

The Effect of Shoe Weight on Sprint Performance: A Biomechanical Perspective

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Received date: June 30, 2015; Accepted date: August 26, 2015; Published date: September 2, 2015

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Abstract

Background: The benefit of light-weight shoes for athletic performance has been recognized in both sport and professional environments. However, the biomechanical mechanism by which reduced shoe weight improves athletic performance is unknown. The aim of this study was to determine the effect of basketball shoe weight on performance and corresponding lower-extremity biomechanics for the example of a 10 m sprint start.

Methods: For twenty-two male recreational athletes, sprint start (3.7 m) and 10 m sprint performances were quantified from timing lights in three basketball shoe conditions (light=352 g; medium=510 g; heavy=637 g). Ground reaction forces and kinematics and kinetics of the lower-extremity joints during the first sprinting stride were determined using 3D-motion analysis and a force platform. A Support Vector Machine analysis and linear regression were performed to analyze biomechanical differences between the shoe conditions and their association with performance.

Results: Average sprint start and 10 m sprint times in the light shoe were significantly reduced compared to the heavy shoe by up to 24 ms (3%) and 32 ms (1.8%), respectively. The reduction in shoe weight led to significantly different ankle joint biomechanics with a 5% increase in peak plantar-flexion velocity in the light shoe that was associated with a decrease in sprint start time.

Conclusion: Lighter basketball shoes enhance sprint start performance, likely by facilitating faster ankle plantar-flexion during the first sprinting stride. This mechanism can promote player performance during important game scenarios and encourages further innovative light-weight shoe concepts not only in sports but also in working environments that require high athletic performance.

Keywords: Shoe weight; Sprint performance; Basketball; Sports biomechanics; Motion Analysis; Support vector machine

Introduction

The ability to start quickly and sprint fast is an essential factor for performance in a variety of sports. Specifically, the sprint start is of high importance in many field and court sports as they require fast acceleration during frequent high-intensity movements [1-3]. In basketball, 15% of the total playing time is spent in high-intensity activities, including up to 55 sprints per game. The vast majority of these sprints (73%) are shorter than 2 s, emphasizing the significance of fast sprint starts for the player's performance [2,4].

High performance in a sprint start results from maximal power generation at the lower extremity joints [5,6], determined by joint kinematics and ground reaction forces (GRFs). Optimizing these biomechanical variables may be achieved by providing appropriate sports equipment. In particular, the modification of shoe properties, such as the reduction of shoe weight, can improve athletic performance [7-9]. In basketball, a reduction in shoe weight led to an increase in jumping and shuffling performance by up to 2% [9]. In addition, basketball players in positions that demand frequent sprints and accelerations, tend to prefer light-weight shoes [10]. However, the effect of basketball shoe weight on sprint start performance is not well understood.

Intuitively, increased shoe weight would limit sprinting performance as the players must produce more mechanical work to accelerate and decelerate the additional mass of their shoes [11]. Further, modified shoe weight may predominantly affect mechanical work performed by the ankle joint, the most proximal joint to the intervention. In support of these assumptions, additional weight added to the feet during normal running increased mechanical work done on the feet and significantly modified ankle biomechanics [12]. For sprinting, however, there is a lack of knowledge regarding how a reduction in shoe weight modifies the biomechanics of the lower extremities and how such modifications relate to performance enhancement. A functional understanding of shoe weight effects on lower extremity biomechanics and the associated sprint start performance would be valuable as it would inform innovative shoe designs as well as training strategies for performance optimization.

Therefore, the purpose of this study was to determine the effect of basketball shoe weight on performance and lower extremity biomechanics during a sprint start. It was hypothesized that:

- (H1) Reduced shoe weight results in increased sprinting performance.
- (H2) Reduced shoe weight results in modified lower extremity kinematics and kinetics, predominantly at the ankle joint.

Materials and Methods

This study was part of a larger research project investigating the effects of basketball shoe weight on performance and lower extremity biomechanics during basketball-related movements. A detailed description of the study design and experimental protocol has been published previously [9].

Participants

Twenty-two male, recreational athletes (mean \pm SD; age 26 ± 3 years, body mass 72.1 ± 8.6 kg, height 1.77 ± 0.07 m, vigorous physical activity 8 ± 3.4 hours/week) volunteered and gave their written informed consent to participate in this study. Participants were male, physically active (>3 hours of vigorous physical activity per week), experienced in sports that require frequent sprint starts (i.e., >2 years of involvement in basketball, soccer, tennis, squash, or football within the last 5 years) and free from lower extremity injury in the past 6 months. Female athletes were excluded from this study in order to avoid previously demonstrated gender effects on lower-extremity biomechanics during running [13]. Ethical approval for research involving human participants was obtained from the University of Calgary's Conjoint Health Research Ethics Board, in spirit of the Helsinki Declaration.

