KINEMATICS AND KINETICS OF BAREFOOT, SHOD, AND SPIKED SPRINTING DURING ACCELERATION AND AT MAXIMUM SPEED

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The purpose of this study was to analyze biomechanical differences between footwear conditions during acceleration and sprinting at maximum speed. Competitive sprinters (n=17) completed 60-m sprints barefoot, in running shoes, and in spiked sprint shoes in a randomized order. Fifty-four force plates (1000 Hz) obtained ground reaction forces over 50 m. Main effects between phases were found in all nine spatiotemporal and kinetic variables ($p<0.001$, $\eta_p^2 \geq 0.728$). Differences in braking and propulsive forces and impulses between footwear conditions seemed larger during acceleration ($p<0.001$, $\eta_p^2=0.38$–0.57) than at maximum speed ($p<0.15$, $\eta_p^2=0.11$–0.38). The findings underlined the importance of kinetic analysis across different sprint phases. Footwear effects on forces and associated joint loads may be considered in the management of overload injury risks.

KEYWORDS: biomechanics, footwear, 3D forces, GRF, impulse, performance, running.

INTRODUCTION: Running and sprinting are required in many recreational sport disciplines and greatly contribute to motor development (Mizushima et al., 2021). Those fundamental activities are associated with loads and impacts that translate to increased joint forces (Alexander et al., 2022), especially in sprinting due to higher speed (Kyröläinen et al., 1999). Footwear affects force-time profiles and kinematic movement patterns because cushioning and bending stiffness in footwear contribute to the absorption and transfer of forces (Rodrigo-Carranza et al., 2022).

Barefoot running, on the contrary, provides no external support in cushioning and bending stiffness. However, barefoot running has emerged as a trend after reports of increased performance and decreased injury occurrence (Davis, 2014). Studies documented higher sprint velocity, reduced angular range in the metatarsophalangeal joint, and greater energy generated during push-off in spike-shod sprinting than in barefoot sprinting (Smith et al., 2014; Toon et al., 2009). On the other hand, Mizushima et al. (2021) reported that long-term effects of barefoot running transfer to sprinting, reducing ground contact time, increasing flight time, and altering foot strike patterns. Such effects were interpreted as beneficial for sprint performance, which may represent one reason for the increasing popularity of barefoot interventions (Davis, 2014). However, the causality of these associations was questioned, arguing that some effects may be by-products instead of determinants of performance (Folland et al., 2017).

As shown, interpretations of these biomechanical effects and their influence on sprint performance have been controversial. Furthermore, the understanding of kinetics during accelerated sprinting is limited as many studies investigated effects on sprint time without analyzing ground reaction forces (GRF) (e.g., Mizushima et al., 2021). A practical obstacle is that force platforms are expensive and, typically, not available in large numbers. As a result, only few studies obtained GRF during sprinting, mainly for only a single step at a specific location (e.g., Smith et al., 2014; Toon et al., 2009). However, mechanics change over the time of an accelerated sprint due to increasing movement speed (Kyröläinen et al., 1999). Therefore, it is reasonable to presume mechanical effects of different footwear conditions during different phases of sprinting.

The objective of the study was to investigate effects of barefoot, shod, and spiked conditions on sprint time, spatiotemporal characteristics, and kinetics throughout the entire acceleration phase and at maximum speed in 60-m sprinting. We hypothesized differences in sprint time and biomechanical determinants between footwear conditions during different sprint phases.

METHODS: Seventeen male competitive sprinters (age: 19.5±1.4 years, body height: 1.73±0.06 m, body mass: 66.8±4.5 kg, personal best 100-m sprint time: 11.2±0.4 s) participated in the study. A-priori power analysis via G*Power 3.1.9.7 revealed that the sample size achieved statistical power of 80% to detect effects of f≥0.32 (i.e., η_p^2≥0.09) at a significance level of p<0.05. All participants were free of injuries and signed written consent. In accordance with the Declaration of Helsinki, the study was approved by the local ethics committee.

Each participant completed a self-selected general and sprint-specific warm-up before performing three 60-m sprints (i.e., barefoot, regular running shoes, spiked sprint shoes) in a randomized order. Participants took approximately 10-min breaks between sprints to prevent fatigue. Sprint time was measured via a photocell system (TC Timing System; Brower Timing Systems, Draper, UT, USA) at the 30-m and 60-m marks. At a sampling frequency of 1000 Hz, 54 force platforms (TF-90100, TF-3055, TF-32120, Tech Gihan, Kyoto, Japan; measurement error<1%, crosstalk<2%) obtained 3D GRF and the point of force application over the first 50 m, including the starting position.

