Effect of Body Mass and Midsole Hardness on Kinetic and Perceptual Variables During Basketball Landing Manoeuvres

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Keywords: footwear, midsole density, layup, shot-blocking, ground reaction force, loading rate

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Abstract

This study investigated the effects of body mass and shoe midsole hardness on kinetic and perceptual variables during the performance of three basketball movements: (i) the first and landing steps of layup, (ii) shot-blocking landing and (iii) drop landing. Thirty male basketball players, assigned into 'heavy' (n=15, mass 82.7±4.3kg) or 'light' (n=15, mass 63.1±2.8kg) groups, performed five trials of each movement in three identical shoes of varying midsole hardness (soft, medium, hard). Vertical ground reaction force (VGRF) during landing was sampled using multiple wooden-top force plates. Perceptual responses on five variables (forefoot cushioning, rearfoot cushioning, forefoot stability, rearfoot stability and overall comfort) were rated after each movement condition using a 150-mm Visual Analogue Scale. A mixed factorial analysis of variance (Body Mass×Shoe) was applied to all kinetic and perceptual variables. During the first step of the layup, the loading rate associated with rearfoot contact was 40.7% higher in the 'heavy' than 'light' groups (P=.014) and 12.4% higher in hard compared with soft shoes (P=.011). Forefoot peak VGRF in soft shoe was higher (P=.011) than hard shoe during shot-block landing. Both 'heavy' and 'light' groups preferred softer to harder shoes. Overall, body mass had little effect on kinetic or perceptual variables.

Keywords: footwear, midsole density, layup, shot-blocking, ground reaction force, loading rate

Introduction

Basketball is a sport which places a considerable amount of stress on the lower extremities of players. Game analyses has shown that players perform an average of 70 jumps per game and vertical impact forces experienced may be up to nine times an individual's body weight (McClay et al., 1994). An inability to attenuate high impact forces on the body might lead to injury (Lephart, 2002). A two-year audit of Canadian intercollegiate basketball found that the most common injuries sustained by players involved the ankle and knee regions (Meeuwise, Sellmer, & Hagel, 2003). This is likely due to the inability of the muscular-skeletal system at these regions to adequately attenuate forces (Irmischer, Harris, Debeliso, Adams, & Shea, 2004). Therefore, appropriate impact force attenuation is important in order to reduce the risk of injury.

The type of shoe worn by a player has been identified as a risk factor for injury in basketball (McKay, Goldie, Payne, & Oakes, 2001). Appropriate performance footwear should effectively attenuate impact forces generated by foot contact with the ground during various impact activities (Nigg, Cole, & Bruggemann, 1995). Sport footwear consists of several components including midsole, outsole, heel counter and upper. Of these, midsole hardness have been predominantly investigated on running and walking to optimize the footwear cushioning properties (Kersting & Bruggemann, 2006; Nigg, Baltich, Maurer, & Federolf, 2012; Sterzing, Schweiger, Ding, Cheung, & Brauner, 2013). However, there are very few studies on jumping and landing activities which simulate the specific loading demands in basketball. The second peak of the vertical Ground Reaction Force (VGRF), which is associated with the rearfoot contact during landing, was found to be higher in a hard shoe compared to medium and soft shoes (Zhang, Clowers, Kohstall, & Yu, 2005). In contrast, another study found no differences in peak VGRF between various midsole hardness conditions from volleyball spike jump landings

(Nolan, Armstrong, & Wojcieszak, 2005). Therefore, studies investigating the effects of midsole hardness on different jumping and landing activities remain inconclusive and warrant further investigation.

A possible explanation for the conflicting results reported by Zhang et al. (2005) and Nolan et al. (2005) might be the unique responses of individuals to the interaction between shoes and tasks. The effects of midsole hardness on internal impact forces have been found to be participant-dependent (Cole, Nigg, Fick, & Morlock, 1995; Kersting & Bruggemann, 2006). A similar conclusion was made when Hreljac (1998) compared biomechanical variables of three participants performing a lateral jump movement in tennis shoes of different midsole hardness. Hreljac (1998) showed that the three players had distinct impact and perception responses with different midsole hardness. Although anthropometric data were not collected, Hreljac (1998) described the three participants as ‘morphologically diverse’. Morphology, in general, refers to the ‘form or structure of any organism and its parts’ (Merriam-Webster, 2015). As most physical characteristics (e.g., height and musculature) are related to a variation in body mass (Diverse Populations Collaborative Group, 2005; Hume, 1966), the difference in body mass across participants might have contributed to the distinct biomechanical responses to shoes of various midsole hardness. Therefore, an investigation into body mass effect would provide insights into landing kinetics and shoe design.

The cushioning properties of a shoe have been stated to be an important regulator of footwear comfort (Nigg, 2010). High correlations have been found between cushioning perception and biomechanical variables in shoes of different midsole hardness in running (Hennig, Milani & Lafortune, 1993). Based on perceptual abilities, participants are expected to modify their running style to avoid high heel impacts during shod running (Milani, Hennig &

Lafortune, 1997). It is, therefore, important to study both biomechanical and perceptual variables in the assessment of injury risk in basketball.

The purpose of this study was to examine the difference in kinetic and perceptual responses between heavy and light players during basketball-specific manoeuvres in shoes of different midsole hardness. It was hypothesised that 1) heavier players would experience higher normalised impact forces than lighter players; 2) softer shoes would provide better force attenuation abilities, and 3) heavier players would prefer softer shoes while light players would prefer harder shoe. Results from this study would advance our current understanding of the stresses the body experiences during landing activities of common basketball-related movements.

