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Soccer shoe bending stiffness significantly alters game-specific physiology in a 25-minute continuous field-based protocol

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The purpose of this study was to investigate the effects of soccer shoes with differing bending stiffness on physiological and performance variables in a game-like situation. A sample of 13 male soccer players was recruited to complete this study. Three soccer shoes with different forefoot bending stiffness (low, medium, high) were compared using a continuous field-based work protocol (the Soccer-25). Participants performed the Soccer-25 while the physiological (rate of oxygen consumption, heart rate, ventilation, and rate of energy expenditure) and performance variables (drill completion times) were recorded. The Soccer-25 consists of seven phases, Drills 1−3 and Shuttle Runs 1−4. A one-way repeated measures ANOVA was used to determine whether there were any significant effects for soccer shoe condition for each of the physiological and performance variables. The medium-stiffness shoe was significantly lower than the high-stiffness shoe for a number of physiological variables, including global oxygen consumption ($p = 0.044$), heart rate during Drills 2 ($p = 0.043$), ventilation during Shuttle Run 4 ($p = 0.016$), global energy expenditure ($p = 0.043$), and rate of energy expenditure during Drills 1 ($p = 0.044$). The low stiffness shoe was not significantly different from the medium- or high-stiffness shoes. No significant differences were found for any of the performance variables. Soccer shoe forefoot bending stiffness significantly affects the physiological variables in a game-like situation.

Keywords: athletic footwear; athletic performance; bending stiffness; cleated shoe; physiology; soccer

1. Background

Soccer is one of the world's most popular sports, with an estimated 270 million people actively involved in the game worldwide, according to the Fédération Internationale de Football Association (FIFA). Successful performance in a soccer game is dependent on a number of factors, including personal fitness, skill level, and strategy. Soccer shoe construction can also affect biomechanical and performance variables. For example, stud geometry has been shown to affect sprinting performance and instep kick ball velocity (Sterzing & Hennig, 2008; Sterzing, Müller, Hennig, & Milani, 2009). Soccer shoe mass has also been shown to affect joint kinematics, with heavier shoes resulting in slower foot linear velocity and greater knee flexion of the kicking leg at ball contact (Moschini & Smith, 2012). However, other studies showed that soccer shoe mass did not alter sprint performance (Sterzing et al., 2009) or instep kick ball velocity (Sterzing & Hennig, 2008). Another shoe property that has been studied is the frictional properties of shoe upper material, which has shown trends for affecting instep kick ball velocity (Sterzing & Hennig, 2008).

Bending stiffness is another modifiable shoe characteristic that can affect performance. Altering sprinting shoe bending stiffness has been shown to improve sprinting performance (Stefanyshyn & Fusco, 2004; Worobets & Wannop, 2015) and jump height (Stefanyshyn & Nigg, 2000). It is suggested that the performance enhancements observed with stiffer midsoles were the result of a reduction in energy loss at the metatarsal−phalangeal joint due to a reduction in midsole bending (Nigg & Segesser, 1992; Stefanyshyn & Nigg, 2000). Notably, however, it was not the stiffest shoe in the study by Stefanyshyn and Fusco (2004) that showed the greatest improvement in sprinting time, but rather a mid-level stiffness shoe. The authors of this study suggested that stiffer shoes may result in an anterior shift of the pressure, thus increasing the lever arm and moments about the ankle joint. As a result, the athletes may not have had strong enough plantarflexor muscles to generate adequate moments in the high-stiffness shoes, thus explaining a reduction in performance (Stefanyshyn & Fusco, 2004).

While some promising biomechanical and performance benefits have been identified through shoe modifications in the above studies, this research has been conducted entirely on isolated drills or movements, such as an instep kick or a short-distance sprint, often in a

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laboratory-based environment. However, 90-minute soccer games consist not only of instep kicks and sprinting, but also of walking, jogging, passing, tackling, and cutting manoeuvres (Burgess, Naughton, & Norton, 2006). Furthermore, a recent meta-analysis showed that during a soccer game, players are working at 70%−80% of their maximal rate of oxygen consumption and at 80%−90% of their maximal heart rate (Alexandre et al., 2012). As the testing setups in previous studies do not closely resemble soccer games, it is not known whether small changes in performance measured during isolated drills will translate to true benefits to the player during a game situation.

