995; Stacoff et al., 1998). The included articles summarised that high-collar shoes were associated with smaller inversion angle and velocity, shorter time to peak inversion, and longer onset time of ankle eversion muscles during landing and/or lateral movements (Fu et al., 2014; Liu et al., 2017; Yang et al., 2017; Yentes et al., 2014), highlighting that high-shoe collars are effective solutions to reduce the risks of ankle sprains during sports. In weight-bearing dorsiflexion test, smaller ankle dorsiflexion and range of motion were found in high-collar shoes compared with low-collar shoes (Yang et al., 2017). One included article examined how collar height interacted with heel counter-stiffness on ankle stability and athletic performance in basketball (Liu et al., 2017). Findings from this study provide further support of the role of collar height in improving ankle stability during sidestep cutting as compared with heel counter-stiffness.

From the performance perspective, however, high-collar shoes would restrict the functional range of movement at ankle joint and thus lead to inferior sport performances (Brizuela et al., 1997; Robinson et al., 1986). Specifically, some studies have found that high-collar shoes were associated with reduced peak plantarflexion moment and power in layup (Yang et al., 2017) and inferior agility and jump performances (Brizuela et al., 1997; Robinson et al., 1986). On the other hand, there are also some studies which failed to find any negative effect on jump performance (Liu et al., 2017; Yang et al., 2017), lateral cutting performance (Lam et al., 2015), agility performance (Liu et al., 2017), and ankle functional tests (Yentes et al., 2014). These inconsistent findings might be due to several methodological differences in shoe collar height/stiffness used and/or testing protocols. It should also be noted that the ankle motion measurements in the included articles (using shoe markers) might be overestimated compared with the actual ankle inversion inside the shoe (Bishop, Nurse, & Bey, 2014). This highlights the need for new measurement techniques (e.g., fluoroscopy, modelling) to be carried out in future studies to ascertain if shoe collar height would influence the biomechanics related to the ankle sprain injuries and performance.

Outsole traction effect

The traction characteristics of the outsole on basketball playing surfaces are determined by the hardness of the rubber and the grooves/tread pattern design. Traction, quantified as the maximum ratio of the horizontal over the vertical GRF without skidding, is considered to be an important factor for performance (i.e., start, stop, change of direction) and injuries (Luo & Stefanyshyn, 2011). It is generally believed that increased traction is related to performance because players may experience a loss of control (e.g., slipping) when traction is insufficient. The included articles demonstrated that increased footwear traction resulted in substantial improvements in jump, sprint and/or cut performances (Luo & Stefanyshyn, 2011; Worobets & Wannop, 2015). One plausible mechanism is that athletes would allow themselves more lean towards the ground, therefore generating larger horizontal GRF (Luo & Stefanyshyn, 2011). The findings from Luo and Stefanyshyn (2011) suggested that while performance would be enhanced as available traction increased, an optimal traction (traction coefficient = 0.82) would exist for linear and curved sprints. Future investigation should be carried out to determine the optimal traction for other basketball movements.

Forefoot bending stiffness effect

Forefoot bending stiffness is an overall bending stiffness (including upper) in the forefoot area around a medio-lateral axis of the shoe. Stiffness may be modulated by incorporating higher density or thicker Ethylene Vinyl Acetate (EVA) midsoles, Thermoplastic Urethane (TPU) inserts, carbon fibre plates or flex grooves. A review article (Stefanyshyn & Wannop, 2016) concluded that forefoot bending stiffness has been demonstrated to be related to injury and performance in sports, as increased bending stiffness in the forefoot area increases the lever arm of the GRF to the metatarsophalangeal (MTPJ) during push-off. Our included articles indicated that higher forefoot bending stiffness in a shoe was associated with better sprint and/or cut (Lam et al., 2018; Worobets & Wannop, 2015) and vertical jump performance (Lam et al., 2018). Altered bending stiffness at MTPJ with the medications of midsole hardness, thickness, flexing groove, and/or material properties may have impact on loading and kinematics other proximal joints such as the ankle and knee (Lam et al., 2018; Park, Lam, Yoon, Lee, & Ryu, 2017; Stefanyshyn & Wannop, 2016; Worobets & Wannop, 2015). There appears to be a specific amount of forefoot bending stiffness for optimal performance.