Methods

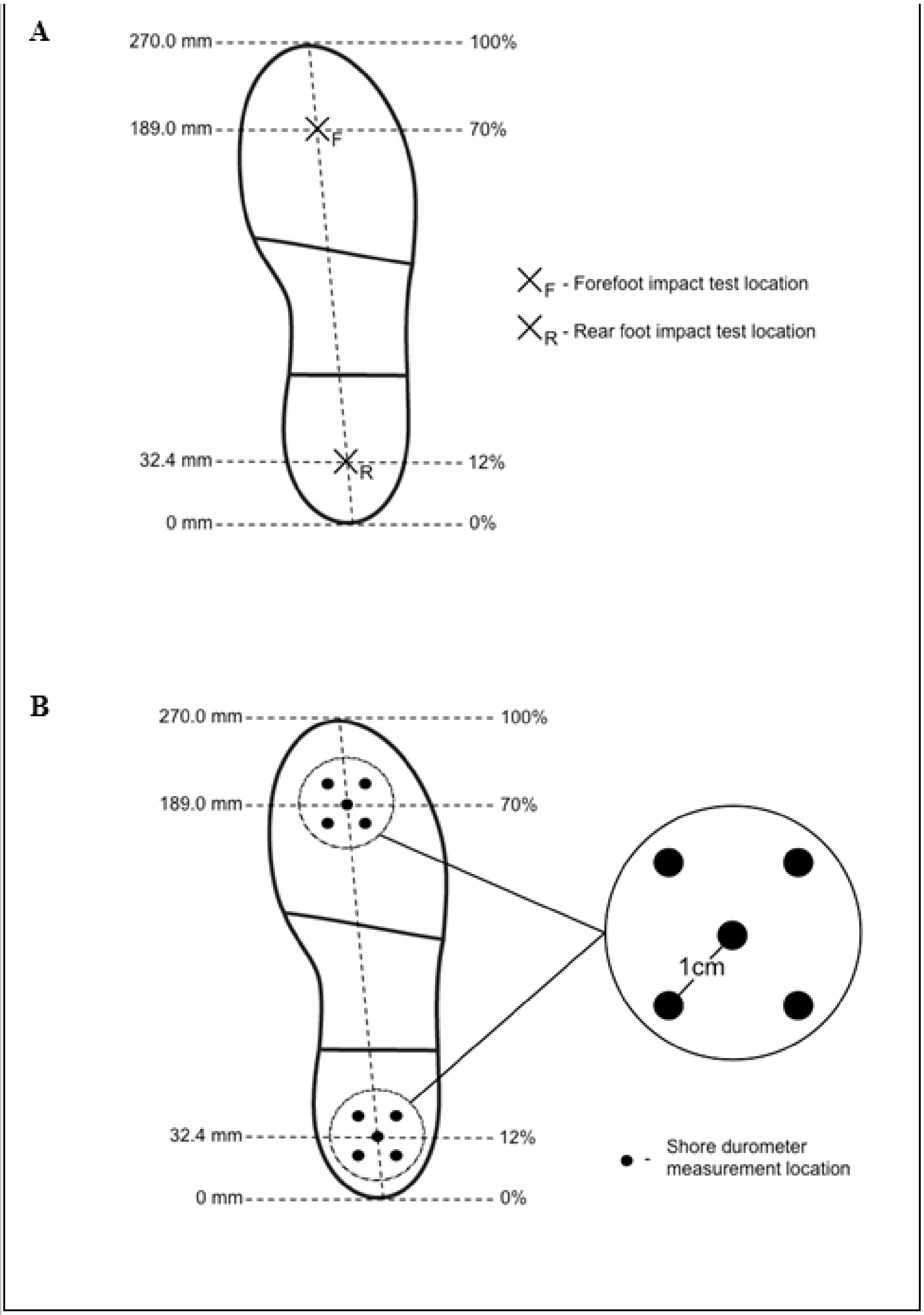
Participants

Thirty male university basketball players (age = 21.8 (2.8) years) with a minimum of five years competitive playing experience participated in this study. Only participants with a foot length of US size 9.0±0.5 for both feet were recruited. Participants were evenly assigned to either 'heavy' (n = 15, body mass = 82.7(4.3) kg, height = 1.81(0.03) m) or 'light' (n = 15, body mass = 63.1(2.8) kg, height = 1.74 (0.04) m) groups according to body mass (mean difference = 19.6 kg, 95% CI [16.8, 22.3], P < .001). The inclusion criteria for the 'heavy' and 'light' groups were a body mass of above 78 kg and below 66 kg respectively. This selection criterion was based on a percentile differentiation (30th and 70th percentile) of a preliminary recruitment list of participants. All participants signed an informed consent form and ethical approval was granted by Nanyang Technological University Institutional Review Board prior to the start of the study.

Shoe conditions

Three identical pairs of US size 9.0 basketball shoes (Li Ning), which only differed in midsole hardness, were manufactured specifically for this study. The shoes were classified as soft (38 Shore C), medium (42 Shore C) and hard (57 Shore C) according to the manufacturer's specifications of midsole hardness. Prior to the start of the study, a Type C shore durometer (Rex Durometers, Rex Gauge Co., Buffalo Grove, IL, USA) was used to determine the material hardness at the forefoot and rearfoot regions of the shoes. Each reading was taken as the average of five measurements at one location (Figure 1, Sterzing et al., 2013).

Figure 1



A: Impact locations using mechanical impact tester; **B:** Hardness measurement locations using shore durometer.

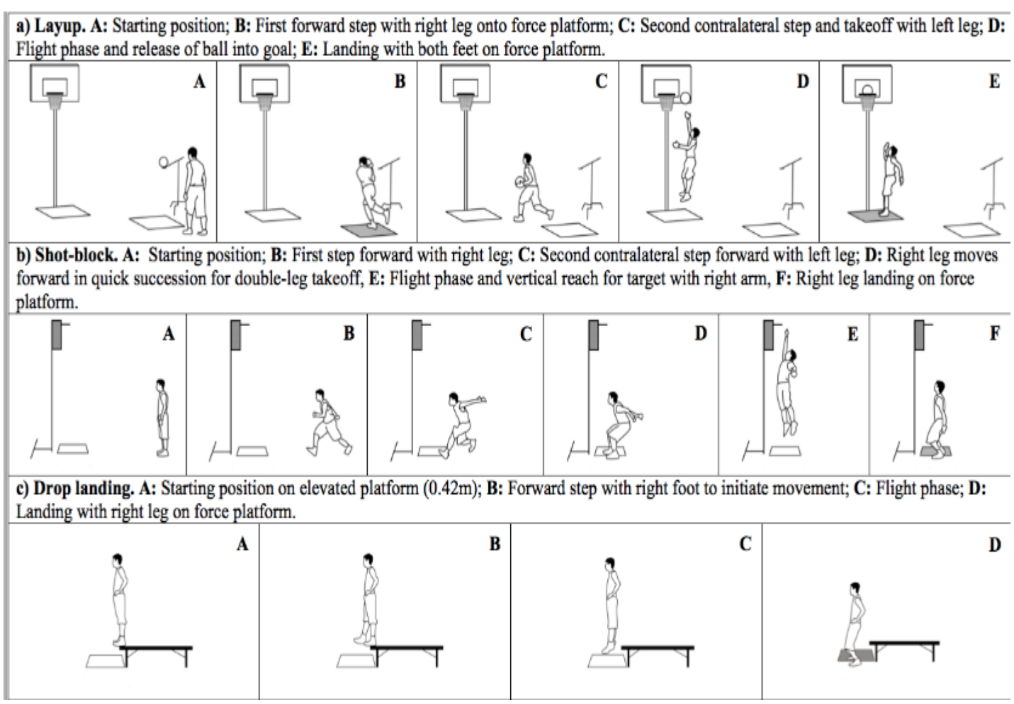
A mechanical impact tester (Exeter Research V2.6, Brentwood, NH, USA) was also used to measure the mechanical impact characteristics of the shoes at the rearfoot and forefoot locations. Thirty consecutive mechanical impact trials were performed at the centre of the forefoot and heel regions with an 8.5-kg constant mass dropped from 50 mm. The trials from 25 to 30 were averaged for the calculation of forefoot and rearfoot cushioning properties. The shoe hardness and cushioning are provided in Table 1.