In addition to biomechanical and performance variables, physiological variables, such as rate of oxygen consumption, can also be used to assess footwear conditions. Thus far, the majority of research with physiological variables has investigated footwear properties during running. For example, heavier shoes have been shown to increase the rate of oxygen consumption (Divert et al., 2008; Franz, Wierzbinski, & Kram, 2012; Frederick, 1984). Research has varied regarding the effect of cushioned shoes on running economy, with studies showing increases (Bosco & Rusko, 1983), decreases (Worobets, Wannop, Tomaras, & Stefanyshyn, 2014), and no change (Nigg, Stefanyshyn, Cole, Stergiou, & Miller, 2003) in rate of oxygen consumption with softer shoes. Shoe bending stiffness has also been shown to alter rate of oxygen consumption in running. Roy and Stefanyshyn (2006) reported a ‘U-shaped’ relationship between shoe stiffness and rate of oxygen consumption, where the shoe with the mid-range stiffness showed a lower rate of oxygen consumption than the control or stiffest shoes. To the author’s knowledge, only one study has investigated the effect of a shoe property (shoe weight) on physiological variables during sport, as opposed to running or walking (Vienneau, Tomaras, Nigg, & Nigg, 2015), and found significant physiological benefits for the lighter shoe in the sport of basketball.

Therefore, the purpose of this study was to investigate the effects of soccer shoes with differing bending stiffness on physiological and performance variables in a game-like situation using a continuous field-based work protocol (the Soccer-25). It was hypothesized that the medium-stiffness soccer shoe would have the optimum bending stiffness to elicit (1) physiological benefits, and (2) performance benefits.

2. Methods

2.1. Participants

A sample of 13 male participants (mean (SD); age: 25.4 (3.2) years, height: 1.73 (0.07) m, body mass: 74.6 (5.7) kg) who were currently playing soccer recreationally participated in this study. All participants gave written informed consent in accordance with the University of Calgary’s Conjoint Health Research Ethics Board policy on research using human participants. All participants stated that they were free from lower extremity injury or pain for at least six months prior to testing.

2.2. Experimental footwear

Three soccer shoe conditions (adidas Nitrocharge, US men’s size 9 and 10) were compared in this study. The soccer shoes had identical uppers and identical stud configurations. The only modification made to the shoes was to the forefoot bending stiffness, which was done through the addition or removal of midsole plates. The bending stiffness was quantified for the size 9 cleats using a three-point bending test with a deformation speed of 0.05 m/s and a maximum deformation of 15 mm. After 2000 precycles, the bending stiffness of the low- and high-stiffness shoes was 37.2% and 200% of the bending stiffness of the medium shoes. The size 9 low-, medium-, and high-stiffness shoes weighed 260, 283, and 295 g, respectively. The material testing and weighing of the size 10 cleats were not done, and the cleats have since been returned to the manufacturer and are no longer available. It is speculated that the size 10 cleats are slightly heavier with comparable stiffness values, as differences in shoe sizes are graded.

2.3. Procedures

In this repeated-measures design, each participant completed five testing sessions on different days at the University of Calgary (day 1) and the Calgary West Indoor Soccer Centre (days 2−5). At least one day of rest was provided between each testing session, and the amount of exercise and time of day for data collection were controlled for all participants. On all testing days, participants wore a heart rate monitor (Polar S810, Polar Electro, Kempele, Finland) and a portable metabolic measurement system (K4b2, COSMED, Rome, Italy). The K4b2 was allowed a 45-minute warm-up time, and an air calibration, reference gas calibration, and flow/volume calibration were performed prior to testing. The room air calibration is necessary to update the baseline of the carbon dioxide and oxygen analyzer to match atmospheric values. The reference gas calibration consisted of sampling a gas with a known concentration of carbon dioxide and oxygen, and was performed immediately prior to and following each test according to the Matheson Certified Calibration Standards. A flow/volume calibration was also performed prior to each test using a 3 L calibration syringe to calibrate the turbine flowmeter. The same turbine flowmeter was used for the same subject to limit differences in turbine flowmeter characteristics.

On day 1, participants completed the Léger 20-m shuttle run test, which is a maximal multi-stage incremental running test used to estimate maximal rate of oxygen consumption to maximal volitional fatigue (Léger & Lambert, 1982). On days 2–5, participants were required to complete a 25-minute continuous field-based protocol, named the Soccer-25.