However, it should be noted that heavier/taller participants do not necessarily require shoes with higher bending stiffness than lighter/smaller participants, highlighting that individuals with differences in body height, mass and MTPJ stiffness would result in distinct responses to shoe bending stiffness (Roy & Stefanyshyn, 2006). A recent study demonstrated that individual MTPJ stiffness is moderately and highly correlated to vertical and leg stiffness in running, respectively (Man, Lam, Lee, Capio, & Leung, 2016). Although the bending stiffness in the midfoot area has the function to control arch deformation during midstance and increase the level arm of the GRF to the ankle joint during push-off, its effect has not been established in basketball. Furthermore, shoe torsional stiffness which is the relative rotation between the forefoot and rearfoot in the front plane of a shoe was related to peak torsion angle, ankle inversion angle and eversion angle in basketball lateral movements (Graf & Stefanyshyn, 2013). In the future, shoe bending and torsional stiffness at both forefoot and midfoot should be further investigated to better understand the coupling mechanism associated with lower limb biomechanics in basketball movements.

Shoe mass effect

Shoe mass is defined as the physical mass of one shoe and it is generally believed to be related to agility performance as lightweight basketball shoes have often been marketed to allow for faster or quicker moves. Contrary to intuition, the included articles did not determine any shoe mass effect on jump, sprint, and cutting performances when participants were blinded or unaware of the tested shoe conditions (Mohr et al., 2016; Worobets & Wannop, 2015). It could be possible that shoe effect on human behaviour is small or non-existent for small weight differences. Previous studies on other sports footwear reported that shoe mass only becomes important for weight difference of above 300 g in running (Nigg & Enders, 2013). Interestingly, when the participants were informed about shoe mass differences, participants wearing the shoes with lighter mass demonstrated better jump and shuffle cut performances (Mohr et al., 2016). This suggests that participants were aware of and/or positive expectation to the functional benefits of lightweight shoe that led to the changes in actual performances (Beedie, Coleman, & Foad, 2007; Kinchington, Ball, & Naughton, 2012; Lam, Fung, & Poolton, 2015). This psychological effect is in line with previous findings of visual perception of a shoe which revealed that the perception of shoe width was related to ankle stability during walking and running (Law, Wong, Chan, & Lam, 2018). All of these findings support the contention (Roberts, Jones, Harwood, Mitchell, & Rothberg,

2001) that the performance benefits of sports equipment under playing conditions could be influenced by psychological factors such as the awareness of and the confidence in the sports equipment modifications. Since comfort perception is highly related to past experience, age, gender, and task difficulty (e.g., Kong & Bagdon, 2010; Lam, Sterzing, & Cheung, 2011; Schubert, Oriwol, & Sterzing, 2011), methodology for valid assessments of footwear comfort require further investigation. In light of the interaction between athletic performance and subjective awareness/comfort perception of shoe modifications, future studies on footwear should implement effective blinding strategies in order to remove potential confounding factors.

Implications, limitations, and future directions

The included articles have demonstrated that shoe modifications would play some roles within an optimal range in enhancing functional benefits in basketball: 1) better shoe cushioning or softer midsole would result in better impact attenuation (GRF, loading rate and/or plantar pressure) in basketball-related movements (Fu et al., 2017, 2013; Lam et al., 2018, 2017; Nin et al., 2016; Wang et al., 2017; Wei et al., 2018; Zhang, Clowers, Kohstall, & Yu, 2005); 2) high-shoe collars are the effective solutions to provide ankle stability and reduce the risks ankle sprains during landing and/or lateral movements (Fu et al., 2014; Liu et al., 2017; Yang et al., 2017; Yentes et al., 2014); 3) Increased footwear traction and forefoot bending stiffness would result in substantial improvement in jump, sprint and/or cut performances (Lam et al., 2018; Luo & Stefanyshyn, 2011; Worobets & Wannop, 2015); and 4) shoes with lighter mass demonstrated the better jump and shuffle cut performances only when the participants were aware of the differences in shoe mass (Mohr et al., 2016).