*** Table 1 ***

Basketball landing manoeuvres

Three basketball-specific manoeuvres selected for this study were (i) the first and landing steps of layup, (ii) shot-blocking, and (iii) drop landing (Figure 2). The layup is a common point-scoring manoeuver while the shot-blocking is often utilised during defensive play. The drop landing is a standard movement task used for evaluating landing impacts (e.g. Bates, Ford, Myer, & Hewett, 2013; Pain & Challis, 2006; Zhang et al., 2005).

Figure 2



(i) Layup. The layup comprises of two contralateral approach steps followed by a single-leg take-off and release of the basketball into a hoop during flight (Figure 2a). The basketball was supported by a tripod adjusted to the chest height of individual players. The movement was designed to simulate the receipt of a chest-pass and subsequent execution of a layup. No dribbling was allowed throughout the movement. Landing onto the force platforms occurred during the first step and final double-leg landing of the layup.

(ii) Shot-blocking. The shot-blocking movement can be characterised by two contralateral approach steps followed by a maximal reach vertical jump (Figure 2b). Prior to the start of the trials, each participant's maximum jump height was measured with a Vertec jump height measurement device (Sports Imports Inc., Columbus, US). A target set at 90% of the participant's maximum jump height was used for all recorded trials. Participants landed with their right leg onto the force platform and their left leg on to the adjacent ground.

(iii) Drop landing. The drop landing movement began with the participant standing on a raised platform set 0.42m above ground (Figure 2c). Participants were instructed to remain erect and look forward while positioning their hands on the hips in order to reduce postural sway. The movement was initiated by taking a small step forward with the right leg. Participants were asked to perform double-leg landing, with their right leg on the force platform and left leg on the adjacent ground.

Procedures

Participants performed five minutes of self-selected warm-up before the start of the trials. Participants were instructed to perform five trials of each movement (layup, shot-blocking, drop landing) in three pairs of test shoes (soft, medium, hard), with three familiarisation trials conducted before the start of each movement. All shoe conditions were completed for each movement before proceeding on to the next movement, summing to nine test conditions. The order of the movements and shoes worn were randomised across participants. Two-minute rest between trials and five-minute rest between shoe conditions were allowed to minimise the fatigue. At the end of each movement in each shoe condition, participants were asked to rate five parameters of shoe comfort on a 150-mm Visual Analogue Scale (VAS).

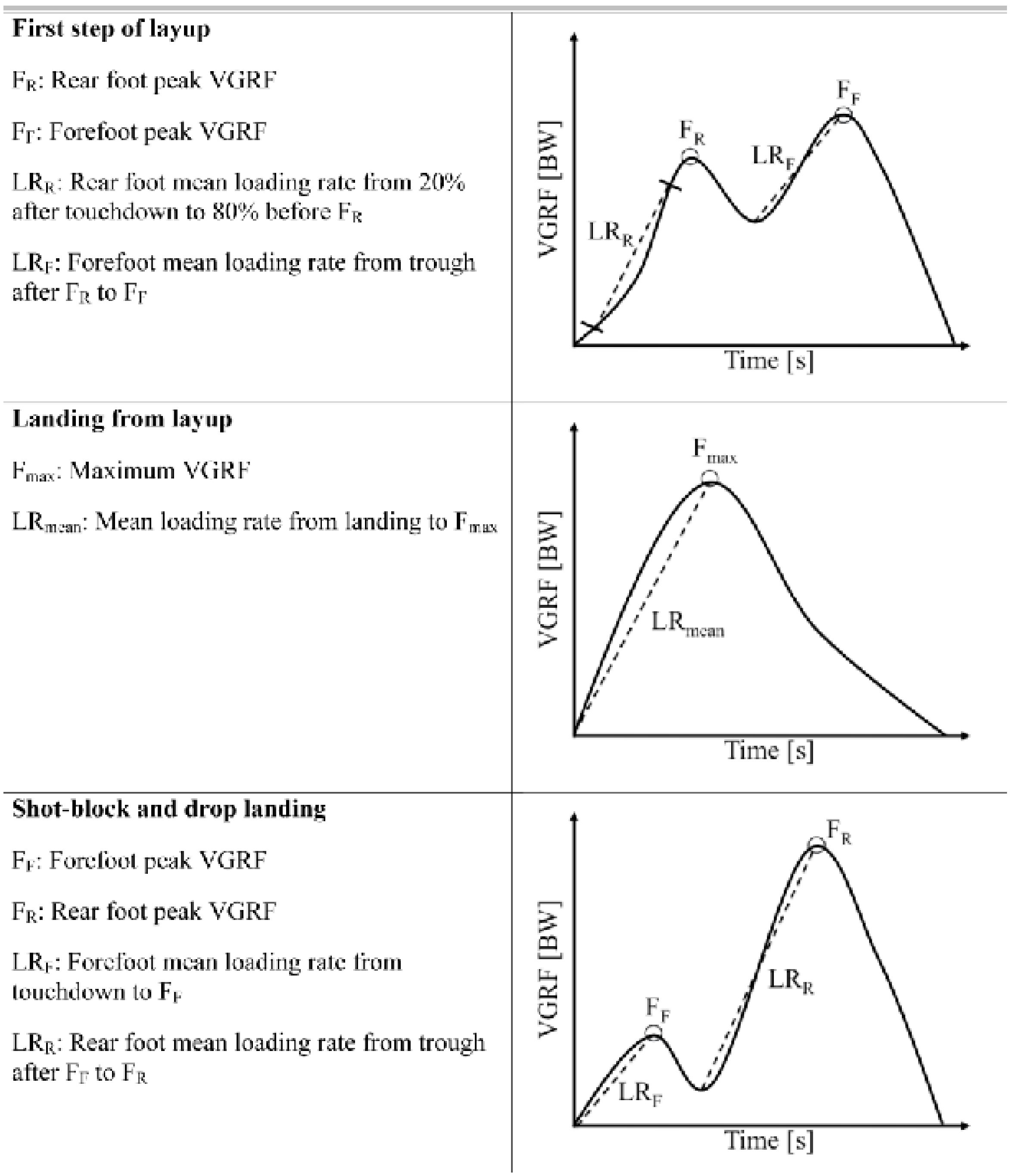
All movements were conducted in a laboratory on a wooden-top surface similar to those found in indoor basketball courts. Two 0.9 m by 0.9 m force plates (Advanced Mechanical Technology Inc, Watertown, MA, USA) were embedded into the ground. The force plates and its surrounding surfaces were covered with a wooden-top basketball surface for evaluation of landing impact in basketball. The VGRF data were sampled at 1000 Hz. For the layup first step, shot-blocking and drop landing, only VGRF data of the landing of the right leg was collected. For the layup landing, VGRF data of the double-leg landing was collected.