Study design

Custom-made fabric bags of different weights were attached to identical pairs of basketball shoes to provide a light (mass per shoe: 352 ± 18 g), medium (510 ± 17 g), and heavy (637 ± 18 g) shoe condition. The range of shoe weights corresponds to the upper and lower weight limits of currently available basketball shoes. The visually identical fabric bags were filled with either plastic pellets, metal pellets or a mixture of both to achieve similar volumes but different weights. The weight bags were strapped around the shoe heel using velcro strips and additional laces to prevent any relative movement between shoe and bag (Figure 1). Pilot tests confirmed that relative movements between shoe and bag did not occur for the light or heavy condition.



Figure 1: Test shoe with attached weight bag.

Participants were randomly assigned to two groups in an experimental study design. Of the 24 participants recruited, 12 were

assigned to the "aware" group, while 12 were assigned to the "blind" group (Table 1). Two participants in the blind group did not complete the study reducing the size of the blind group to 10. Participants in the blind group were not informed about the study intervention while shoe weight differences were disclosed to the aware group. A questionnaire confirmed that the "blind" group was unable to differentiate between shoe conditions during exercise [9].

Experimental protocol

After a standardized warm-up program, each participant performed six 10 m sprints in each of the three shoe conditions in a balanced randomized order. Participants were instructed to accomplish these tasks at a maximum level of effort starting from a static standing position with their non-dominant leg in front and the contralateral leg behind the start line. A standing sprint was selected to represent an activity that would reflect movements experienced in actual competition. The start and finish lines were marked with timing gates. A third timing gate was set up in a distance of 3.7 m from the start (Figure 2b). The dominant leg was determined as the participant's preferred leg to kick a ball. Participants were asked to maintain a defined starting posture for all trials and conditions. Participants were free to choose the start of each sprint trial and were only instructed to hit a force platform embedded within the floor during their first stride of the dominant leg (Figure 2a). The rationale of analyzing the dominant leg was to capture each participant's maximum performance during the first sprinting stride. As field sport athletes gradually develop more beneficial muscle architecture within the dominant leg [14], it was assumed that push-off performance would be greatest on the dominant side. After each trial the subjects cleaned their shoes on first a wet and then a dry towel to maintain a consistent level of traction and to avoid slipping. Participants were given rest periods of 90 s between trials to avoid fatigue.

Data collection

The timing gate system provided two performance outcomes: Sprint time for the 10 m distance (10 m sprint performance) and sprint time for the 3.7 m distance (sprint start performance). 3D-kinematics and GRFs of the first stride of the dominant leg were collected using a high-speed motion analysis system (8 cameras/240 Hz; Motion Analysis Corporation, Santa Rosa, CA, USA) and a force platform (2400 Hz; Kistler), respectively. 13 retro-reflective markers were mounted above the right and left side of the anterior and posterior iliac spine, thigh, shank, and shoe and recorded during each first stance phase. In addition, static recordings of the participants in an upright standing position were made after mounting additional markers over the greater trochanter, medial and lateral knee and ankle joints to define joint centers.

Data processing

The raw marker trajectories were reconstructed using Cortex software (Motion Analysis Corp., Santa Rosa, CA, USA) and imported into KinTrak software (Human Performance Laboratory, Calgary, Canada). Both kinematic and GRF data were filtered using a fourth-order Butterworth low-pass filter with cut-off frequencies at 12 Hz and 50 Hz, respectively. Filtered kinematic data and synchronized GRFs were used as the input for an inverse dynamics model in order to calculate joint angular velocity, moments and power in the sagittal plane for the ankle, knee and hip joint. Each biomechanical variable was time-normalized to the duration of the stance phase of the first

sprinting step. The instant of initial foot contact and toe-off were determined from the vertical GRFs (threshold 20 N). In addition, each kinetic variable was amplitude-normalized to the body weight of the

corresponding participant. Due to poor recording quality of kinematic data, two participants in the aware group had to be excluded from the biomechanical analysis.