It is important to consider some limitations that should be addressed in the future. Firstly, we summarised only the shoe modifications reported in the included articles in basketball literature, other modifications such as outsole structures, toe, box, heel cup, heel-to-toe drop, midsole thickness, toe-spring (forefoot rocker), forefoot/heel flares and upper material (breathability, elasticity) that have been investigated in studies on running and other court sports footwear require further investigation.

Secondly, the response to specific shoe modifications could be interplayed with the participants' playing level (Brauner et al., 2012; Lam et al., 2018), body anthropometry (Nin et al., 2016) and preferred movement pattern (Nigg et al., 2015). Furthermore, there is a lack of female data in our review. Female athletes were reported to have higher injury risks in various cutting and landing tasks compared with their male counterparts (Hootman, Dick, & Agel, 2007; Landry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2009; Quatman, Ford, Myer, & Hewett, 2006). Future studies should examine the relationship between the optimal designs of shoe modification and performance in various groups of players.

Thirdly, while the included articles have investigated the key-movements including layup, linear and curved sprint, side-step cut, and countermovement jump and landing, the tested movements does not seem ecologically valid because most studies were conducted in a controlled laboratory setting (e.g., Fu et al., 2013; Nin et al., 2016; Zhang et al., 2005). For instance, it has been demonstrated that the typical drop landing task used in a laboratory may not produce valid biomechanical data and may not control centre of mass any better than performing sport-specific landing tasks (Collings, Gorman, Stuelcken, Mellifont, & Sayers, 2019). Furthermore, the drop landing task might lead to higher kinematics and kinetics asymmetries between lower limbs (Collings et al., 2019). These suggest that future research should improve the representativeness of tasks used to assess the biomechanics of movement as task selection greatly impacts biomechanical data. Regarding data processing and analysis technique, all included studies used discrete values such as peak force or range of motion to compare biomechanical differences at key events, Moving forward, examining the entire waveform (e.g., statistical parametric mapping, principal component analysis) and incorporating inter-limb coordination (e.g., continuous relative phase) would provide additional insights to the underlying mechanism of the biomechanics and joint coordination in basketball movements. In the future, machine learning techniques can be applied to examine the complex relationships among inter-connected factors such as velocity of foot before landing, stiffness of lower extremity joints, stiffness of soft-tissue compartments, landing geometry of the leg contacting the ground, material properties of surface and shoe sole to basketball movements.

Fourthly, it is questionable if there is an ideal basketball shoe incorporating all modifications for typical basketball movements, as basketball players are required to perform a large number of vertical movement (layup, one and two-footed jumps), anterior–posterior movement (linear and curved runs, and acceleration and deceleration), lateral movement (lateral cuts), and rotation movement (V-cut/L-cut and pivot) in a game (Ben Abdelkrim et al., 2007). Moreover, the role of the heel cushioning in basketball key-movements is unclear as many basketball-related movements imposed high loading on the forefoot and midfoot (Lam et al., 2017; Leong et al., 2018). Future work should consider how to incorporate different shoe modifications in different sport movements.

Finally, the shoe wearing time effect is not clear in basketball movement. Degradation of shoe feature was associated with the altered lower limb biomechanics and reduced shoe cushioning and comfort perception in running, badminton, and basketball (Hong, Lam, Wang, & Cheung, 2016; Kong, Candelaria, & Smith, 2009; Lam, Liu, Wu, Liu, & Sun, in press; Mills, 2001; Verdejo & Mills, 2004). A microscopic study found that the decrease in the air content in the EVA after thousands of impacts could lead to permanent changes of material shape and cellular structures, and thereby inferior cushioning performance (Mills & Rodriguez-Perez, 2001). Future studies should examine if shoe degradation would impact injuries biomechanics and sport performance in each of the shoe modifications (e.g., shoe cushioning, traction, bending stiffness) in basketball.