A 150-mmVAS was used by participants to rate five comfort perception items which were (i) forefoot cushioning [very hard (0 mm) to very soft (150 mm)], (ii) forefoot stability [very unstable (0 mm) to very stable (150 mm)], (iii) rearfoot cushioning [very hard (0 mm) to very soft (150 mm)], (iv) rearfoot stability [very unstable (0 mm) to very stable (150 mm)], and (v) overall comfort [very poor (0 mm) to very good (150 mm)]. The VAS is commonly used to assess subjective perceptions of comfort in athletic shoes (Lam, Sterzing, & Cheung, 2011; O'Leary, Vorpahl, & Heiderscheit, 2008; Sterzing et al. 2013) and has been found to demonstrate substantial inter-day reliability for comfort variables in the assessment of basketball shoes (Lam et al., 2011). A standard set of definitions for all perception variables were described to all participants prior to the assessment.

Data Processing

A custom MATLAB (Mathworks, Inc., Natwick, MA, USA) code was used to process all kinetic data. Raw VGRF data was passed through a fourth-order Butterworth low-pass filter. Cut-off frequencies, determined from previous studies on similar movements (Janssen, Sheppard, Dingley, Chapman & Spratford, 2012; Sell et al., 2006) and visual inspection of the data, were set at 60 Hz for the layup first step and 150 Hz for all other landings. The onset of the impact phase was determined when the VGRF exceeded a 10 N threshold. All data was normalised to body weight by division (Mullineaux et al., 2006). Peak VGRF and mean loading rate for all movements were calculated (Figure 3). Due to the similar impact characteristics between the layup first step and a running step of a heel-striker, the mean loading rate during the rearfoot contact for this step was calculated from 20% to 80% before the first impact peak (Boyer & Nigg, 2006; Butler, Davis, & Hamill, 2006). All other mean loading rates were calculated from 0% to 100% before each impact peak (forefoot and rearfoot). This is consistent with previous landing studies using similar movements (Hargrave, Carcia, Gansneder, & Shultz, 2003; Quatman, Ford, Myer, & Hewett, 2005).

Figure 3



Statistical analysis

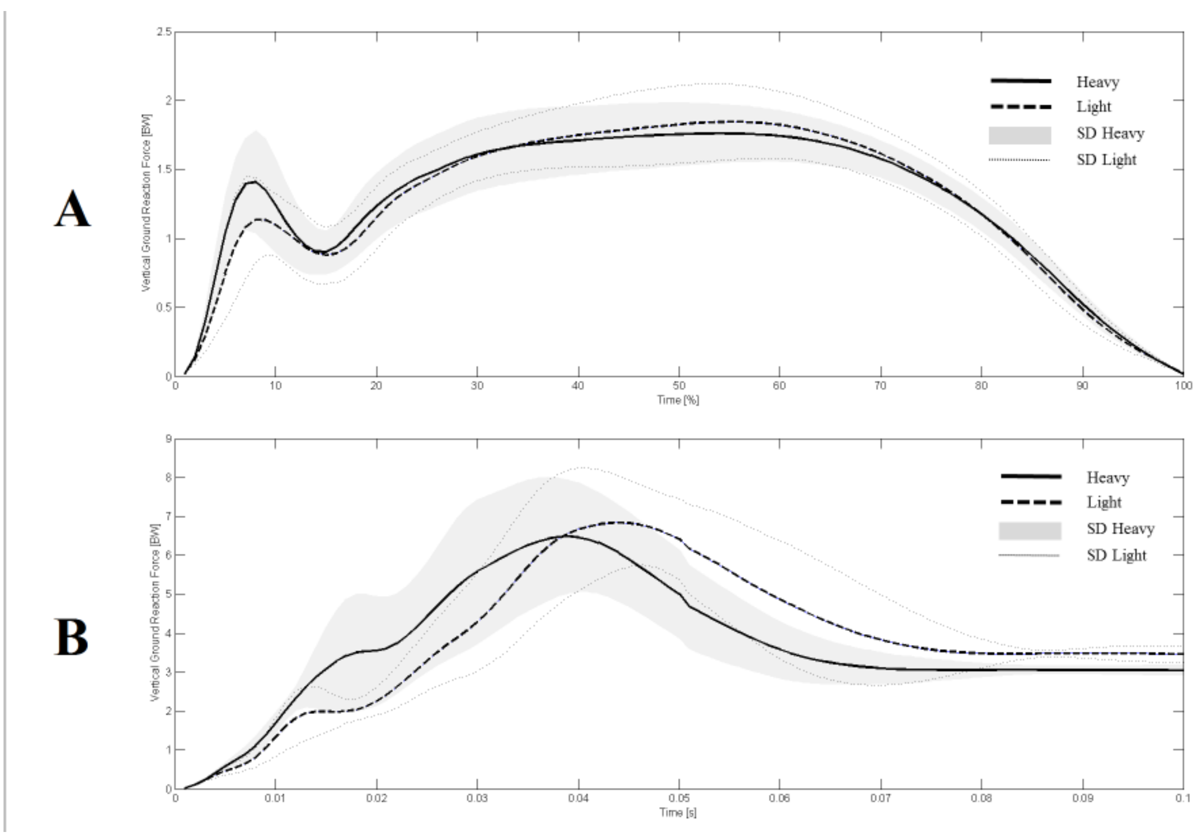
All statistical analyses were performed using SPSS 21.0 (IBM Corp., Armonk, NY, USA).