For each step, the following variables were derived with the threshold of 20 N of the vertical force detecting touchdown and toe-off: step length (i.e., antero-posterior distance between the previous and current step's center of pressure locations at toe-off) and frequency (i.e., 1 divided by the time between current and previous step's touchdowns), ground contact and flight times (i.e., the durations of foot contact and no foot contact with the ground, respectively), braking and propulsive mean forces and impulses (i.e., anteroposterior direction, normalized to body mass). Instantaneous movement speed at each step was calculated as the distance between the current and the previous steps' last ground contacts divided by the time between the steps. The distance, at which maximum speed was determined, defined the transition from acceleration to maximum-speed phase. Each variable's mean of the steps of each phase was calculated for further analysis.

Statistical analysis was conducted via Office Excel 2021 (Microsoft Corporation, Redmond, WA, USA) and PASW Statistics 18 (SPSS Inc, Chicago, IL, USA). Data were presented as mean±standard deviation. Normal distribution and sphericity were assessed via Shapiro-Wilk and Mauchly's tests. Two-way analysis of variance (ANOVA) with repeated measures examined effects of conditions (barefoot, shod, and spiked) and phases (acceleration and maximum-speed). Effect sizes were expressed as partial eta squared (η_p^2). Significance level was set at p<0.05.

RESULTS: Across all trials, participants reached maximum speed within 32.2–44.0 m (barefoot), 30.2–44.2 m (shod), and 30.6–43.1 m (spiked) (p=0.301, η_p^2=0.072, 1-β=0.253). This corresponded with 23.7±2.7 and 5.6±2.0 steps measured during acceleration and at maximum speed, respectively, across all footwear conditions. Descriptive statistics of all variables and main effects of conditions for both phases were presented in Table 1. Main effects of phases were significant (p<0.001, η_p^2≥0.728, 1-β=1) for all variables. Interactions (phases*conditions) were documented for step length (p<0.05, η_p^2=0.213, 1-β=0.709), flight time (p<0.05, η_p^2=0.179, 1-β=0.609), and propulsive impulse (p<0.01, η_p^2=0.289, 1-β=0.878). No interactions were found for speed (p=0.121, η_p^2=0.124, 1-β=0.425), step frequency (p=0.856, η_p^2=0.006, 1-β=0.061), contact time (p=0.149, η_p^2=0.112, 1-β=0.385), braking force (p=0.585, η_p^2=0.033, 1-β=0.132), propulsive force (p=0.527, η_p^2=0.039, 1-β=0.150), and braking impulse (p=0.841, η_p^2=0.011, 1-β=0.075).

Table 1: Mean±standard deviation of all variables in barefoot, shod, and spiked conditions during acceleration and at maximum speed, including ANOVA results for effects of conditions and post-hoc comparison.

Variable	Barefoot	Shod	Spiked	p	η_p^2	1-β
30-m time [s]	4.47±0.13 #	4.46±0.13 #	4.40±0.15	***	0.63	1.00
60-m time [s]	7.70±0.23 #	7.73±0.23 #	7.58±0.25	***	0.63	1.00

Acceleration	Speed [m/s]	7.71±0.27	7.58±0.30	7.73±033	0.05	0.17	0.59
	Step length [m]	1.66±0.06 #	1.68±0.08	1.69±0.07	0.03	0.19	0.66
	Step frequency [1/s]	4.56±0.26 $#	4.42±0.25 #	4.48±0.26	***	0.55	1.00
	Contact time [ms]	132±12 $#	139±10	136±10	***	0.38	0.98
	Flight time [ms]	99±8	98±9	98±9	0.46	0.04	0.14
	Braking force [N/kg]	2.73±0.42 $#	2.95±0.58 #	3.33±0.72	***	0.57	1.00
	Propulsive force [N/kg]	5.09±0.31 $#	4.97±0.19 #	5.22±0.23	***	0.53	1.00
	Braking impulse [N·ms/kg]	96±15 #	100±22 #	108±20	***	0.38	0.97
	Propulsive impulse [N·ms/kg]	540±48 $#	572±43	584±33	***	0.40	0.98
Maximum speed	Speed [m/s]	9.35±0.31 #	9.26±0.31 #	9.47±0.33	***	0.51	1.00
	Step length [m]	2.00±0.09 $#	2.04±0.09	2.05±0.07	***	0.44	0.99
	Step frequency [1/s]	4.69±0.28 $#	4.56±0.29	4.62±0.23	***	0.41	0.99
	Contact time [ms]	97±8 $#	101±8 #	99±7	***	0.50	0.99
	Flight time [ms]	118±10	119±9	118±7	0.39	0.06	0.20
	Braking force [N/kg]	3.91±0.53 #	4.05±0.62 #	4.38±0.69	**	0.28	0.87
	Propulsive force [N/kg]	4.70±0.45	4.47±0.36 #	4.75±0.36	0.01	0.23	0.76
	Braking impulse [N·ms/kg]	171±26	177±37	187±35	0.15	0.11	0.39
	Propulsive impulse [N·ms/kg]	251±20 #	255±15 #	268±22	***	0.38	0.97

Note: $=significantly different from shod, #=significantly different from spiked, **=p<0.01, ***=p<0.001.