Specifically, anaerobic threshold was defined as (1) a non-linear increase in ventilation, (2) the point of excessive carbon dioxide production, and (3) an increase in the respiratory exchange ratio (Wasserman, 1987; Wasserman, Whipp, Koyal, & Beaver, 1973). A Certified Exercise Physiologist experienced in the identification of anaerobic threshold identified all anaerobic thresholds and provided recommendations on the shuttle run stage that would indicate exercise intensity below anaerobic threshold for each subject. Day 1 also served as an overview session, whereby each participant was instructed regarding the drills portion of the Soccer-25. Following verbal instruction and demonstration of each drill, participants performed one lap of the Soccer-25 at sub-maximal effort.

On days 2, 3, 4 and 5, the participants performed the Soccer-25 while physiological (oxygen consumption, heart rate, ventilation, and rate of energy expenditure) and performance variables (drill completion times) were recorded. Day 2 was a familiarization day. Participants were instructed to complete the entire session in one of the shoe conditions, and were not informed that this data would not be analyzed. Days 3, 4 and 5 consisted of the three shoe conditions under investigation, in a randomized order. The participants were blinded to which soccer shoe condition they were wearing.

The Soccer-25 consists of seven phases, which are timed and monitored according to a standardized protocol (Table 1). Phases 1, 3 and 5 were three minutes in duration, and consisted of a constant speed 20-m shuttle run at the assigned Léger stage one level below the player's anaerobic threshold. Phases 2, 4 and 6 consisted of a standardized set of soccer-specific drills. The participants were asked to complete all drills at maximal effort. The order of progression through the drills portion of the circuit was standardized as follows: (1) Shooting accuracy: two penalty shots 10 m from an indoor-sized net; (2) Header drill: two simulated header jumps; (3) Shooting accuracy: repeat of Step 1; (4) Header drill: repeat of Step 2; (5) Modified Illinois agility test: fully described elsewhere (Hachana et al., 2013); however, the drill dimensions were modified to 10 m × 10 m to better fit the testing area; (6) Passing accuracy: two passes aimed at a target 10 m in front of the player; (7) Dribbling: 5 m forward dribbling, 90° left turn, 5 m further dribbling, return to starting position; (8) Passing accuracy: repeat of Step 6; (9) Modified Bangsbo sprint drill: fully described elsewhere (Bangsbo, 1994); however, the sprint distances were shortened to 5 m before the pivot and 10 m after the pivot due to space constraints; (10) 25-m sprint: maximum effort 25-m linear sprint (Figure 1). Timing lights (Brower TC Timing System, Draper, UT, USA) were used to provide drill completion times for the modified Illinois drill, the modified Bangsbo drill, and the 25-m sprint. Finally, phase 7 consisted of a 3-minute constant speed shuttle run at the Léger level that was deemed to be equivalent to anaerobic threshold for each participant (i.e., one level above previous shuttle run stages in phases 1, 3, and 5), in order to simulate an elevated level of effort often required in the closing stages of a game.

Table 1. Detailed timing for the Soccer-25.

Start	End	Activity	Phase
00:00	03:00	Constant speed shuttle run 1	Phase 1
03:15	03:30	Header 1, Shot 1	
03:35	03:50	Header 2, Shot 2	
04:05	04:15	Modified Illinois drill 1	
04:30	04:45	Pass 1, Pass 2	
04:55	05:00	Dribble 1	Phase 2
05:10	05:25	Pass 3, Pass 4	
05:40	05:55	Modified Bangsbo drill 1	
06:05	06:10	25-m sprint 1	
06:25	06:40	Header 3, Shot 3	
06:45	07:00	Header 4, Shot 4	
07:15	10:15	Constant speed shuttle run 2	Phase 3
10:30	10:45	Header 5, Shot 5	
10:50	11:05	Header 6, Shot 6	
11:20	11:30	Modified Illinois drill 2	
11:45	12:00	Pass 5, Pass 6	
12:10	12:15	Dribble 2	Phase 4
12:25	12:40	Pass 7, Pass 8	
12:55	13:10	Modified Bangsbo drill 2	
13:20	13:25	25-m sprint 2	
13:40	13:55	Header 7, Shot 7	
14:00	14:15	Header 8, Shot 8	
14:30	17:30	Constant speed shuttle run 3	Phase 5
17:45	18:00	Header 9, Shot 9	
18:05	18:20	Header 10, Shot 10	
18:35	18:45	Modified Illinois drill 3	
19:00	19:15	Pass 9, Pass 10	
19:25	19:30	Dribble 3	Phase 6
19:40	19:55	Pass 11, Pass 12	
20:10	20:25	Modified Bangsbo drill 3	
20:35	20:40	25-m sprint 3	
20:55	21:10	Header 11, Shot 11	
21:15	21:30	Header 12, Shot 12	
21:45	24:45	Constant speed shuttle run 4	Phase 7

