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Research article

Does Shoe Collar Height Influence Ankle Joint Kinematics and Kinetics in Sagittal Plane Maneuvers?

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Abstract

The Objective of the study is to investigate the effects of basketball shoes with different collar heights on ankle kinematics and kinetics and athletic performance in different sagittal plane maneuvers. Twelve participants who wore high-top and low-top basketball shoes (hereafter, HS and LS, respectively) performed a weight-bearing dorsiflexion (WB-DF) maneuver, drop jumps (DJs), and lay-up jumps (LJs). Their sagittal plane kinematics and ground reaction forces were recorded using the Vicon motion capture system and Kistler force plates simultaneously. Moreover, ankle dorsiflexion and plantarflexion angles, moment, power, stiffness, and jump height were calculated. In the WB-DF test, the peak ankle dorsiflexion angle ($p = 0.041$) was significantly smaller in HS than in LS. Additionally, the peak ankle plantarflexion moment ($p = 0.028$) and power ($p = 0.022$) were significantly lower in HS than in LS during LJs but not during DJs. In both jumping maneuvers, no significant differences were found in the jump height or ankle kinematics between the two shoe types. According to the WB-DF test, increasing shoe collar height can effectively reduce the ankle range of motion in the sagittal plane. Although the HS did not restrict the flexion–extension performance of the ankle joint during two jumping maneuvers, an increased shoe collar height can reduce peak ankle plantarflexion moment and peak power during the push-off phase in LJs. Therefore, a higher shoe collar height should be used to circumvent effects on the partial kinetics of the ankle joint in the sagittal plane.

Key words: Shoe collar height, ankle joint, kinematics, kinetics, jumping maneuver.

Introduction

Jumping maneuvers, including double-leg drop jumps (DJs) and single-leg lay-up jumps (LJs), are basic forms utilized in basketball training and competition (McClay et al., 1994). In both defense and offense, athletes take-off and land in abrupt movements, including making sudden stops and moving upward at high speed (Ben Abdelkrim et al., 2007). These jumping and landing maneuvers combined with high-intensity confrontations are major risk factors for ankle injury in basketball players, and have resulted in an ankle injury rate of 3.85 per 1000 participants (Leanderson et al., 1993; McKay et al., 2001). Furthermore, previous epidemiological studies have reported similar ankle sprain injury rates in male collegiate basketball players and female players (Agel et al., 2007; Dick et al., 2007). Among all such incidents in one study, almost half (45.0%) occurred during landing (McKay et al., 2001). To reduce ankle injury risk, several suggestions were proposed, including wearing appropriate footwear, using braces, taping, and performing muscle strengthening exercises. From the perspective of footwear design, high-top shoes (HS) were developed to prevent ankle sprains in basketball (Robinson et al., 1986).

Studies on HS have mainly focused on the shoe effect and ankle motion in the frontal plane (Ottaviani et al., 1995; Ricard et al., 2000). One study reported that HS significantly reduced ankle inversion by 4.5° (Ricard et al., 2000); however, other studies have shown no collar effect on ankle frontal plane motion during ground contact (Fu et al., 2014; Greene et al., 2015). Contrastingly, the shoe effect on sagittal plane ankle biomechanics is very limited, in addition to having an inconsistent effect on athletic performance, although ankle flexion–extension movement is involved in both single-leg and double-leg jumps. Moreover, allegations have been made that that HS may limit the ankle dorsiflexion range of motion (RoM) in certain scenarios (vertical jumps and leaps) and subsequently negatively affect athletic performance. Brizuela et al. (Brizuela et al., 1997) reported that the increased restriction by HS limited ankle joint RoM in the frontal and sagittal planes. They further indicated that high-support shoes reduced athletic performance in both vertical jumping and running, probably because of the restriction of ankle dorsiflexion–plantarflexion kinetics. However, it is worth noting that both vertical jump and running maneuvers in Brizuela et al.'s study cannot fully represent athletic activities occurring during real sports scenarios, such as in a basketball training program or a game. Furthermore, Lam et al. (2015) reported that HS restricted the total range of ankle dorsiflexion (−8.1%) in cutting maneuvers without changing athletes' performance times. They also found that such a shoe collar effect only appeared during the maximum effort of cutting maneuvers. According to our review of relevant literature, the effect of shoe collar height on ankle sagittal plane moment, power (product of the joint moment and the joint angular velocity) (Yeow et al., 2009), stiffness (the change in joint moment divided by the change in joint angle) (Farley et al., 1998), or performance in basketball jumping maneuvers remains unclear.