Conclusion

Basketball shoe evolution is challenging and complicated because the material and structural design of the shoe have to take into full considerations the various typical basketball movements in different directions. This systematic review summarised that: 1) better shoe cushioning or softer midsole is related to better impact attenuation in the passive/unanticipated situations; 2) high-shoe collars are effective in improving ankle stability in jumping and cutting tasks; 3) increased shoe traction and forefoot bending stiffness can improve basketball jump, sprint, and/or cut performances, and; 4) lighter shoe mass results in better jump and/or cut performances when the shoe mass is being aware of. Understanding the interaction of all the shoe modifications is therefore necessary for basketball coaches and scientist to optimise the players' lower limb biomechanics to reduce the risk of injury while enhancing athletic performance. Further research that examines the complex relationships among shoe modifications and human factors will provide additional insights to the development of basketball footwear.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Jingyi S. Chia http://orcid.org/0000-0001-7022-4489
Pui W. Kong http://orcid.org/0000-0001-9531-9214

References

Barrett, J. R., Tanji, J. L., Drake, C., Fuller, D., Kawasaki, R. I., & Fenton, R. M. (1993). High- versus low-top shoes for the prevention of ankle sprains in basketball players. A prospective randomized study. *The American Journal of Sports Medicine*, *21*, 582–585. doi:10.1177/036354659302100416

Beedie, C. J., Coleman, D., & Foad, A. J. (2007). Positive and negative placebo effects resulting from the deceptive administration of an ergogenic aid. *International Journal of Sport Nutrition and Exercise Metabolism*, *17*, 259–269. doi:10.1123/ijsnem.17.3.259

Ben Abdelkrim, N., El Fazaa, S., & El Ali, J. (2007). Time-motion analysis and physiological data of elite under-19-year-old basketball players during competition. *British Journal of Sports Medicine*, *14*, 69–75. doi:10.1136/bjsm.2006.032318

Besier, T. F., Lloyd, D. G., & Ackland, T. R. (2003). Muscle activation strategies at the knee during running and cutting maneuvers. *Medicine & Science in Sports & Exercise*, *35*, 119–127. doi:10.1249/01.MSS.0000043608.79537.AB

Bishop, J. L., Nurse, M. A., & Bey, M. J. (2014). Do high-top shoes reduce ankle inversion? A dynamic x-ray analysis of aggressive cutting in a high-top and low-top shoe. *Footwear Science*, *6*, 21–26. doi:10.1080/19424280.2013.834981

Borowski, A. L., Yard, E. E., Fields, S. K., & Comstock, D. R. (2008). The epidemiology of US high school basketball injuries, 2005-2007. *The American Journal of Sports Medicine*, *36*, 2328–2335. doi:10.1177/0363546508322893

Bouché, R. T. (2010). Racquet Sports: Tennis, Badminton, Squash, Racquetball, and Handball. In M. B. Werd & E. L. Knight (Eds.), *Athletic Footwear and Orthoses in Sports Medicine* (pp. 215–223). New York, NY: Springer Science & Business Media.

Brauner, T., Zwinzscher, M., & Sterzing, T. (2012). Basketball footwear requirements are dependent on playing position. *Footwear Science*, *4*, 191–198. doi:10.1080/19424280.2012.674980

Brizuela, G., Llana, S., Ferrandis, R., & Garcia-Belenguer, A. C. (1997). The influence of basketball shoes with increased ankle support on shock attenuation and performance in running and jumping. *Journal of Sports Sciences*, *15*, 505–515. doi:10.1080/026404197367146

Cantwell, J. D. (2004). The Physician Who Invented Basketball. *The American Journal of Cardiology*, *93*, 1075–1077. doi:10.1016/j.amjcard.2003.12.068