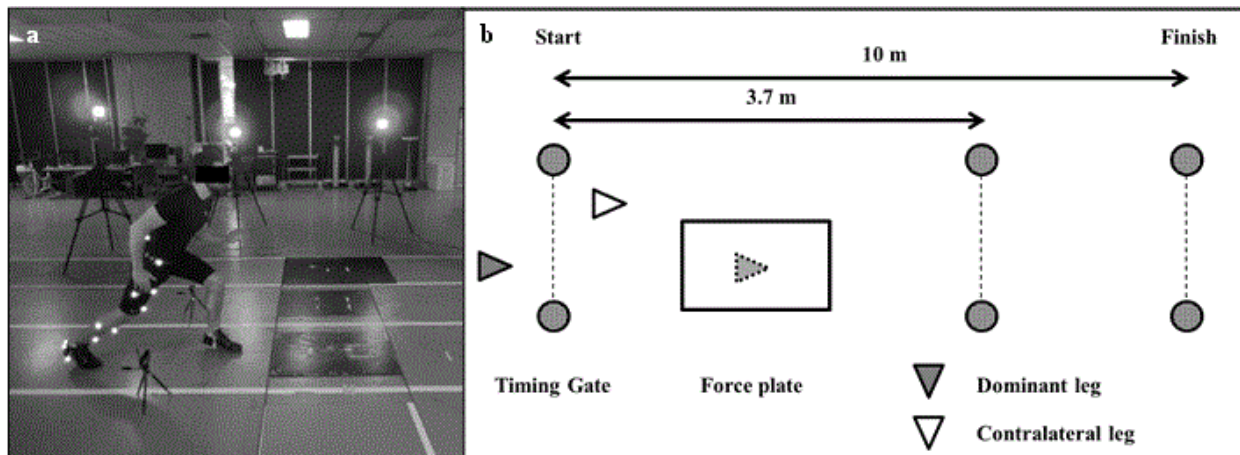


Figure 2: (a) Participant before sprint start, (b) Schematic of sprinting task.

Experimental Group	n	Age [years]	Height [cm]	Weight [kg]	Shoe size [US]	Vigorous activity [Hours / week]
Blind	10	25.7 ± 4.6	176 ± 5	72 ± 11	10.0 ± 0.7	8.0 ± 4.5
Aware	12	25.3 ± 2.2	177 ± 9	72 ± 7	9.9 ± 0.9	8.0 ± 2.3
Overall	22	25.5 ± 3.4	177 ± 7	72 ± 9	10.0 ± 0.8	8.0 ± 3.4

Table 1: Group descriptives (Mean ± SD).

Data analysis

A Support Vector Machine (SVM) was used to analyze differences in biomechanical variables between the shoe conditions. Only sprinting trials in the light and heavy shoe were considered as the SVM analysis only permits comparisons between two conditions. The light and heavy shoe conditions were selected because the shoe weight effect on performance and biomechanics was expected to be most prominent and detectable between these conditions. The SVM is a vector-based supervised pattern recognition technique that separates the input data by determining an optimal separating hyperplane between the data [15,16]. Using a SVM has the advantage that several time-continuous variables can be analyzed at once and compared between two groups without subjectively pre-selecting certain discrete time points. This avoids the risk that selected discrete time points may not be sensitive to potential differences between the compared groups [17]. For the purpose of this study, biomechanical differences between the light and heavy shoe were only considered relevant if they relate to the performance outcome. Previous research and sprinting coaches have mainly suggested the following variables to promote sprint start performance: High vertical and propulsive GRFs [18,19] and high angular velocities of the lower-extremity joints in the sagittal plane [20–22], leading to a high concentric joint power (joint moment x joint angular velocity) [5]. Therefore, the input for the SVM was a data matrix containing data rows, of individual trials and data columns of time-normalized waveforms of 11 biomechanical variables: Vertical and anterior-posterior GRFs, and sagittal angular velocities, moments

and power of the ankle, knee, and hip joint. The waveforms were arranged in series so that each individual sprinting trial consisted of 1100 data points (11 Variables * 100 normalized data points for one stance phase). Consequently, the input matrix had the following dimensions: 240 rows (20 participants * 12 trials) x 1100 columns. For the comparison between trials in the light and heavy shoe condition, classification rates using a leave-one-out cross-validation approach were determined [17]. In addition, the SVM provides a discriminant vector that is perpendicular to the separating hyperplane and indicates the most prominent differences between the two conditions. A high loading of the discriminant for a specific variable is the result of a consistent difference across participants in the input data between the compared conditions. Therefore, the absolute discriminant loadings for each variable were summed across the stance phase. This approach allowed us to quantify the type of variable (forces, velocity, moment, power) and the lower extremity joint that showed the most prominent differences between the light and heavy condition. The projections of the input data onto the discriminant vector were used to reconstruct the mean waveforms for each variable and to visually demonstrate biomechanical differences between the light and heavy shoe condition.