2.4. Statistics

During the Soccer-25, statistical analysis was conducted for a variety of different time combinations of the physiological

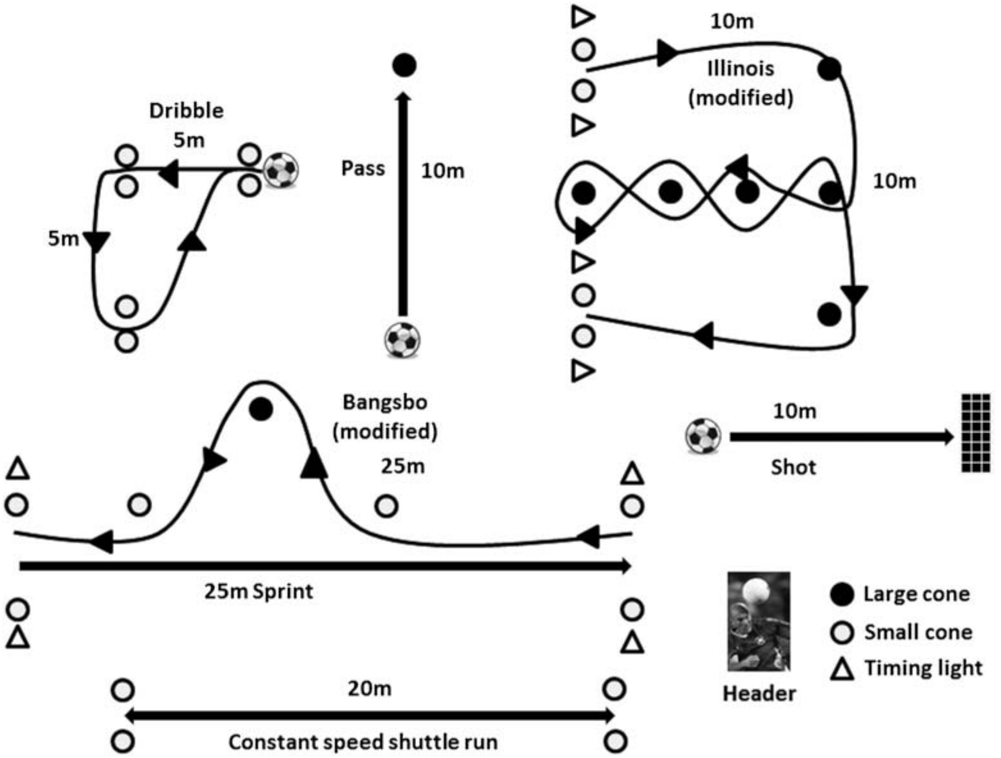

Figure 1. Schematic diagram of the layout of the Soccer-25 testing protocol. See Table 1 for detailed timing of the circuit.

performance variables. More specifically, the three shoe conditions were compared for the following time frames:

(1) Constant speed shuttle run 1 (Phase 1)
(2) Constant speed shuttle run 2 (Phase 3)
(3) Constant speed shuttle run 3 (Phase 5)
(4) Constant speed shuttle run 4 (Phase 7)
(5) Drills 1 (Phase 2)
(6) Drills 2 (Phase 4)
(7) Drills 3 (Phase 6)
(8) Global (summation of Phases 1−7)

The means for each of the physiological variables were calculated for the last minute of each of the shuttle run phases. Additionally, a global value was calculated as the accumulation of each variable across the entire Soccer-25 (e.g., total oxygen consumed (L), total energy expended (kcal)). Furthermore, the means of each drill completion time were calculated for each participant across all circuits for each shoe condition. A one-way repeated measures ANOVA was used to determine whether there were any significant effects for testing condition (between-day differences) for each of the physiological and performance variables. Where a significant main effect was found, *post hoc t*-tests were performed to find precisely where statistical differences existed between shoe conditions. All statistical tests were completed using IBM SPSS statistics (Version 20.0; SPSS Inc., Chicago, IL) and Microsoft Office Excel 2007 (Microsoft Corp., Redmond, Washington, USA) and all tests of significance were performed with an alpha level set at 0.05.