Based on the considerations above, the purpose of this study was to investigate the effects of wearing HS

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and LS on (1) ankle angle excursion during a weight-bearing dorsiflexion (WB-DF) maneuver; and (2) ankle joint kinematics (contact angle and RoM), kinetics (moment, power, and stiffness), and jump performance (jump height) in the sagittal plane during drop jumps and lay-up jumps. It was hypothesized that wearing HS would decrease peak ankle dorsiflexion angle and ankle RoM, and correspondingly affect ankle joint torque, power, stiffness, and jump height during jumping tasks.

Methods

Participants

Twelve male collegiate basketball players (age: 23.7 ± 0.6 years, height: 1.80 ± = 0.05 m, and body mass: 73.6 ± 6.9 kg) with a minimum of 4 years of experience in basketball events were recruited for this study. A post-hoc power analysis was executed and revealed that a sample size of 12 was sufficient to minimize the probability of Type II error for our variables of interest (Faul et al., 2007). Participants filled out surveys of lower extremity musculoskeletal injury prior to testing. The inclusive criteria for individuals was the absence of lower extremity musculoskeletal injury in the previous 6 months, including any history of ankle sprain, or chronic ankle instability / functional ankle instability. Each participant also had good athletic ability at the time of testing and did not perform any strenuous exercise 24 hours prior to the tests. All participants provided informed consent before the study, which was approved by the Institutional Review Board of Shanghai University of Sport.

Experimental protocol

Testing shoes: HS (mass: 368g) and LS (mass: 346g) used in this study incorporated a foam midsole with a Zoom Air© cushioning unit in the heel region (Nike Inc. Beaverton, US). Both shoes had an identical design regarding the outsole, midsole, and appearance, except for a 4.3 cm difference in the shoe collar height, which was measured from the highest point of LS collar in the front to the comparable highest point of HS collar (Figure 1). During the testing, all participants used the same lacing pattern and wore the same type of basketball socks to avoid the influence of various shoelaces and socks. Shoe sizes US 9.0 and 9.5 were used in this study.

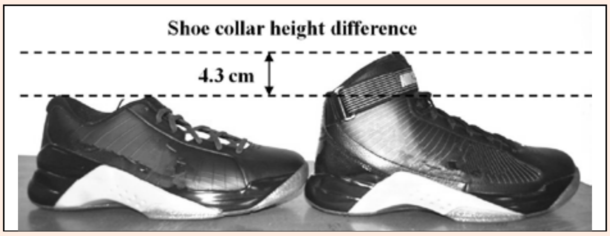

Figure 1. Experimental shoes. Low-top shoe (left), High-top shoe (right).

WB-DF maneuver: After the participants maintained a natural stance position with feet shoulder width apart in parallel, the experimenter provided the verbal signal “start.” Subsequently, the participants squatted by gradually flexing their ankles until they could no longer subjectively squat or heel off (i.e., lift from the floor) (Figure 2) (Bennell et al., 1998). All participants were required to hold on to a vertical bar to avoid the trunk from leaning forward during the process and to maintain a straight upper body (Figure 2). WB-DF is commonly performed to determine the end-points of the ankle motion. In our study, we used it as a baseline to compare to the ankle motions in the other two jumping maneuvers. Three successful trials were conducted for each shoe condition. The shoe order was randomized for all participants.