Collings, T. J., Gorman, A. D., Stuelcken, M. C., Mellifont, D. B., & Sayers, M. G. (2019). Exploring the justifications for selecting a drop landing task to assess injury biomechanics: A narrative review and analysis of landings performed by female netball players. *Sports Medicine*, *49*, 385–395. doi:10.1007/s40279-018-01045-x

Cong, Y., Lam, W. K., Cheung, J. T., & Zhang, M. (2014). In-shoe plantar tri-axial stress profiles during maximum-effort cutting maneuvers. *Journal of Biomechanics*, *47*, 3799–3806. doi:10.1016/j.jbiomech.2014.10.028

DeLee, J. C. (1995). Fractures of the base of the fifth metatarsal, 2nd. In D. E. Baxter (Ed.), *The foot and ankle in sport* (pp. 98–107). St. Louis: Mosby.

Fleischmann, J., Mornieux, G., Gehring, D., & Gollhofer, A. (2013). Medial compressible forefoot sole elements reduce ankle inversion in lateral SSC jumps. *Journal of Applied Biomechanics*, *29*, 346–353. doi:10.1123/jab.29.3.346

Frederick, E. C. (1995, June 28- 30). Biomechanical requirements of basketball shoes. In M. Shorten, A. Knicker, & G. P. Bruggemann (Eds.). *Proceedings of the second symposium of the ISB working group on functional footwear* (18–19). Cologne: International Society of Biomechanics.

Fu, W., Fang, Y., Gu, Y., Huang, L., Li, L., & Liu, Y. (2017). Shoe cushioning reduces impact and muscle activation during landings from unexpected, but not self-intiated drops. *Journal of Science & Medicine in Sport*, *20*, 915–920. doi:10.1016/j.jsams.2017.03.009

Fu, W., Fang, Y., Liu, Y., & Hou, J. (2014). The effect of high-top and low-top shoes on ankle inversion kinematics and muscle activation in landing on a tilted surface. *Journal of Foot and Ankle Research*, *7*, 14. doi:10.1186/1757-1146-7-14

Fu, W., Liu, Y., & Zhang, S. (2013). Effects of footwear on impact forces and soft tissue vibrations during drop jumps and unanticipated drop landings. *International Journal of Sports Medicine*, *34*, 477–483. doi:10.1055/s-0032-1327696

Graf, E. S., & Stefanyshyn, D. (2013). The effect of footwear torsional stiffness on lower extremity kinematics and kinetics during lateral cutting movements. *Footwear Science*, *5*, 101–109. doi:10.1080/19424280.2013.789561

Harmer, P. A. (2005). Basketball injuries. *Medicine & Sport Science*, *49*, 31–61. doi:10.1159/000085341

Hong, Y., Lam, W. K., Wang, S., & Cheung, J. T. (2016). Changes in comfort perception and direction change performance of badminton shoes with extensive usage time. *Footwear Science*, *8*, 13–17. doi:10.1080/19424280.2015.1130753

Hootman, J. M., Dick, R., & Agel, J. (2007). Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *Journal of Athletic Training*, *42*, 311–319. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1941297/pdf/i1062-6050-42-2-311.pdf

Kim, J. H., Lee, K. K., Kong, S. J., An, K. O., Jeong, J. H., & Lee, Y. S. (2014). Effect of anticipation on lower extremity biomechanics during side- ad cross-cutting maneuvers in young soccer players. *The American Journal of Sports Medicine*, *42*, 1985–1992. doi:10.1177/0363546514531578

Kinchington, M., Ball, K., & Naughton, G. (2012). Relation between lower limb comfort and performance in elite footballers. *Physical Therapy in Sport*, *13*, 27–34. doi:10.1016/j.ptsp.2011.02.001

Kong, P. W., & Bagdon, M. (2010). Shoe preference based on subjective comfort for walking and running. *Journal of the American Podiatric Medical Association*, *100*, 456–462. doi:10.7547/1000456