3. Results

3.1. Physiological variables

For day 1 of testing, the mean (SD) maximum Léger shuttle run stage achieved was 10.3 (1.9), corresponding to an estimated maximal rate of oxygen consumption of 57.1 mL/kg/min (Stickland, Petersen, & Bouffard, 2003).

Mean values for each shoe condition for each of the physiological variables across the entire Soccer-25 protocol are plotted in Figure 2. The major differences existed between the medium- and high-stiffness shoes. Specifically, the medium-stiffness shoe showed a significantly lower global oxygen consumption than the high-stiffness shoe ($p = 0.044$), and strong trends for a lower rate of oxygen consumption during Drills 1 ($p = 0.060$) and Drills 2 ($p = 0.051$, Figure 2(a)). The medium-stiffness shoe showed a significantly lower heart rate than the high-stiffness shoe during Drills 2 ($p = 0.043$), and similar trends during Drills 3 ($p = 0.065$), Shuttle Run 4 ($p = 0.065$) and Global ($p = 0.063$, Figure 2(b)). The medium-stiffness shoe also showed a significantly lower ventilation than the high-stiffness shoe during Shuttle Run 4 ($p = 0.016$, Figure 2(c)). Finally, the global total energy expenditure

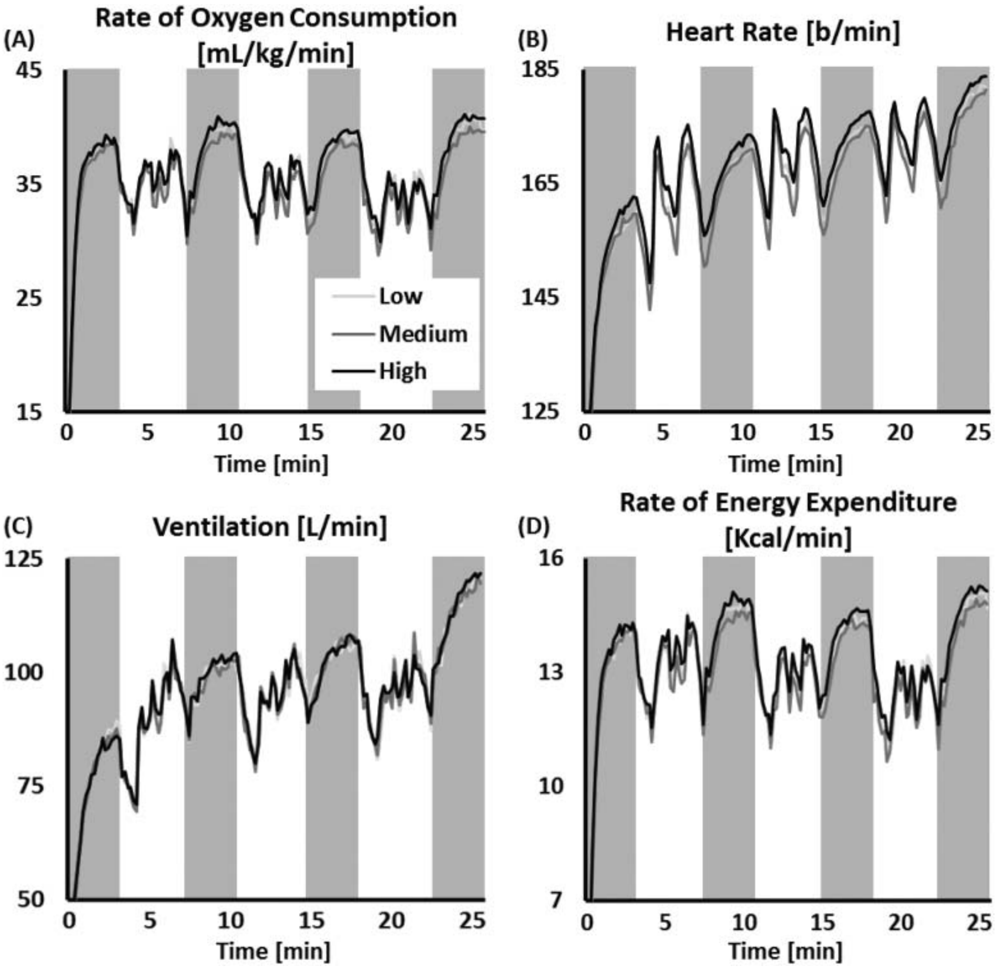

Figure 2. Mean values for all data points during the Soccer-25 for each of the shoe conditions for (a) oxygen consumption, (b) heart rate, (c) ventilation, (d) rate of energy expenditure ($N = 13$).