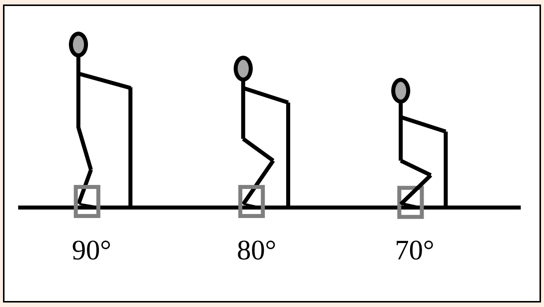

Figure 2. Diagram depicting the measurement of weight-bearing ankle dorsiflexion.

Jumping maneuvers: For DJ, participants were instructed to “step off the platform from a height of 60 cm, land with both feet on the two force plates separately, and then immediately jump as high as possible with the shortest possible contact time” (Huang et al., 2013). Meanwhile, participants crossed their arms in front of the chest with both hands placing on the shoulder during the drop jump to avoid different arm motion that may affect landing mechanics. Meanwhile, no ball or basket was used in DJ. For LJ, which is a common point-scoring maneuver in basketball, all participants stepped on one force plate with the second contralateral step after the first forward step, and subsequently jumped up with maximum efforts to drop the ball into the basket (Figure 3a). They were required to hold the ball with two hands before releasing it. The participants rested for 2 and 5 min between trials and maneuvers, respectively. For each participant, all trials (3 trials × 2 shoe conditions × 2 jumping tasks) were completed within 2 hours and the shoe order was randomized.

Kinematics: The sagittal plane kinematics of the dominant lower extremity (defined as the preferred kicking leg) (Zhang et al., 2016) were acquired using a 16-camera infrared three-dimensional (3D) motion capture system (Vicon T40, Oxford Metrics, UK) at a sampling rate of 120 Hz. Moreover, 28 retroreflective markers (diameter: 14.0 mm) were attached to the lower limb to define the foot, shank, and thigh segments (Fu et al., 2017). Specifically, retroreflective markers were placed on the following locations to define the ankle joint: lateral and medial epicondyles of the knees, shank (for tracking markers), lateral and medial malleoli of the ankles, first and fifth metatarsal heads, second metatarsal heads, and calcaneous (Figure 3b). The ankle joint center was