Statistical analysis

The three fastest trials, i.e., the three lowest times for each participant and condition for both the sprint start and 10m sprint were retained for further analysis. A linear mixed effects model [23] was used to examine the effects of 'shoe weight' and 'group' on 10 m and

sprint start times as well as 'shoe weight by group' interaction effects. 'Shoe weight', 'group' and 'shoe weight by group' interactions were considered fixed effects while subject was treated as a random effect. This procedure allowed accounting for the within-subject variability across three trials for each condition as opposed to aggregating the data to one mean value and losing this information. The model also accounted for the correlation between trials from the same subject, thus avoiding the violation of independence assumptions. Bonferroni corrected post-hoc tests were carried out to determine pairwise comparisons between the shoe conditions. For SVM results, a two-stage binomial test procedure were applied to determine whether the classification rates were higher than chance to indicate significant differences between the biomechanical input data. According to a binomial distribution with a success probability of 0.5, the

classification of one subject was considered statistically significant if at least 9 out of 12 trials were classified correctly. The overall classification was considered significant if at least 14 out of the 20 subjects were correctly classified. The biomechanical variable that was most affected by shoe weight differences was used as an independent variable in a simple linear regression analysis with sprint start time as the dependent variable. For this analysis, the means of the respective biomechanical variable and sprint start performance were calculated for each subject across all trials and conditions. All statistical tests were carried out using IBM SPSS statistics (v.20; SPSS Inc., Chicago, IL) using a significance level of $\alpha=0.05$.

Results

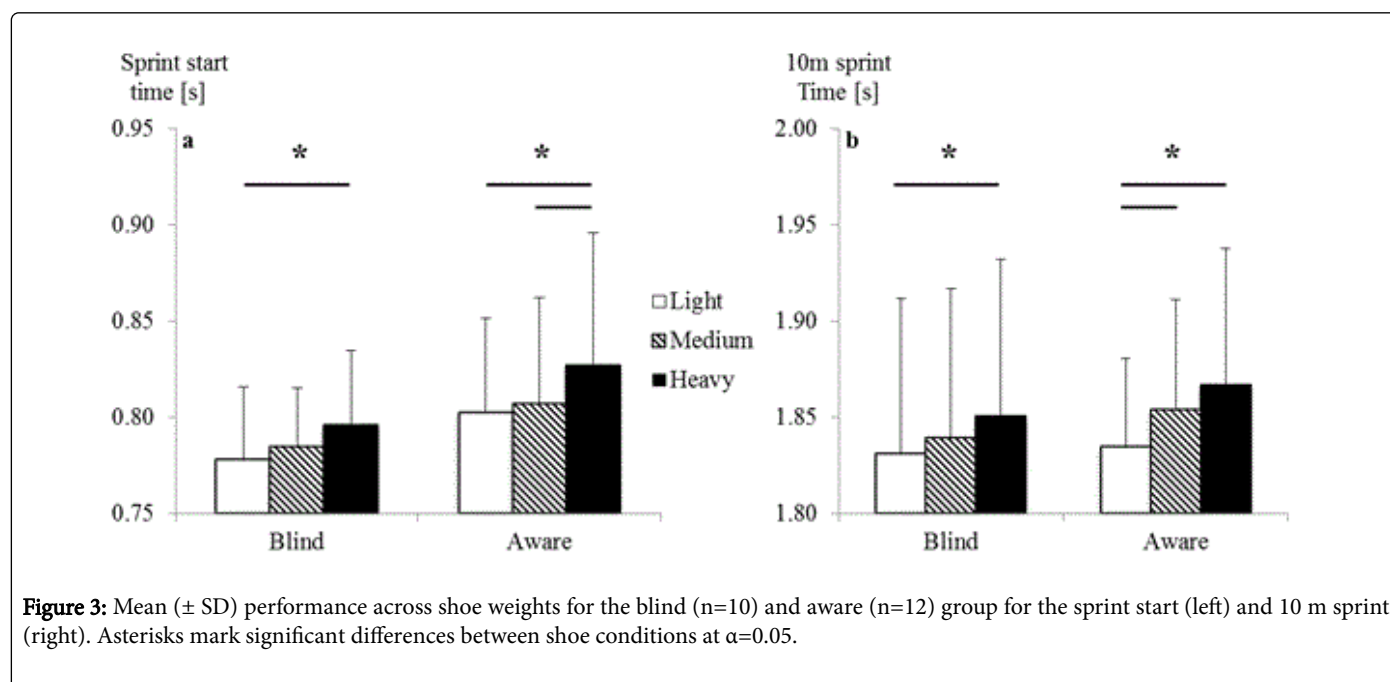


Figure 3: Mean (\pm SD) performance across shoe weights for the blind (n=10) and aware (n=12) group for the sprint start (left) and 10 m sprint (right). Asterisks mark significant differences between shoe conditions at $\alpha=0.05$.