was significantly lower in the medium-stiffness shoe than in the high-stiffness shoe ($p = 0.043$), as well as the rate of energy expenditure for Drills 1 ($p = 0.044$), and a trend for Drills 3 ($p = 0.066$, Figure 2(d)).

3.2. *Performance variables*

There were no significant differences in times between the shoe conditions for the modified Illinois drill, the modified Bangsbo drill, or the 25-m sprint (Figure 3).

4. Discussion

The current study was successfully able to use the Soccer-25 circuit to evaluate three soccer shoes differing in forefoot bending stiffness. Significant differences were found only between the medium-stiffness and the high-stiffness conditions for all physiological variables, thus partially supporting hypothesis (1). When players completed the Soccer-25 in the medium shoe, significantly lower rate of oxygen consumption, heart rate, ventilation, and rate of energy expenditure were required than in the high-stiffness shoe in varying phases of the Soccer-25. Furthermore, when considering the entire circuit, players consumed less oxygen and expended fewer calories in the medium-stiffness shoe than in the high-stiffness shoe. No performance effects were observed between any of the shoe conditions, thus rejecting hypothesis (2).

It has been estimated that during a soccer game, players work at 70% to 80% of their maximal rate of oxygen consumption, and 80% to 90% of their maximal heart rate (Alexandre et al., 2012). In the current study, the maximal rate of oxygen consumption is estimated to be 57.1 mL/kg/min. Based on the players' age, a maximal heart rate of 195 b/min can also be estimated. The results of this study show that the constant speed shuttle run portions of the Soccer-25, on average, corresponded to approximately

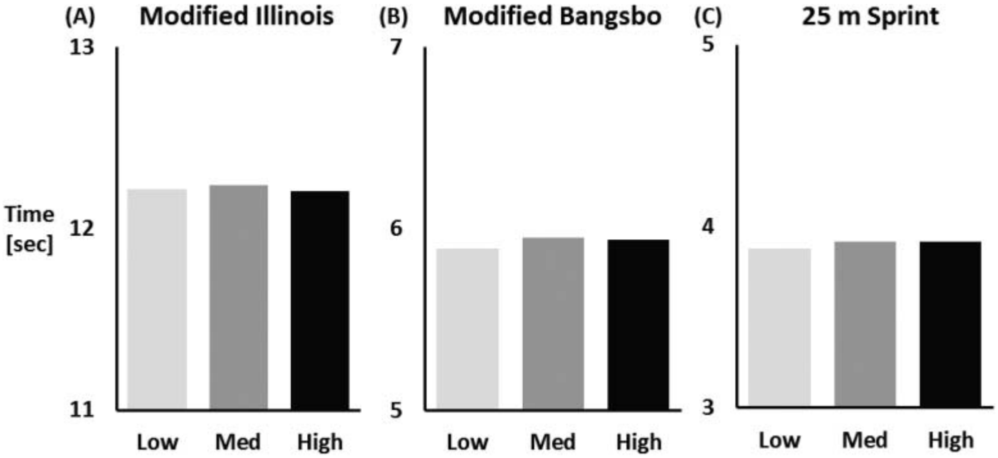

Figure 3. Mean performance times for each of the shoe conditions for the (a) modified Illinois agility test, (b) modified Bangsbo sprint drill, and (c) 25-m sprint ($N = 13$).

70% and 90% of the players' maximal rate of oxygen consumption and heart rate, respectively. Thus, the Soccer-25 is a more realistic and holistic approach for investigating the effect of shoe bending stiffness than studying individual drills in a laboratory setting.

The players exhibited the greatest benefit in the medium-stiffness shoes. The low stiffness condition did not elicit any significant differences from either the medium-stiffness or the high-stiffness shoe conditions. Examination of the data shows that the low-stiffness condition was consistently midway between the medium-stiffness and high-stiffness conditions across most physiological variables of the Soccer-25 phases. This observed relationship between the shoe conditions provides more support for a U-shaped relationship between bending stiffness and physiological variables. This relationship has also been found previously (Roy & Stefanyshyn, 2006), and differs from the linear relationship reported with added shoe mass (Franz et al., 2012; Frederick, Daniels, & Hayes, 1984).