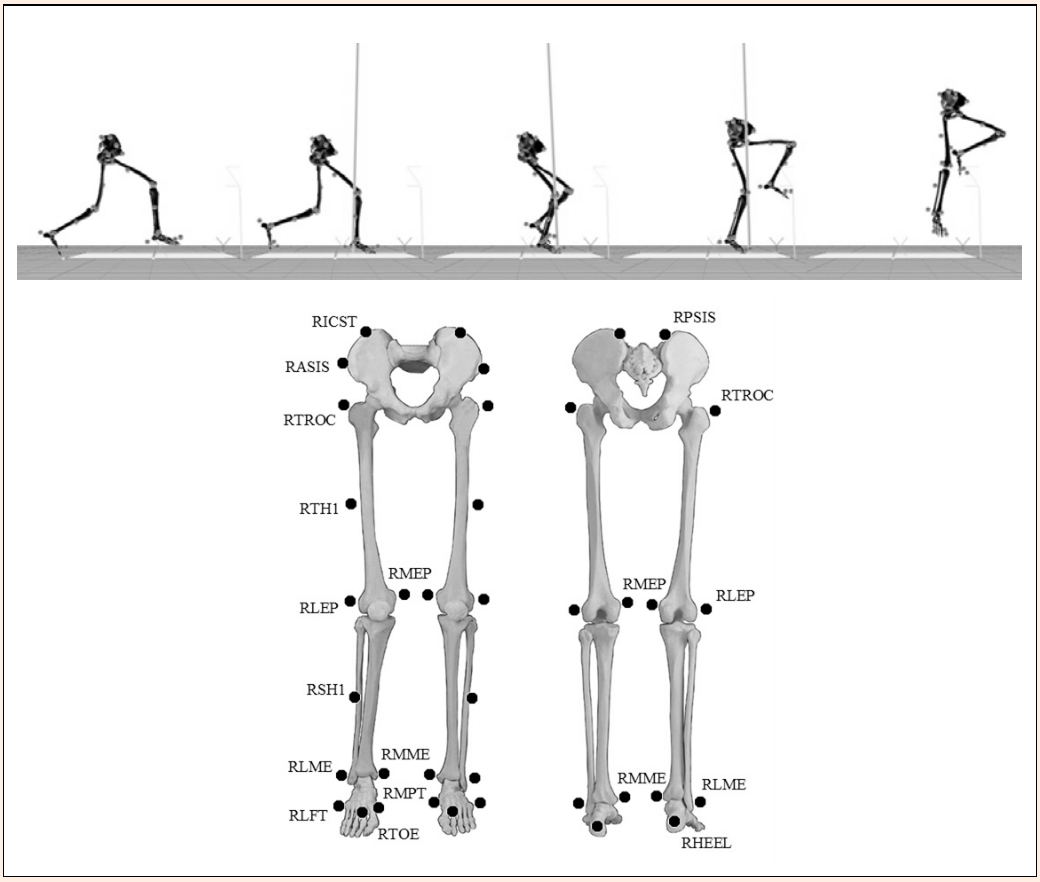

Figure 3. Touchdown, downward, and push-off phases in typical LJ footwork (top). The yellow lines show resultant ground reaction forces. Reflective marker set used in the present study (bottom). Where right side markers only are listed, the positioning is identical for the left side. Specifically, for the right thigh, RTH1, RLEP, and RMEP were used as tracking markers. For the right shank, RSH1, RLME, and RMME were used as tracking markers. For the right foot, RLME, RMME, RTOE, and RHEEL were used as tracking markers.

defined as the midpoint between the medial and lateral aspects of the malleolus markers. One researcher did the marker placement for all subjects to minimize the subjectivity of the study.

Ground reaction forces: Ground reaction force (GRF) data were collected using two 90 × 60-cm^2 force plates (9287B, Kistler Corporation, Switzerland) flush with the surrounding floor at a sampling rate of 1200 Hz. The GRF and kinematic data were collected simultaneously using the Vicon system.

Data analysis

Sagittal plane ankle kinematics: The trajectory of the reflective markers were filtered using a fourth-order Butterworth low-pass filter at a cut-off frequency of 7 Hz (Horita et al., 2002). The force data were resampled at 60 Hz to calculate torques and power outputs based on a previous study (Ruan and Li, 2008). Visual 3D software (4.00.20, C-Motion Inc., MD, USA) was used to calculate ankle variables in the sagittal plane (Zhang et al., 2012). Ankle kinematics included the touchdown angle (θ_0), maximum and minimum angles (θ_{min} and θ_{max}), the RoM ($\theta_{RoM} = \theta_{max} - \theta_{min}$), and angle excursion during the downward phase ($\Delta\theta = \theta_0 - \theta_{min}$). The jump height, calculated using $v_0^2 / 2g$ (where v_0 is the vertical take-off velocity), was used to determine jumping performance (Bosco et al., 1983). The Cardan sequence for calculating ankle joint angles was X–Y–Z, which is equivalent to the flexion / extension–inversion / eversion–axial rotation.

The peak plantarflexion moment (M_{max}), peak plantarflexion power (P_{max}), and stiffness (k) of the ankle joint were determined using inverse dynamics analysis (Winter, 2009). Peak internal plantarflexion moment and power were identified during the push-off phase (from maximum knee flexion to the instant of take-off). Specifically, joint power was calculated using $P = M \times \omega$ (Yeow et al., 2009), where ω refers to angular velocity. Joint stiffness was calculated using $k = \Delta M / \Delta\theta$ (Farley et al., 1998), where ΔM refers to the change in moment, and $\Delta\theta$ refers to the angle excursion during the downward phase of landing. All kinetic values were normalized to body mass.