Performance

The sprinting times (mean \pm SD) for each task, shoe condition, and group are displayed in Figure 3. Shoe weight had a significant main effect on both sprint start ($P<0.001$) and 10 m sprint times ($P<0.001$). There was no significant interaction effect between "group" and "shoe weight" for the sprint start ($P=0.435$) or 10m sprint ($P=0.476$). There was no significant main effect of "group" on sprint start ($P=0.24$) or 10 m sprint times ($P=0.694$). For the sprint start, average sprinting times in the blind and aware group were significantly reduced by 2.3% ($P=0.013$) and 3% ($P<0.001$) in the light shoe compared to the heavy shoe. Similarly, for the 10 m sprint, average sprinting times in the blind and aware group were significantly reduced by 1.1% ($P=0.046$) and 1.8% ($P<0.001$) in the light shoe compared to the heavy shoe. In addition, in the aware group, sprinting times were significantly reduced in the medium compared to the heavy shoe (2.4%, $P<0.001$) for the sprint start and in the light compared to the medium shoe (1.1%, $P=0.046$) for the 10m sprint. The high magnitudes of the standard deviations, as apparent from Figure 3, result from the natural between-subject variation in sprinting times in a repeated measures design.

Biomechanics

For the biomechanical analysis, only sprinting trials in the light and heavy shoe were considered (see Data Analysis). Further, due to the absence of an interaction effect on performance between the aware and the blind group, the biomechanical analysis was performed for one group including all participants.

The average classification rate of the SVM across all participants was 81.67%. For 16 out of 20 participants, at least 9 out of the 12 trials were correctly classified leading to a significant classification (Figure 4a). Figure 4b shows the sum of the discriminant loadings for each biomechanical variable as well as the overall mean loading on the discriminant. The five variables that were most affected (higher than overall mean) by the change from the light to the heavy shoe were the ankle angular velocity, ankle moment, anterior-posterior force, knee velocity, and hip power. The mean reconstructed waveforms for the light and heavy condition and the corresponding discriminant loadings for these variables are displayed in Figure 5. The most affected biomechanical variable, mean ankle angular velocity was decreased in the light shoe during the dorsiflexion phase in the first 50% of stance and increased during the plantar-flexion phase in the second 50% of stance, particularly before push-off (Figure 5a). The mean horizontal

breaking force was increased in the heavy shoe condition while there was no consistent trend between the shoe conditions for the horizontal propulsion force (Figure 5d). There was a consistent increase in knee flexion velocity during the first 40% of stance in the light shoe (Figure 5e). Hip power was most significantly affected for the first 10% of stance where the light condition demonstrated an increase in mean hip power (Figure 5f).

Mean peak plantar-flexion velocity significantly predicted mean sprint start time ($p < 0.001$, $R^2 = 0.173$). An increase in peak plantar-flexion velocity predicted a decrease in sprint start time, corresponding to an increase in performance (Figure 6).

Discussion

The effect of basketball shoe weight on performance and lower extremity biomechanics was investigated during a sprint start. The results support our hypotheses, that there would be a significant increase in sprint start performance with decreasing shoe weight and that a reduction in shoe weight would predominantly lead to modifications of ankle joint biomechanics

Performance

The current study was conducted with two different groups; one group that was blinded to the intervention and one group in which shoe weight differences were disclosed. Such a study design is essential to differentiate between isolated shoe effects and psychological effects due to expectancies towards the study intervention [9,24]. Both groups showed a performance increase by up to 3% in the light shoe compared to the heavy shoe during the sprint start and 10 m sprint. In the blind group, the performance increase was present despite the fact that participants were not able to perceive weight differences between the shoes. This supports our first hypothesis that reduced basketball shoe weight enhances sprint start performance. Nevertheless, the results of the aware group may better represent the benefit of light shoes for sprint start performance as they reflect a real-world scenario, in which athletes purposely select their shoes based on criteria like shoe weight [25]. Interestingly, for both the sprint start and the 10m sprint, average times were reduced by 25 ms in the light shoe compared to the heavy shoe. This indicates that the performance benefits of the light shoe primarily occurred within the first two or three steps of the sprint start and were carried on to the 10 m mark.