DISCUSSION: Major findings of the study included kinetic differences between the three footwear conditions, primarily in the acceleration phase, whereas spatiotemporal characteristics showed stronger effects at maximum speed. Condition*phase interactions revealed effects of conditions that depended on the sprinting phase. Those findings recommended analyzing across sprint stages when investigating biomechanical differences between footwear conditions.

Differences in braking and propulsive forces and impulses during acceleration showed the influence of different conditions on kinetic key components of sprinting. A previous study reported that barefoot runners adjust joint angles and leg stiffness, influencing force development and avoiding local overloading during ground contact (De Wit et al., 2000). Regular running shoes, as used in the shod condition in the current study, incorporate cushioning material and midsole designs to reduce injury risks (Davis, 2014). Cushioning mechanisms distribute forces over longer time, aiming to reduce impact force peaks at a given impulse but also delaying the generation of propulsive forces (Aguinaldo & Mahar, 2003). Those alterations may explain currently observed longer contact time and reduced propulsive mean force in shod than in barefoot sprints, especially during acceleration. Despite greater propulsive impulse in shod than in barefoot during acceleration, the overall effect on performance seems not beneficial, considering lower average speed during acceleration as well as maximum speed and longer 60-m sprint time. One explanation may be longer contact time, greater braking force, and a trend towards greater braking impulse that mitigate the effect of greater propulsive impulse on overall speed.

On the contrary, sprint spike shoes incorporate stiff spike plates, increasing bending stiffness, limiting metatarsophalangeal dorsiflexion, and reducing energy loss (Toon et al., 2009; Smith et al., 2014). Forces are more directly transferred, which was seen in greater braking and propulsive forces in spiked than in other conditions. Based on statistical significance and effect sizes, this effect on forces was evident especially during acceleration. Furthermore, the spikes enhance friction and facilitate propulsion during push-off. This is particularly advantageous in the acceleration phase, where propulsive mean force is likely a determinant of greater sprinting acceleration (Gleadhill & Nagahara, 2021). Increased forces and impulses during both braking and propulsion seemed beneficial as spiked sprinting achieved higher maximum speed and higher acceleration. The latter was supported by shorter 30-m sprint time and higher maximum speed after the same acceleration distance. However, greater braking and propulsive forces may be associated with higher loads, presenting risks of overuse injuries.

Differences in spatiotemporal characteristics became more evident at maximum speed, which is determined by stride length and step frequency (Mattes et al., 2021). Greater propulsive

impulse contributed to extended step length in shod and spiked compared to barefoot sprinting. Shorter step length in barefoot was coupled with higher step frequency and shorter ground contact time. Short ground contact time was commonly considered to enhance sprint performance (Davis, 2014), but alternative interpretations suggest reduced contact time to be a consequence rather than the cause of altered step length and frequency (Folland et al., 2017). In fact, currently observed maximum speed was higher in barefoot than in shod sprinting, but no difference was found in sprint times. These observations indicate that barefoot sprinters may outperform shod sprinter at maximum speed but not during acceleration.
It is unclear whether potentially higher fatigue rate in barefoot may mitigate beneficial effects at maximum-speed sprinting beyond the measured distance of 50 m. The current data also does not answer whether acute alterations in mechanics after barefoot sprinting may translate to subsequent spiked sprinting. Both considerations deserve attention in future research and may present practical implications in training protocols and warm-up strategies involving barefoot drills. Barefoot instead of spiked drills could be used when reducing forces and impulses is desired (e.g., to reduce loading-related injury risk or during post-injury recovery).

CONCLUSION: The study demonstrated the effect of different footwear conditions on sprinting biomechanics and emphasized the importance of kinetic analysis during different sprint phases. Effects of conditions varied between different phases of sprinting, which suggests that research should attempt to understand kinetic effects in a large range of instantaneous speeds. The findings are relevant for a broad spectrum of sports that involve sprints as we conclude that applied sport scientists and developers may refine footwear for distinct athletes based on sprint distances commonly observed in particular cases.

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