Statistical analyses

All dependent variables were normally distributed based on the Shapiro–Wilk test. Paired t-tests were performed to determine differences in all variables (jump height and ankle joint kinematics and kinetics) between the HS and LS types of shoes (17.0, SPSS Inc., Chicago, IL, USA). The significance level was set at $\alpha = 0.05$.

Results

Sagittal plane ankle kinematics

In the WB-DF maneuver, θ_{min} was significantly higher (*p* = 0.041) and θ_{RoM} was significantly lower (p = 0.034) when wearing HS compared to wearing LS (Table 1 and Figure 4a). During DJs and LJs, no significant differences were observed in the jump height or any ankle kinematics between the two shoe types (Table 1 and Figures 4b and c).

In LJ, wearing HS led to a significant decrease in M_{max} *(p = 0.028)* and P_{max} (p = 0.022) (Table 2 and Figure 5). However, no significant differences were observed in any variables during the DJ tasks (Table 2 and Figure 5).

Table 1. Effect of shoe collar height on ankle angle at touchdown (θ_0), maximum and minimum ankle angles (θ_{min} and θ_{max}), ankle range of motion (θ_{ROM}), ankle angle excursion during the downward phase ($\Delta\theta$), and the jump height (*h*) in the weight-bearing dorsiflexion (WB-DF) maneuver, drop jump (DJ), and lay-up jump (LJ) tasks.

Tasks	Shoes	θ_0 (°)	θ_{min} (°)	θ_{max} (°)	θ_{ROM} (°)	$\Delta\theta$ (°)	*h* (cm)
WB-DF	**HS**	N/A	85.0 ± 8.9*	112.8 ± 3.5	27. 0± 6.7*	N/A	N/A
	LS	N/A	77.1 ± 7.3	108.9 ± 4.8	32.2 ± 6.6	N/A	N/A
	Mean difference (95% CI	N/A	7.9 (4.7−11.1)	3.9 (.7−7.1)	-5.2 (-8.7−-1.7)	N/A	N/A
	Cohen's *d*	N/A	.971	.928	.782	N/A	N/A
	Post-hoc power	N/A	66.2%	62.3%	52.2%	N/A	N/A
DJ	**HS**	125.6 ± 9.2	90.8 ± 11.2	140.7 ± 8.7	50.0 ± 9.3	34.7±7.9	.344 ± .054
	LS	125.8 ± 6.1	88.1 ± 7.5	140.3 ± 8.1	52.1 ± 8.0	37.7±7.9	.342 ± .053
	Mean difference (95% CI	-0.2 (-3.8−3.4)	2.1 (-2.5−6.7)	0.4 (-2.5−3.3)	-2.1 (-3.9−-0.3)	-3.0 (-6.3−0.3)	.002 (-.016−.020)
	Cohen's *d*	.026	.283	.048	.242	.379	.037
	Post-hoc power	2.9%	10.3%	3.3%	8.6%	15.2%	3.1%
LJ	**HS**	117.8 ± 5.4	104.3 ± 7.2	136.2 ± 10.3	31.8 ± 8.1	13.6±5.8	.38 ± .05
	LS	116.0 ± 6.0	103.6 ± 5.7	134.1 ± 10.6	30.6 ± 6.7	12.4±4.5	.41 ± .04
	Mean difference (95% CI	1.8 (.2−3.4)	.7 (-08−2.2)	2.1 (-.3−4.5)	1.2 (-.5−2.9)	1.2 (.1−2.3)	-0.03 (-.05−-.01)
	Cohen's *d*	.315	.108	.201	.161	.231	.662
	Post-hoc power	11.8%	4.5%	7.1%	5.9%	8.2%	36.9%

* Significantly different from LS (p < 0.05).