Kong, P. W., Candelaria, N. G., & Smith, D. R. (2009). Running in new and worn shoes: a comparison of three types of cushioning footwear. *British Journal of Sports Medicine*, *43*, 745–749. doi:10.1136/bjsm.2008.047761

Lam, G. W. K., Park, E. J., Lee, K. K., & Cheung, J. T. M. (2015). Shoe collar height effect on athletic performance, ankle joint kinematics and kinetics during unanticipated maximum-effort side-cutting performance. *Journal of Sports Sciences*, *33*, 1738–1749. doi:10.1080/02640414.2015.1011206

Lam, W. K., Fung, H. T., & Poolton, J. M. (2015). Footwear fit perception with or without attention. *Footwear Science*, *7*, 181–190. doi:10.1080/19424280.2015.1084388

Lam, W. K., Lee, K. K., Park, S. K., Ryue, J., Yoon,S, H., & Ryu, J. (2018). Understanding the impact loading characteristics of a badminton lunge among badminton players. *PloS One*, *13*, e0205800. doi:10.1371/journal.pone.0205800

Lam, W. K., Lee, W. C. C., Lee, W. M., Ma, C. Z. H., & Kong, P. W. (2018). Segmented forefoot plate in basketball footwear: Does it influence performance and foot joint kinematics and kinetics? *Journal of Applied Biomechanics*, *34*, 31–38. doi:10.1123/jab.2017-0044

Lam, W. K., Liebenberg, J., Woo, J., Park, S. K., Yoon, S. H., Cheung, R. T., . . . Ryu, J. (2018). Do running speed and shoe cushioning influence impact loading and tibial shock in basketball players? *PeerJ*, *6*, e4753. doi:10.7717/peerj.4753

Lam, W. K., Liu, H., Wu, G. Q., Liu, Z. L., & Sun, W. (in press). Effect of shoe wearing time and midsole hardness on ground reaction forces, ankle stability and perceived comfort in basketball landing. *Journal of Sports Sciences*. doi:10.1080/02640414.2019.1633158

Lam, W. K., Ng, W. X., & Kong, P. W. (2017). Influence of shoe midsole hardness on plantar pressure distribution in four basketball-related movements. *Research in Sports Medicine*, *25*, 34–47. doi:10.1080/15438627.2016.1258643

Lam, W. K., Qu, Y., Yang, F., & Cheung, R. T. H. (2017). Do rotational shear-cushioning shoes influence horizontal ground reaction forces and perceived comfort during basketball cutting maneuvers? *PeerJ*, *5*, e4086. doi:10.7717/peerj.4086

Lam, W. K., Sterzing, T., & Cheung, J. T. (2011). Reliability of a basketball specific testing protocol for footwear fit and comfort perception. *Footwear Science*, *3*, 151–158. doi:10.1080/19424280.2011.630680

Landry, S. C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2009). Gender differences exist in neuro-muscular control patterns during the pre-contact and early stance phase of an unanticipated side-cut and cross-cut maneuver in 15-18 years old adolescent soccer players. *Journal of Electromyography & Kinesiology*, *19*, 370–379. doi:10.1016/j.jelekin.2008.08.004

Law, J. C. L., Wong, T. W. L., Chan, D. C. L., & Lam, W. K. (2018). Effects of shoe top visual patterns on shoe wearer's width perception and dynamic stability. *Perceptual & Motor Skills*, *125*, 682–695. doi:10.1177/0031512518783456

Leong, H. F., Lam, W. K., Ng, W. X., & Kong, P. W. (2018). Center of pressure and perceived stability in basketball shoes With soft and hard midsoles. *Journal of Applied Biomechanics*, *34*, 284–290. doi:10.1123/jab.2017-0120

Liu, H., Wu, Z., & Lam, W. K. (2017). Collar height and heel counter-stiffness for ankle stability and athletic performance in basketball. *Research in Sports Medicine*, *25*, 209–218. doi:10.1080/15438627.2017.1282352

Losito, J. M. (2008). Basketball and volleyball. In M. B. Werd & E. L. Knight (Eds.), *Athletic footwear and orthotics in sports medicine* (pp. 275–281). New York, NY: Springer.