While the results are in agreement with previous studies demonstrating the performance benefit of lightweight shoes during running [7,26,27] other studies have reported no effects of lighter soccer shoes on running performance [28]. However, this is most likely due to the small weight reduction of only 70 g that was investigated in the soccer study. In basketball, the weight of available shoes on the market varies by up to 300 g, which is reflected by the shoe conditions selected for this current study. Our findings show that a weight reduction as small as 150 g can lead to improvements in sprint start performance by 2.4% with even greater improvements by 3% for weight reductions of 300 g. For a basketball player, a 3% increase in sprint start performance could mean being 25 ms faster than an opponent resulting in a successful fast break or chase for a ball. In addition to practical applications in sports, the effects of reduced shoe

weight on sprinting performance should also be considered for the design of shoes in professional environments, e.g., fire-fighter boots. In fact, reduced weight of fire-fighter boots have been shown to lead to improved fire-fighter performance, i.e., decreased metabolic cost and reduced likelihood of tripping during an obstacle course [29,30]. Enhanced sprinting performance may be an additional benefit of reduced shoe weight that encourages light-weight boot concepts for fire-fighters.

Biomechanics

The lower extremity biomechanics and GRFs during the first sprinting stride of participants performing in the light or heavy shoe were significantly different and could be classified correctly for more than 75% of the sample. The sagittal ankle joint angular velocity was the biomechanical variable that was most affected by the reduction in shoe weight. These results support our second hypothesis that a reduction in shoe weight leads to modified lower extremity biomechanics during a sprint start, with the ankle joint being most affected. During a sprinting stride, the ankle joint produces an exclusive plantar flexor moment (Figure 5b).

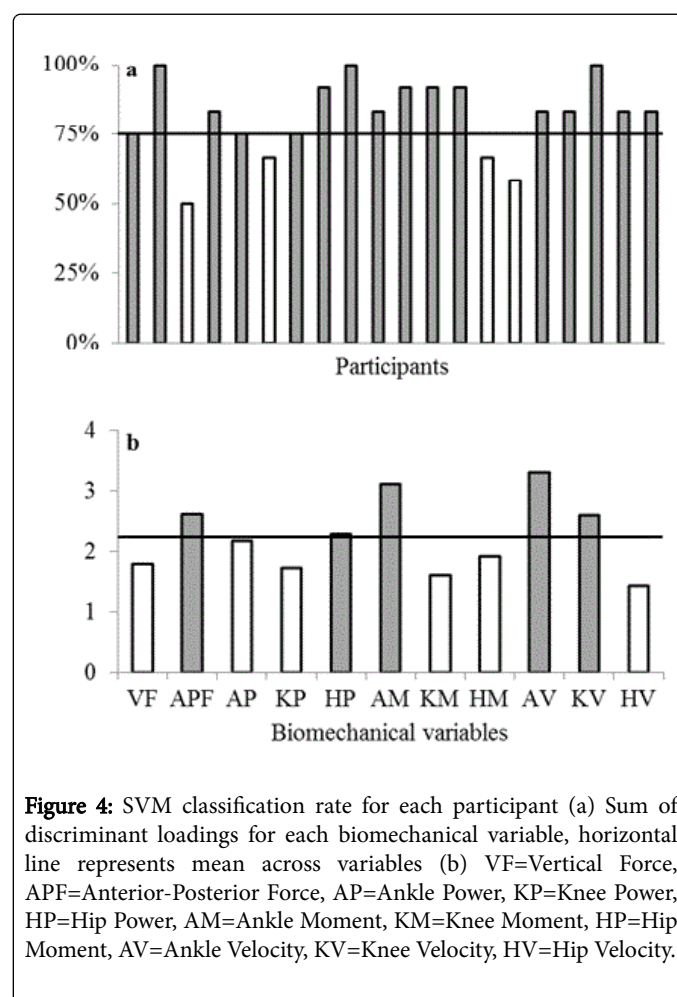


Figure 4: SVM classification rate for each participant (a) Sum of discriminant loadings for each biomechanical variable, horizontal line represents mean across variables (b) VF=Vertical Force, APF=Anterior-Posterior Force, AP=Ankle Power, KP=Knee Power, HP=Hip Power, AM=Ankle Moment, KM=Knee Moment, HM=Hip Moment, AV=Ankle Velocity, KV=Knee Velocity, HV=Hip Velocity.