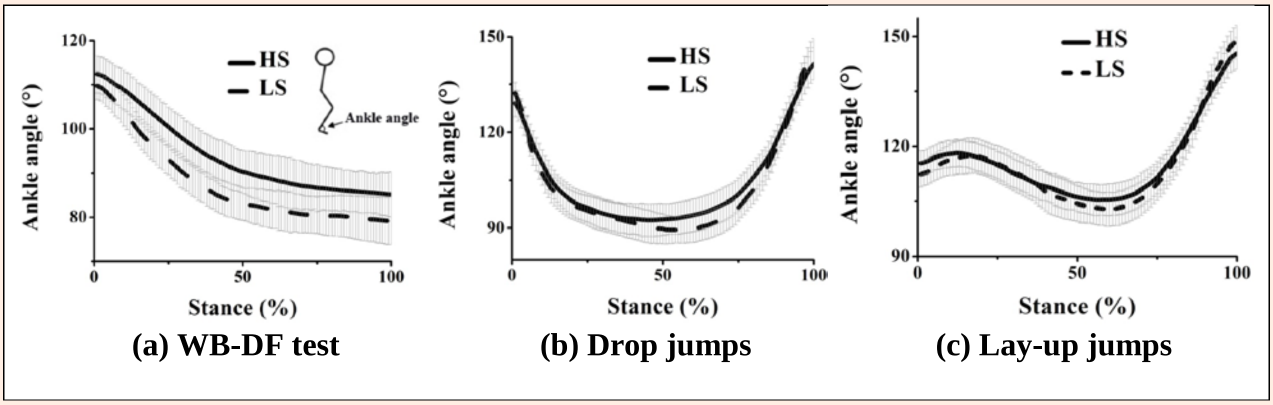

Figure 4. Ensemble curves of sagittal plane ankle joint angles when wearing HS and LS during the stance phase (time %) of different tasks.

Discussion

Studies have mostly focused on determining whether HS can limit ankle inversion in the frontal plane. By contrast, little is known about the effects of HS on ankle biomechanics and performance during sagittal plane maneuvers. Our study investigated the biomechanical characteristics of the ankle joint in the sagittal plane in two common basketball jumping maneuvers, namely DJs and LJs, when the participants wore HS and LS. The results partially supported our hypothesis that HS reduced the ankle dorsiflexion angle and θ_{RoM} during the WB-DF test and the peak ankle joint moment and power during lay-up, although changes in the height of the two maneuvers did not occur.

HS significantly constrained ankle WB-DF movement. A similar finding was previously reported (Rowson et al., 2010), where participants' peak ankle dorsiflexion angles were smaller by an average of 7.2% when wearing HS than when wearing LS during an inertially invoked dorsiflexion movement. The authors suggested that the peak ankle angle was reduced mainly because of the shoe

Table 2. **Effects of shoe collar height on peak ankle plantarflexion torque (Mmax), peak ankle plantarflexion power (Pmax), and ankle joint stiffness (k) during DJ and LJ tasks (normalized by body mass).**

Tasks	Shoes	M_{max} ($N \cdot m \cdot kg^{-1}$)	P_{max} ($W \cdot kg^{-1}$)	k ($N \cdot m \cdot kg^{-1}/°$)
DJ	HS	1.50 ± .65	9.93 ± 3.85	.045 ± .025
	LS	1.37 ± .61	9.52 ± 3.55	.035 ± .014
	Mean difference (95% CI)	.13 (-.05−.31)	.41 (.04−.77)	.010 (-.024−.044)
	Cohen's *d*	.206	.111	.493
	Post-hoc power	7.3%	4.6%	22.6%
LJ	HS	3.14 ± .65*	13.11 ± 4.4*	.265 ± .191
	LS	4.19 ± .83	19.21 ± 7.0	.313 ± .255
	Mean difference (95% CI)	-1.05 (-1.9−-.20)	-6.10 (-11.9−-.30)	-.048 (-.147−.0511)
	Cohen's *d*	1.409	1.043	.213
	Post-hoc power	93.2%	72.4%	7.5%

* Significantly different from LS ($p < 0.05$).