Lu, T. W., & Chang, C. F. (2012). Biomechanics of human movement and its clinical applications. *Kaohsiung Journal of Medical Sciences*, *28*, s13–s25. doi:10.1016/j.kjms.2011.08.004

Luo, G., & Stefanyshyn, D. (2011). Identification of critical traction values for maximum athletic performance. *Footwear Science*, *3*, 127–138. doi:10.1080/19424280.2011.639807

Man, H. S., Lam, W. K., Lee, J., Capio, C. M., & Leung, A. K. (2016). Is passive metatarsophalangeal joint stiffness related to leg stiffness, vertical stiffness and running economy during sub-maximal running? *Gait & Posture*, *49*, 303–308. doi:10.1016/j.gaitpost.2016.07.004

McInnes, S. E., Carlson, J. S., Jones, C. J., & McKenna, M. J. (1995). The physiological load imposed on basketball players during competition. *Journal of Sports Sciences*, *13*, 387–397. doi:10.1080/02640419508732254

Mills, N. J., & Rodriguez-Perez, M. A. (2001). Modelling the gas-loss creep mechanism in EVA foam from running shoes. *Cellular Polymers*, *20*, 79–100. doi:10.1177/026248930102000201

Mohr, M., Trudeau, M. B., Nigg, S. R., & Nigg, B. M. (2016). Increased athletic performance in lighter basketball shoes: shoe or psychology effect? *International Journal of Sports Physiology & Performance*, *11*, 74–79. doi:10.1123/ijspp.2014-0538

Nigg, B. M. (2010). *Biomechanics of sports shoes*. Calgary: Topline Printing Inc.

Nigg, B. M., Baltich, S., Hoerzer, S., & Enders, H. (2015). Running shoes and running injuries: mythbusting and a proposal for two new paradigms: 'preferred movement path' and 'comfort filter'. *British Journal of Sports Medicine*, *49*, 1290–1294. doi:10.1136/bjsports-2015-095054

Nigg, B. M., & Enders, H. (2013). Barefoot running – some critical considerations. *Footwear Science*, *5*, 1–7. doi:10.1080/19424280.2013.766649

Nin, D. Z., Lam, W. K., & Kong, P. W. (2016). Effect of body mass and midsole hardness on kinetic and perceptual variables during basketball landing manoeuvres. *Journal of Sports Sciences*, *34*, 756–765. doi:10.1080/02640414.2015.1069381

Padegimas, E. M., Stepan, J. G., Stoker, G. E., Polites, G. M., & Brophy, R. H. (2016). Epidemiology and severity of sports and recreational injuries presenting to a tertiary adult emergency department. *Physician & Sportsmedicine*, *44*, 263–268. doi:10.1080/00913847.2016.1171683

Paquette, M. R., Zhang, S., & Baumgartner, L. D. (2013). Acute effects of barefoot, minimal shoes and running shoes on lower limb mechanics in rear and forefoot strike runners. *Footwear Science*, *5*, 9–18. doi:10.1080/19424280.2012.692724

Park, S. K., Lam, W. K., Yoon, S., Lee, K. K., & Ryu, J. (2017). Effects of forefoot bending stiffness of badminton shoes on agility, comfort perception and lower leg kinematics during typical badminton movements. *Sports Biomechanics*, *16*, 374–386. doi:10.1080/14763141.2017.1321037

Quatman, C. E., Ford, K. R., Myer, G. D., & Hewett, T. E. (2006). Maturation leads to gender differences in landing force and vertical jump performance: a longitudinal study. *The American Journal of Sports Medicine*, *34*, 806–813. doi:10.1177/0363546505281916

Randazzo, C., Nelson, N. G., & McKenzie, L. B. (2010). Basketball-related injuries in school-aged children and adolescents in 1997-2007. *Pediatrics*, *126*, 727–733. doi:10.1542/peds.2009-2497