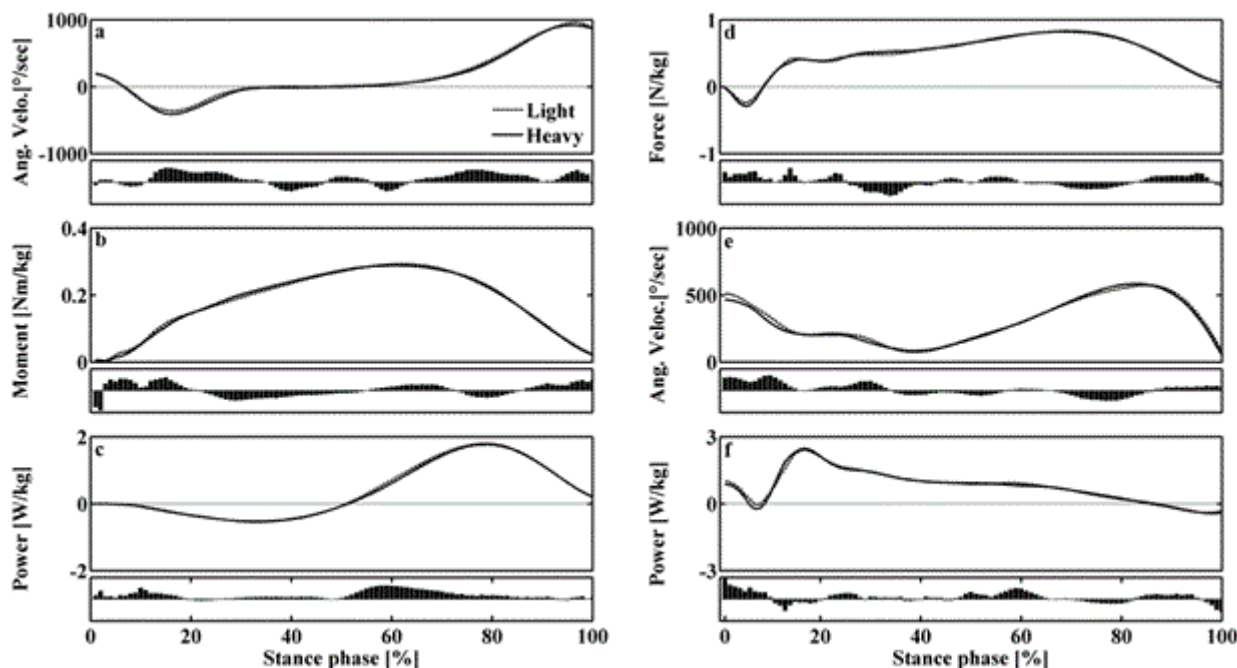


Figure 5: Reconstructed mean waveforms (n=20) for the light (dotted line) and heavy (solid line) shoe during the stance phase of the first sprint start stride (top panel) and mean SVM discriminant loadings (bottom panel) for ankle angular velocity (a), ankle moment (b), ankle power (c), horizontal ground reaction force (d), knee angular velocity (e), hip power (f). Positive values represent ankle plantar-flexion, propulsion forces, knee flexion, and hip extension. Note that positive discriminant loadings represent higher values in the light shoe.

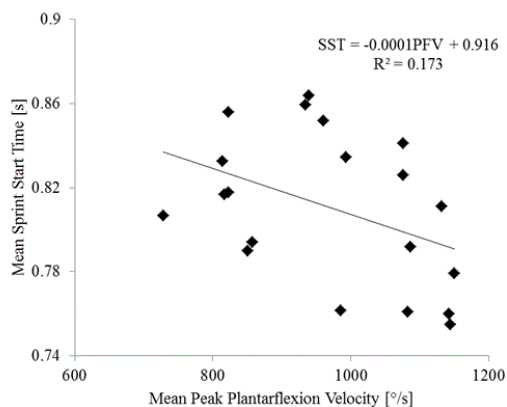


Figure 6: Simple linear regression between mean peak plantarflexion velocity (PPF) and mean sprint start time (SST).

Therefore, the dorsiflexion phase in the first 50% of stance represents energy absorption (negative joint power) while the plantar-flexion phase in the second 50% of stance represents energy generation (positive joint power) [31]. In the light shoe, the dorsiflexion velocity was decreased while the plantar-flexion velocity was increased compared to the heavy shoe. It can be speculated that the additional shoe mass of the heavy shoe led to a faster heel drop after ground contact and limited the acceleration of the heel before push-off. These changes in ankle angular velocity in the light shoe likely led to a

slightly decreased negative power (lower energy absorption) after ground contact and an increased positive power (higher energy generation) before push-off (Figure 5c). This was confirmed by an additional discrete analysis, showing a significant increase in average peak plantar-flexion velocity (5%) and resultant energy generation (15%) at the ankle joint in the light shoe compared to the heavy shoe.