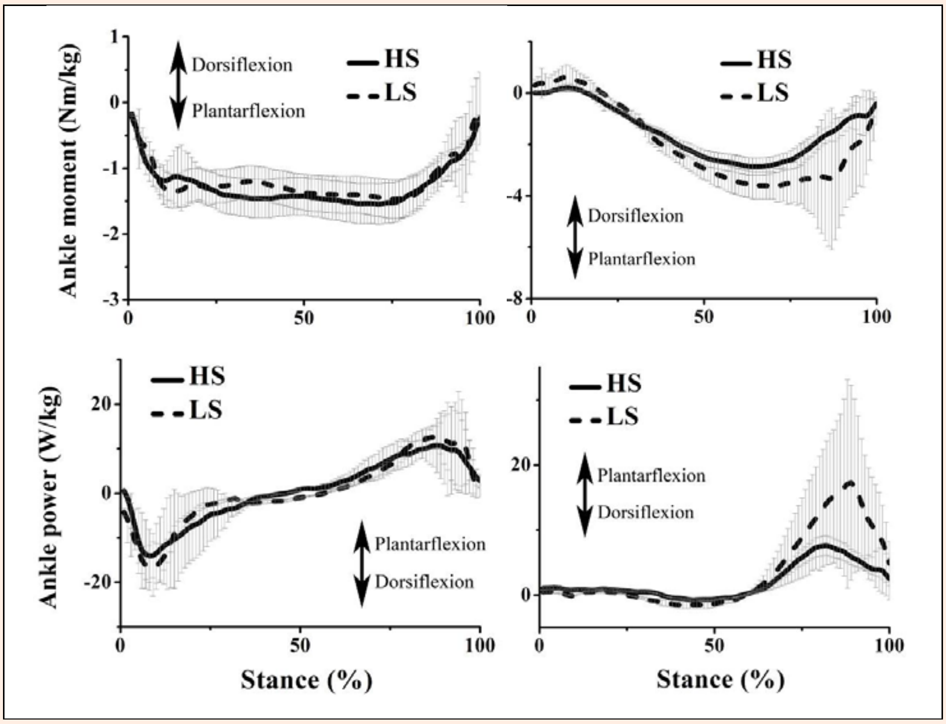

Figure 5. **Effects of shoe collar height on ankle joint moment and joint power in the sagittal plane during the stance phase in drop and lay-up jumps.**

collar height and collar material, which affected the flexibility and deformation of the shoe as a whole. However, in the present study, the HS that were used did not restrict ankle flexion–extension movement during the dynamic jumping maneuvers. Our data also showed that ankle RoM was much higher during the DJ task than during the WB-DF task (50.0° vs. 27.0° for HS and 52.1° vs. 32.2° for LS, respectively), and that the differences mainly existed in plantarflexion but not in dorsiflexion. Meanwhile, the minimum angle of the participants' ankle joints in the WB-DF task was 77.1° ± 7.3°, which was much smaller than the corresponding angles during the DJs (88.1° ± 7.5°) and LJs (103.6° ± 5.7°). Therefore, a possible reason for not observing differences in ankle kinematics during the jumping maneuvers between the HS and LS types is that neither of these jumps reached the limitation boundary of the dorsiflexion that the current high-top collar design can induce. This assumption can also partially explain the lack of differences in the kinematics of the ankle flexion–extension movement between HS and LS during both DJs and LJs.

To prevent ankle sprain, special garments (e.g., ankle braces) and footwear (e.g., HS) are designed to immobilize the ankle joint in the frontal plane. Studies have variously demonstrated that these designs may or may not be useful in restricting ankle inversion–eversion movement in different activities (Fu et al., 2014; Greene et al., 2015; Ricard et al., 2000). Moreover, several reports have described how these designs affect ankle sagittal motion, despite the initial intention to constrain frontal movement. For instance, braces significantly reduced the ankle RoM in the sagittal plane by 8.9° ± 2.4° compared with the effects of standard netball shoes in cutting tasks (Greene et al., 2015).