Roberts, J., Jones, R., Harwood, C., Mitchell, S., & Rothberg, S. (2001). Human perceptions of sports equipment under playing conditions. *Journal of Sports Sciences*, *19*, 485–497. doi:10.1080/026404101750238944

Robinson, J. R., Frederick, E. C., & Cooper, L. S. (1986). Systematic ankle stabilization and the effect on performance. *Medicine & Science in Sports & Exercise*, *18*, 625–628. doi:10.1249/00005768-198612000-00004

Roy, J. P., & Stefanyshyn, D. J. (2006). Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. *Medicine & Science in Sports & Exercise*, *38*, 562–569. doi:10.1249/01.mss.0000193562.22001.e8

Schubert, C., Oriwol, D., & Sterzing, T. (2011). Gender and age related requirements of running shoes: a questionnaire on 4501 runners. *Footwear Science*, *3*, s148–s150. doi:10.1080/19424280.2011.575850

Shorten, M., & Mientjes, M. I. V. (2011). The 'heel impact' force peak during running is neither 'heel' nor 'impact' and does not quantify shoe cushioning effects. *Footwear Science*, *3*, 41–58. doi:10.1080/19424280.2010.542186

Stacoff, A., Avramakis, E., Siegenthaler, R., & Stussi, E. (1998). High-cut shoes and lateral heel stability during cutting movements in floorball. *Journal of Biomechanics*, *31*, 178. doi:10.1016/S0021-9290(98)80358-8

Stefanyshyn, D. J., & Wannop, J. W. (2016). The influence of the forefoot bending stiffness of footwear on athletic injury and performance. *Footwear Science*, *8*, 51–63. doi:10.1080/19424280.2016.1144652

Verdejo, R., & Mills, N. (2004). Heel-shoe interactions and the durability of EVA foam running-shoe midsoles. *Journal of Biomechanics*, *37*, 842–848. doi:10.1016/j.jbiomech.2003.12.022

Wang, X., Zhang, S., & Fu, W. (2017). Changes in impact signals and muscle activity in response to different shoe and landing conditions. *Journal of Human Kinetics*, *56*, 5–18. doi:10.1515/hukin-2017-001

Wei, Q., Wang, Z., Woo, J., Liebenberg, J., Park, S. K., Ryu, J., … Lam, W. K. (2018). Kinetics and perception of basketball landing in various heights and footwear cushioning. *PloS One*, *13*, e0201758. doi:10.1371/journal.pone.0201758

Worobets, J., & Wannop, J. W. (2015). Influence of basketball shoe mass, outsole traction, and forefoot bending stiffness on three athletic movements. *Sports Biomechanics*, *14*, 351–360. doi:10.1080/14763141.2015.1084031

Yang, Y., Fang, Y., Zhang, X., He, J., & Fu, W. (2017). Does shoe collar height influence ankle joint kinematics and kinetics in sagittal plane maneuvers? *Journal of Sports Science & Medicine*, *16*, 543–550.

Yentes, J. M., Kurz, M. J., & Stergiou, N. (2014). Lower extremity injury in female basketball players is related to large difference in peak eversion torque between barefoot and shod conditions. *Journal of Sport & Health Science*, *3*, 227–232. doi:10.1016/j.jshs.2012.11.004

Zelko, R. R., Torg, J. S., & Rachun, A. (1979). Proximal diaphyseal fractures of the fifth metatarsal: treatment of the fractures and their complications in athletes. *The American Journal of Sports Medicine*, *7*, 95–101. doi:10.1177/036354657900700205

Zhang, S., Clowers, K., Kohstall, C., & Yu, Y. J. (2005). Effects of various midsole densities of basketball shoes on impact attenuation during landing activities. *Journal of Applied Biomechanics*, *21*, 3–17. doi:10.1123/jab.21.1.3

Zvijac, J., & Thompson, W. (1996). Basketball. In D. J. Caine, C. G. Caine, & K. J. Lidner (Eds.), *Epidemiology of sports injuries* (pp. 86–95). Champaign US: Human Kinetics.