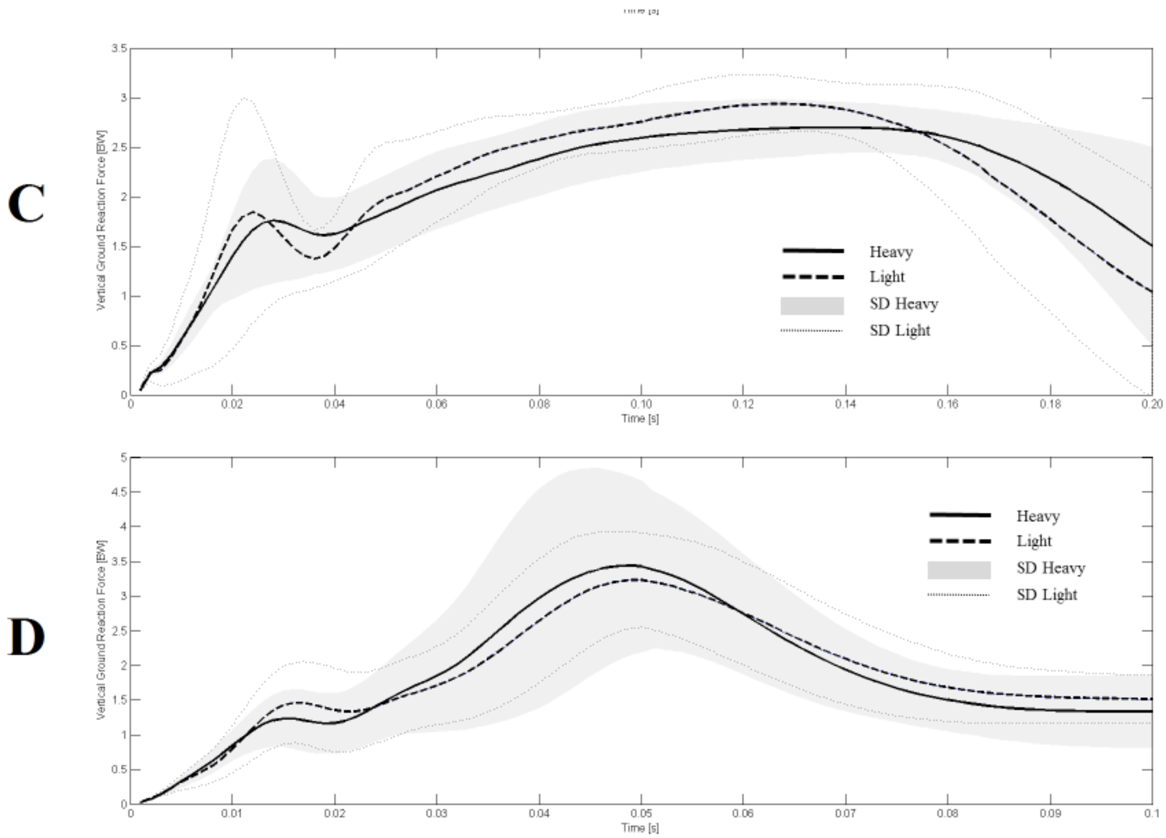
Descriptive statistics (mean and standard deviation) of kinetic and perceptual variables were computed across movement, group and shoe conditions. A 2 × 3 two-way (Body mass × Shoe) mixed factorial analysis of variance (ANOVA) was performed on each kinetic and perceptual parameter. Bonferroni corrected post-hoc tests were performed accordingly. The level of significance was set at $P < 0.05$ for all analyses. Greenhouse-Geisser's epsilon adjustment was used in all cases when Mauchley's test indicated that the sphericity assumption had been violated.

Results

The mean ensemble VGRF profiles of each movement between the heavier and lighter participants are compared in Figure 4. All participants were observed to adopt a toe-to-heel landing style from height while the first step of the layup was executed in a heel-to-toe manner.

Figure 4





During the first step of the layup, rearfoot loading rate in the heavy group was 40.7% higher than the light group (P = .014, Table 3). A significant shoe effect (P = .011) was also found in this phase of the layup, with the rearfoot loading rate found to be 12.4% higher in the hard shoe than the soft shoe. In shot-block, there was also a main effect of shoe (P = .011) with 7.7% higher peak forefoot force in the soft than the hard shoes. No shoe differences were found in peak VGRF or loading rates during layup landing or drop landing. No interaction of Body Mass × Shoe was detected for any kinetic variables.

*** Table 2 ***

Participants were able to discriminate forefoot and rearfoot cushioning intensity between at least two out of the three shoe conditions (soft vs medium, soft vs hard, medium vs hard) for all movements (Table 3). There was poor subjective discrimination between stability ratings for all movements, such that participants were only able to rate the hard shoe as higher rearfoot stability than the soft shoe during the performance of the layup ($P < 0.05$). In terms of overall comfort, both heavy and light groups preferred soft shoes compared to the hard shoe in the shot-block and drop landing movements regardless of body mass ($P < 0.05$).

*** Table 3 ***

Discussion

This study investigated the effects of body mass and shoe midsole hardness on impact forces and shock attenuation in basketball on a realistic playing surface. Alongside biomechanical loadings, perceptual responses of the player to changes in shoe midsole hardness were also studied. The main findings in the present study were: 1) there was little effect of body mass on force attenuation during basketball landing activities; 2) softer shoes did not necessary provide better force attenuation abilities than harder shoes, and 3) both heavy and light groups preferred softer shoes regardless of body mass.