Although the current study showed no differences in ankle kinematics between the two shoe types in jumping, the collar height effect on sagittal plane ankle motion cannot be ignored because we observed a smaller ankle RoM and minimum angle in WB-DF when the participants wore HS rather than LS. Based on these findings, we suggest that considering only the increased stability of the ankle joint when designing external support systems (e.g., braces and HS) might not only affect ankle inversion–eversion movement but also dorsiflexion performance. Moreover, the inconsistent findings across studies (Fu et al., 2014; Greene et al., 2015; Ricard et al., 2000) regarding the restrictive effect of collar height might be attributed to different shoe materials, collar structures, etc. Therefore, additional quantitative studies are warranted to determine the optimization of protective intensities.

Interestingly, peak plantarflexion moment and power were significantly reduced ($p < 0.05$) during the push-off stage of LJ but not DJ when wearing HS compared to LS, whereas jump height was similar between the two shoe conditions. The differential findings between the two jumping maneuvers are largely due to different upper extremity positions, movement patterns, force requirements, goals, etc. Boyer et al. (2009) reported that wearing different unstable shoes affected the ankle moment and peak positive power in the sagittal plane, which might be caused by different contributions of the agonistic and antagonistic muscles around the ankle joints. In addition, HS were associated with the decreased amplitude of muscle activities, delayed activation timing, and changed proprioceptive input of the foot–ankle complex upon landing on a tilted surface (Fu et al., 2014). These findings suggested that one may feel “safer” wearing HS than wearing LS, subconsciously leading to lower muscle activation and subsequently decreased ankle moment and power during high-intensity maneuvers (e.g., LJs). On the other hand, a greater internal plantarflexor moment and / or power is required during take-off to achieve a higher jump height. However, in the current study, the same jump height was found with lesser peak plantarflexion moment in HS. It is, therefore, logical to assume that if the same jump height can be achieved with lesser joint torque, then presumably less effort is being exerted and this would be advantageous to an athlete. Nevertheless, this assumption still needs further confirmation. Furthermore, in jumping maneuvers, performance depends on the total power and work output of the lower extremity rather than the ankle joint alone (Stefanyshyn and Nigg, 2000); therefore, increased ankle plantarflexion power does not necessarily result in jump height improvement. Collectively, the higher collar height affected sagittal ankle power output during the push-off phase in LJs, which might be partially due to changes in the coordination of active and antagonist muscles.

Limitations in the current study are acknowledged along with proposed future directions for research. First, we did not collect surface electromyographic (EMG) data to simplify the design by focusing on joint kinematics and kinetics and to mimic basketball jumping activity by limiting the experimental devices that were attached to the participants. However, our findings based on current measurements may be more appropriately interpreted with some understanding of muscle activities. Therefore, we suggest that future research should incorporate EMG data to gain a more comprehensive understanding of the neuromuscular reaction to different shoe types. Meanwhile, since the current study focused on the biomechanical changes at ankle joint, other joints, i.e., knee and hip joints, were not considered. Additionally, we recommend that future research focus on shoe collar properties, including material hardness and structures and their effects on the mechanical responses of the ankle joint. Ideally, more types of basketball movements should also be considered. Finally, it is noted that chronic and functional ankle instability may influence ankle mechanics during WB-DF and jumping maneuvers, and these effects might persist beyond a 6-month period.

Conclusions

In the WB-DF maneuver, an increased shoe collar height effectively reduced ankle RoM in the sagittal plane. However, during DJs and LJs, shoe collar height did not affect ankle kinematics in the sagittal plane and had no effect on jump height. Although the HS used in this study did not restrict the flexion–extension performance of the ankle joint during two jumping maneuvers, an increased shoe collar height can reduce peak ankle plantarflexion moment and peak power during the push-off phase in LJs. Lesser peak plantarflexion moment and power with a similar jump height found in HS during LJ suggested that less effort was being exerted by the ankle joint, and this would be advantageous to athletic performance.

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Key points

- An increased shoe collar height effectively reduced ankle joint ROM in the sagittal plane in weight-bearing dorsiflexion maneuver.
- Shoe collar height did not affect sagittal plane ankle kinematics and had no effect on performance during realistic jumping.
- Shoe collar height can affect the ankle plantarflexion torque and peak power during the push-off phase in lay-up jump.

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