Sprint start performance is highly correlated with the production of horizontal propulsive forces during ground contact [22]. In order to achieve high propulsive forces, athletes have to generate maximum joint power at the hip, knee and ankle joint in a proximal to distal order [5,6,22]. Since the ankle transfers the power generated by the leg to the ground before push-off, it plays an important role for high horizontal sprinting velocities [5]. Therefore, the increase in plantar-flexion velocity and corresponding ankle power in the light shoe compared to the heavy shoe during the second 50% of the stance phase might explain the increased sprint start performance in the light shoe. This assumption was confirmed by a significant correlation between the peak plantar-flexion velocity before push-off and sprint start performance. Peak plantar-flexion velocity explained 17% of the variance in sprint start time, which generally corresponds to a low correlation. However, one would not expect ankle angular velocity to primarily predict sprint start time since other variables such as hip extension velocity during the stance phase [21,22] or other joint power variables during the recovery phase [32] also contribute to the performance outcome. Regardless, the role of ankle plantar-flexion velocity should be considered when designing shoe technologies or training programs with the goal to optimize sprint start performance in court-sport athletes such as basketball players. In fact, high-velocity

training programs that involve fast ankle plantar-flexion exercises have been shown to improve sprint start performance [33].

In addition to modified ankle joint biomechanics, the reduction in shoe weight also led to a decrease in horizontal breaking force and an increase in initial knee flexion velocity and hip extension power after ground contact. A decrease in horizontal breaking force after ground contact has traditionally been suggested to improve sprint start performance [20,34]. Furthermore, increased knee flexion and hip extension, representing a more “active touchdown”, might reduce horizontal breaking forces [20]. Consequently, the reduced horizontal breaking forces, as a result of a more active touchdown in the light shoe, indicates a second mechanism of how lighter shoes have the potential of improving sprinting performance. It may be speculated that the additional mass of the heavy shoe, associated with a higher momentum of the foot during the swing phase, could not be sufficiently decelerated before ground contact, resulting in a higher horizontal breaking impulse. However, since other authors have reported very low correlations between the horizontal breaking force and sprinting velocity [22], future studies have to further investigate this mechanism, particularly by examining the biomechanics of the swing leg.

Limitations

For the purpose of this study, sprint start performance was determined based on linear 10 m sprints from a standing start position. In field and court-sports such as basketball, sprint starts may often include changes in direction, flying starts, or initial turns. However, these scenarios are difficult to standardize and varying skill levels between participants might blur a shoe effect. In addition, the generalizability of this study’s findings to the maximum velocity phase of a sprint might be limited as it considerably differs from the early acceleration phase with respect to force and kinematic patterns [34]. Finally, due to the weight bag located at the rear part of the shoes, the weight distribution of the test shoes did not perfectly represent the weight distribution of basketball shoes available on the market. However, by adding the weight close to the rear outer sole and around the ankle joint – the main weight sources in basketball shoes – the shoe modifications were designed to mimic shoe weight increases in a real-world scenario as closely as possible while keeping other shoe properties constant.

Summary and Conclusion

A reduction in basketball shoe weight led to an increase in sprint start performance by up to 3% corresponding to a reduction in sprinting times by 25-30 ms. In a basketball game, this additional time could positively influence important game scenarios. A biomechanical analysis revealed that the performance benefit of a light shoe during a sprint start may be explained by two mechanisms: (1) Optimized ankle joint biomechanics and (2) Reduced horizontal breaking forces. Specifically, the reduced mass of the light shoe was speculated to facilitate higher ankle plantar-flexion velocities before push-off leading to a higher energy generation in the ankle joint and subsequently higher propulsive forces. Accordingly, peak plantarflexor velocity was significantly associated with the sprint start time. This study mainly addresses shoe manufactures that are encouraged to further improve light-weight shoe concepts for court-sport athletes such as basketball players but also for workers who rely on high athletic performance, e.g., fire-fighters. In addition, the identified role of ankle plantar-flexor velocity for the sprint start might be valuable knowledge for coaches

with the goal to improve sprint start performances of court-sports teams.

Acknowledgements

The authors would like to thank Adidas International for providing the testing shoes. The results of the current study do not constitute endorsement of the product by the authors or the journal. The authors would also like to thank Dr. Tak Fung for his support with statistical analyses. The authors declare no conflict of interest.

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This article was originally published in a special issue, entitled: "**Ergonomics Consideration For Footwear**", Edited by Rami Hashish, Los Angeles