VGRF profile across movements

The basketball layup is a complex movement comprising of a run-up, takeoff and landing phase. Previous studies on the layup have only focused on the landing phase (McClay et al., 1994). The current study added to the literature by considering also the impact forces associated with the run-up in order to fully understand the stresses on the body during the execution of the movement. Our results suggested that the VGRF pattern of the layup first step was similar to that during heel-strike running (Lieberman et al., 2010; Hamill & Gruber, 2012). For the landing of a layup, players experienced large impact forces exceeding 7 BW (Table 2, Figure 4). These VGRF values are slightly lower than the impact forces of up to 9 BW reported by McClay and colleagues (1994), which measured landing performance of professional National Basketball Association (NBA) players on metal-top force plate. It was highly possible that the discrepancy in VGRF measured in the present study was due to the different skill competency of our participants. The use of a wooden-top force plate might have also contributed to this difference to some extent. It is believed that the results of the present study would be representative of a larger population of competitive players using typical playing surface.

In both the shot-blocking and drop landing tasks, rearfoot peak VGRF was found to be more than twice the forefoot force. This is consistent with previous studies (Weinhandl, Smith, & Dugan, 2011; Zhang et al., 2005) reporting on landing movements where participants adopted a toe-to-heel landing style. Despite being a common defensive manoeuver, the impact forces associated with the shot-blocking in basketball have not been well documented. Previous investigations of similar movements included the jump-blocking in volleyball (Hughes, Watkins, & Owen, 2010; Salci, Kentel, Heycan, Akin, & Korkusuz, 2004) and stop-jump tasks (Chappell, Yu, Kirkendall, & Garrett, 2002; Yu, Lin, & Garrett, 2006). The magnitudes of VGRF found in the present study are in similar range with previous findings on the volleyball block (Hughes et al., 2010). This suggested that the mechanical demands of a shot-blocking in basketball are similar to that of a volleyball block. However, the kinematic characteristics of both movements might be different and further investigation is required.

Body mass effect on VGRF

The results of this study suggest that body mass has little effect on kinetics during basketball manoeuvres. Heavy players had higher rearfoot loading rate of the layup first step than the lightweight player. For all participants, the initial ground contact of the layup first step was made with the heel. This initial contact with the ground is also known as the impact phase of a step. Higher rates of loading during this impact phase have been found to correlate with higher incidences of lower limb injuries (Hamill, Miller, Noehren, & Davis, 2008; Pohl, Mullineaux, Milner, Hamill, & Davis, 2008). Therefore, heavy players might expose to a greater risk of lower limb injuries than lighter players when performing the layup first step. Due to the highly repetition in game situation, the first step of layup might be helpful to evaluate the impact activities in basketball.

This study attempted to determine the effect of body mass by recruiting two groups of participants with a mean body mass difference of approximately 30%. Previous studies investigating the effect of additional mass on VGRF variables during various jumping related activities have utilised either an external load (5-10%, Makaruk & Sacewicz, 2011) or pulley-system (10-40%, Leontijevic et al., 2012) to vary the total mass. Markovic and Jaric (2007) proposed a maximum dynamic hypothesis, which suggested that the muscular system of the lower limbs is designed to optimise dynamic output when loaded with an individual’s own weight. Based on this hypothesis, external loading would have likely reduced dynamic output, possibly through kinetic and kinematic alterations to movement. Therefore, this study sought to present a more valid assessment of the effect of body weight on kinetic variables by ensuring that the movement pattern of participants were not compromised by external influences such as the use of a weighted vest (Makaruk & Sacewicz, 2011). It was possible that heavier participants compensated for the additional body mass with an adaptation to landing technique. Since motion data were not captured in this study, future studies should include other measurements such as kinematics, joint loadings, and accelerometry to allow a more comprehensive analysis of the influence of body mass on landing mechanics and force attenuation.

A standard 8.5-kg drop mass from a 50-mm drop height was used in this study to quantify the mechanical cushioning performance of the test shoes. We acknowledge that the impact energy of this test is equivalent to the approximate mass of a 70-kg individual performing slow running, which may not truly reflect our heavier participants (mean body mass = 82.7 kg). Increasing the missile mass or drop height on the impact test may reveal additional insight into the cushioning capability of the test shoes in response to various mass. Nevertheless, the standard mechanical tests performed deem sufficient to characterise the general shoe properties and allow good comparison with other footwear studies.

Midsole hardness on VGRF

While most kinetic variables did not differ among the three shoes, forefoot peak VGRF was indeed higher in the soft shoe than hard shoe during the shot-blocking movement (Table 3). This result contradicts our hypothesis that softer shoes would provide better force attenuation. A possible explanation for this might be that the sole had ‘bottom-out’ during the landing from the movement. This ‘bottom-out’ out effect would have significantly reduced the shock absorption capability of the shoe (Shariatmadari, English, & Rothwell, 2012). While generally it would be difficult to ‘bottom-out’ the midsole for a normal shoe with an affixed midsole, the design of the test shoe in this study comprised of a removable midsole insert which may have contributed to this ‘bottom-out’ effect. Further investigation is warranted to confirm the relationship between midsole hardness and impact force attenuation. Nonetheless, these results suggested that decreased midsole hardness may display distinct cushioning performance at forefoot and rearfoot and thus the evaluation of midsole hardness should also take the mechanical impact scores into account in order for better judgement in footwear performance.

The lack of difference in VGRF variables between shoe conditions in the drop landing task was contrary to results reported by Zhang et al. (2005) who found that forefoot peak VGRF was significantly higher for normal (55 Shore C) and hard (70 Shore C) midsoles than the soft (40 Shore C) midsole during a drop landings from similar heights. In their study, however, a portion of the shoe lateral upper was cut to facilitate kinematic data collection. This alteration might have affected the participant’s landing technique as it has been found that the fit of the upper construction of a shoe significantly affects motion control (Van Gheluwe, Kerwin, Roosen, & Tielemans, 1999). It was possible that the similar impact characteristics reported for all midsole hardness conditions was due to the alteration of landing kinematics in each shoe condition during the movement. Landing in a harder shoe has been found to result in a higher initial pronation and pronation velocity, which in turn increases the deceleration distance; and subsequently decreases initial force (Nigg, Bahlsen, Luethi, & Stokes, 1987). Although the harder midsole would be expected to result in higher impact forces, the changes to initial landing kinematics would have produced changes opposite in direction (Nigg et al., 1987). If these changes were of a similar order of magnitude, little differences would be observed in landing VGRF between hardness conditions. Further investigation into landing kinematics, especially at the ankle and foot complex is warranted to better understand of the effect of midsole hardness on landing activities.