Roy and Stefanyshyn (2006) reported that subjects with increased body mass exhibited the greatest decrease in the rate of oxygen consumption when running in the medium-stiffness shoe compared to the low-stiffness shoe ($R^2 = 0.602$, $p = 0.002$). The players in the current study were very homogeneous, in that 11 of the 13 players had a body mass between 70.3 and 78.9 kg, making it difficult to perform a similar correlation. However, the remaining two players were outliers, one heavier (83.7 kg) and one lighter (59.5 kg); the data from these two outliers were further examined. The decrease in the rate of oxygen consumption between the medium-stiffness shoe and both the low- and high-stiffness shoes was greater for the heavier player, in agreement with the previous findings. It is possible that stiffer shoes are better able to resist the higher forces applied by a heavier player, thus reducing the energy loss at the metatarsal–phalangeal joint. It is not known why the high-stiffness shoes in this and previous studies have not elicited the greatest benefits. It may be that high-stiffness shoes are uncomfortable for the player, which then negatively affects their performance. This evidence suggests that future research should investigate shoes with forefoot bending stiffness that is individualized to players based on their body mass in order to maximize the benefits of the stiffness.

This study found no significant differences in the performance variables, contrary to previous results (Stefanyshyn & Fusco, 2004; Worobets & Wannop, 2015). In fact, the drill times differed by less than 1% between conditions, on average across all participants. In general, the combination of both an improved performance and lower oxygen and energy cost in a given shoe condition is unlikely, as it would require the subjects to use less energy while performing at a higher work rate. In this study, the players performed at the same work rate while using less oxygen and energy in the medium-stiffness condition. Therefore, in a game scenario, while players would not be able to sprint faster in the medium-stiffness shoe, they would be able to maintain the same speed as their opponent, while feeling less fatigued. Conversely, one could speculate that in the previous literature cited above where performance differences were found, that no changes in physiological variables would have been observed.

A limiting factor to this study is that the shoe masses differed, which could affect the variables of interest. However, the differences were small, with the medium- and high-stiffness shoes being 23 and 35 g heavier than the low-stiffness shoe, respectively. It has previously been reported that in running, the rate of oxygen consumption increases by 1% for each 100 g of mass added to the shoe (Frederick et al., 1984). While there is no direct comparison for soccer-specific movements, it can be speculated that the differences in the physiological variables found in the current study due to differing shoe stiffness exceed those that would be expected based on the small differences in shoe mass.

Another limitation is that the data for differing shoe conditions were collected on different days. This was necessary as the Soccer-25 is a maximal effort circuit; however, this may cause variations in a few factors. First, the caloric intake prior to testing was not controlled for, and therefore may have varied across days. Small differences in physiological variables have been shown to be the result of exercising in a fasted compared to a non-fasted state (Bray, Whipp, & Koyal, 1974; Segal, Presta, & Gutin, 1984). Therefore, for future studies, it is suggested that fasting be required prior to testing, in addition to controlling for time of day of testing and amount of exercise prior to testing. Second, as a result of testing across days, the temperature, humidity and/or barometric pressure in the testing venue could have changed slightly. While the portable metabolic system was calibrated relative to these environmental factors, variations could have slightly affected the data or the actual performance of the players. However, a reliability assessment of the Soccer-25 was done (unpublished data), and showed a high between-day reliability. Specifically, intra-class correlation coefficients of 0.80−0.97 and technical errors of measurement of 1.2%−4.2% were quantified across all physiological variables during all phases of the Soccer-25. Additionally, by introducing a familiarization session to the current study, it is expected that learning effects would be further minimized.

5. Conclusion

The results of this study show that soccer shoe forefoot bending stiffness significantly affects physiological variables in a game-like situation. The medium-stiffness shoe exhibited lower rate of oxygen consumption, heart rate, rate of energy expenditure and ventilation compared to the high-stiffness shoe. Drill completion times did not differ significantly between the shoe conditions. Finally, shoe stiffness may have to be modified to different athletes' body weights in order to maximize the benefit of applying such a technology.

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No potential conflict of interest was reported by the authors.

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