Perceptual variables

Both heavy and light groups preferred softer to harder shoes when executing basketball manoeuvres. The lack of between-group difference in any VAS variables suggests that perceptual responses to shoe cushioning intensity, stability level and overall comfort preference are independent of body mass.

Cushioning intensity was found to be consistently rated according to midsole hardness conditions. This finding is consistent with a previous study on heel-toe running which found clear subjective discrimination of three shoe hardness conditions (Sterzing et al., 2013). For both layup and drop landing, subjective discrimination of forefoot cushioning intensity was weaker with no differences found between medium and other shoe conditions, compared to rearfoot cushioning intensity. For both shot-blocking and drop landing tasks, the rearfoot peak VGRF was more than twice the forefoot peak VGRF, suggesting that a certain threshold of impact force may be required for neural feedback of the body before an individual can accurately differentiate shoe conditions.

While shoe stability is rated as one of the most important basketball footwear features (Brauner, Zwinzscher, & Sterzing, 2012), participants were only able to perceive the soft shoe to be more stable than the hard shoe during the layup movement but not the shot-blocking or drop landing. It was possible that a lateral movement component incorporated in the layup made it easier for players to assess and rate stability more effectively. This suggests that layup movement may be a useful protocol in evaluating footwear stability as the unilateral nature of the layup movement is expected to have higher demand in shoe stability than the other two landing tasks. To confirm this speculation, future studies should incorporate in-shoe plantar pressure and higher shoe demanding tasks such as cutting and shuffling.

Conclusion

This study showed that heavier players exhibited higher loading rate during the initial contact of the layup first step but not in other tested landing activities. This suggests that heavier players may be at a greater risk of suffering from lower limb injuries than lighter players, though risk factors other than loading rate must also be considered. Participants preferred softer than harder shoes regardless of body mass when executing basketball-related manoeuvres. Among different shoes, higher forefoot peak force was only observed in soft shoe during shot-blocking landing while rearfoot stability could only be differentiated during the layup, indicating that shot-blocking and layup may be more useful in evaluating basketball footwear than the traditional drop landing task.

Word Count: 4049 (main text)

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Figure Captions

Figure 1. Impact test and durometer measurements locations.

Figure 2. Sequence of three selected basketball manoeuvres: (a) layup, (b) shot-blocking and (c) drop landing.

Figure 3. Definition of kinetic variables extracted from vertical ground reaction forces (VGRF).

Figure 4. Mean ensemble vertical ground reaction force (VGRF) versus time profile of heavier and lighter participants: A. layup first step (right leg), B. layup landing (double-leg), C. shot-blocking landing (right leg), and D. drop landing (right leg).

Table 1. Dimensions and mechanical properties of tested shoes.

	Soft (38 Shore C)		Medium (42 Shore C)		Hard (57 Shore C)	
	Forefoot	Rearfoot	Forefoot	Rearfoot	Forefoot	Rearfoot
Midsole hardness [C]	38.4 (0.5)	37.2 (1.2)	41.0 (1.2)	41.4 (1.3)	57.2 (1.8)	57.6 (2.1)
Shoe thickness [mm]	19.0	30.0	19.0	30.0	19.0	30.0
Peak acceleration [g]	19.1 (0.1)	10.6 (0.0)	19.0 (0.2)	10.9 (0.1)	18.2 (0.1)	11.4 (0.1)

Table 2. Normalised kinetic variables during each movement task expressed in mean (standard deviation). All forces are in units of body weight [BW] and mean loading rates are in units of body weight per second [BW/s].

		Shoe Midsole Hardness			ANOVA results									
					Interaction			Body mass			Shoe			
		Soft	Medium	Hard	P	η_p^2	β	P	η_p^2	β	P	η_p^2	β	Post-hoc
Layup first step (right leg)														
F_F	L	1.91(0.26)	1.93(0.26)	1.87(0.22)	.114	.075	.440	.407	.025	.129	.480	.026	.170	-
	H	1.84(0.21)	1.83(0.21)	1.85(0.20)										
F_R	L	1.30(0.36)	1.32(0.35)	1.30(0.37)	.331	.039	.239	.089	.100	.398	.645	.016	.118	-
	H	1.53(0.41)	1.51(0.36)	1.58(0.39)										
LR_F	L	8.6(3.3)	8.6(3.2)	8.3(2.8)	.286	.044	.267	.736	.004	.063	.284	.044	.268	-
	H	8.4(2.9)	9.4(4.5)	8.9(3.9)										
LR_R	L	54.6(22.5)	57.6(22.4)	61.8(23.0)	.556	.021	.144	**.014**	.198	.717	**.011**	.149	.784	H>S
	H	78.8(32.6)	77.8(24.8)	88.2(30.5)										
Layup landing (double leg)														
F_{max}	L	7.29(1.73)	6.72(1.53)	6.98(1.73)	.076	.088	.514	.287	.040	.182	.600	.018	.131	-
	H	6.43(0.78)	6.69(1.08)	6.41(0.90)										
LR_m	L	213.9(108.4)	173.6(80.6)	191.5(106.9)	.132	.070	.414	.289	.040	.181	.446	.028	.183	-
	H	164.9(48.7)	176.6(55.6)	158.3(41.8)										
Shot-blocking landing (right leg)														
F_F	L	1.58(0.47)	1.55(0.44)	1.49(0.45)	.661	.015	.114	.100	.094	.375	**.011**	.148	.781	S>H
	H	1.34(0.37)	1.26(0.35)	1.25(0.41)										
F_R	L	3.31(0.61)	3.20(0.58)	3.17(0.56)	.430	.030	.190	.137	.077	.315	.100	.079	.465	-
	H	2.97(0.95)	2.73(0.68)	2.92(0.66)										
LR_F	L	95.6(28.2)	91.1(26.4)	93.2(25.9)	.475	.026	.172	.332	.034	.159	.122	.072	.429	-
	H	85.1(20.7)	81.9(19.1)	87.9(23.5)										
LR_R	L	108.5(42.1)	97.3(27.2)	97.3(27.2)	.546	.021	.147	.647	.008	.073	.105	.077	.456	-
	H	98.8(61.8)	86.4(46.4)	97.4(48.6)										
Drop landing (right leg)														
F_F	L	1.29(0.34)	1.17(0.25)	1.23(0.32)	.104	.078	.457	.124	.082	.334	.116	.074	.438	-
	H	1.09(0.19)	1.09(0.22)	1.08(0.20)										
F_R	L	3.33(0.63)	3.40(0.97)	3.29(0.63)	.206	.055	.330	.425	.023	.123	.319	.040	.246	-
	H	3.78(0.90)	3.45(1.05)	3.50(0.95)										
LR_F	L	96.1(32.0)	86.9(19.0)	94.2(31.8)	.821	.007	.079	.702	.005	.066	.065	.093	.541	-

	H	92.3(27.1)	85.9(19.1)	89.2(18.2)										
LR_R	L	122.4(46.4)	122.6(51.1)	120.9(48.5)	.301	.042	.257	.910	.000	.051	.260	.047	.285	-
	H	135.2(57.5)	117.5(56.2)	119.2(50.0)										

Note. L=light; H=heavy; F_F=forefoot peak force; R_F=rearfoot peak force; LR_F=forefoot mean loading rate; LR_R=rearfoot mean loading rate; F_{max}=maximum impact force; LR_m=mean loading rate; η_p^2=partial eta squared; β=observed power. Significant *p*-values ($P < .05$) are shown in bold.

Table 3.Perceptual variables during each movement task expressed in mean (standard deviation). All Visual Analogue Scale (VAS) ratings are expressed in millimetres [mm] on a 150-mm scale.

		Shoe Midsole Hardness			ANOVA results									
					Interaction			Body mass			Shoe			
		Soft	Medium	Hard	*P*	η_p^2	β	*P*	η_p^2	β	*P*	η_p^2	β	Post-hoc
Layup														
Forefoot Cushioning	L	97.9(29.7)	87.7(31.4)	77.7(28.5)	.749	.010	.094	.086	.102	.405	**.016**	.137	.742	S>H
	H	109.9(25.4)	102.5(35.0)	97.8(25.9)										
Forefoot Stability	L	104.4(24.0)	96.0(26.4)	98.9(23.1)	.637	.016	.121	.179	.063	.265	.588	.019	.134	-
	H	109.4(21.9)	108.7(27.9)	110.8(20.1)										
Rearfoot Cushioning	L	110.5(17.8)	105.1(31.6)	92.3(28.8)	.788	.008	.086	.320	.035	.165	**<.001**	.287	.990	S>H, S>M
	H	116.5(17.6)	115.5(21.6)	97.4(19.5)										
Rearfoot Stability	L	112.5(18.9)	103.6(23.2)	107.4(24.4)	.134	.069	.411	.538	.014	.092	**.035**	.113	.639	S>H
	H	116.7(19.4)	114.1(17.1)	104.4(15.6)										
Overall Comfort	L	111.7(24.4)	98.1(25.2)	104.1(25.5)	.681	.014	.109	.325	.035	.162	.053	.100	.574	-
	H	118.9(18.6)	108.9(27.4)	105.9(23.6)										
Shot-blocking														
Forefoot Cushioning	L	100.9(27.0)	85.9(29.3)	72.9(32.3)	.465	.027	.176	.104	.092	.368	**.001**	.227	.952	S>H, M>H
	H	107.4(29.0)	106.2(30.7)	89.5(30.3)										
Forefoot Stability	L	105.9(23.9)	96.6(28.1)	103.6(20.1)	.522	.023	.155	.353	.031	.149	.350	.037	.228	-
	H	111.1(19.0)	108.3(24.2)	106.1(20.8)										
Rearfoot Cushioning	L	114.7(20.3)	105.9(25.8)	85.7(25.5)	.727	.011	.099	.363	.030	.145	**<.001**	.483	1.000	S>M, S>H, M>H
	H	121.8(15.8)	108.9(22.6)	94.8(23.6)										
Rearfoot Stability	L	109.9(26.1)	102.3(25.8)	102.0(22.6)	.539	.022	.149	.548	.013	.090	.476	.026	.171	-
	H	108.9(17.1)	110.0(15.9)	107.3(22.0)										
Overall Comfort	L	113.7(23.2)	97.2(24.3)	95.5(28.0)	.405	.032	.201	.413	.024	.126	**.011**	.150	.787	S>H
	H	113.1(16.0)	110.1(28.8)	100.5(25.6)										
Drop landing														
Forefoot Cushioning	L	104.1(24.1)	82.7(29.0)	76.6(27.5)	.595	.018	.132	.421	.023	.124	**<.001**	.276	.986	S>H
	H	107.1(30.1)	89.7(37.7)	90.2(36.2)										
Forefoot Stability	L	102.7(25.5)	96.3(25.2)	101.5(20.8)	.629	.016	.123	.543	.013	.091	.465	.027	.176	-
	H	101.7(25.9)	102.5(26.2)	108.9(19.4)										
Rearfoot Cushioning	L	110.9(18.8)	98.9(26.2)	83.5(29.1)	.697	.013	.106	.553	.013	.089	**<.001**	.474	1.000	S>H, M>H, S>M
	H	117.1(19.3)	106.5(23.5)	84.2(34.1)										
Rearfoot Stability	L	103.5(20.4)	100.9(23.0)	107.8(22.3)	.710	.012	.103	.736	.004	.063	.696	.013	.106	S>M, S>H

	H	106.3(24.3)	106.1(19.2)	106.2(20.9)									
Overall Comfort	L	108.1(22.9)	90.3(25.1)	94.8(26.2)	.836	.006	.076	.472	.019	.108	**.008**	.160	.820
	H	113.3(24.1)	99.6(28.0)	97.1(31.0)									

Note. L=light; H=heavy; η_p^2=partial eta squared; β=observed power. Significant *p*-values (P <.05) are shown in bold.