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ABSTRACT

Purpose: No study has assessed the acute effect of caffeine supplementation on 100-m sprint running in athletics, and caffeine's net ergogenicity on 100-m sprint running remains unclear. We investigated the acute effects of caffeine supplementation on 100-m sprint running performance in a field test. **Methods:** Thirteen male collegiate sprinters were subjected to 100-m sprint running time trials (TTs) after the ingestion of 6 $mg \cdot kg^{-1}$ body weight caffeine or placebo supplementation in a double-blind, counterbalanced, randomized, and crossover design. Sprint velocity was measured with a laser system, and sprint time was calculated from the data in which the effects of environmental factors that would act as confounding factors on sprint time during TTs were eliminated. **Results:** The corrected 100-m sprint time was significantly shortened by 0.14 sec with caffeine supplementation compared with placebo (placebo: 11.40 ± 0.39 sec, caffeine: 11.26 ± 0.33 sec, $P = 0.007$, $g = -0.33$). The corrected sprint time up to 60 m during TTs was also significantly shorter with caffeine supplementation than with placebo ($P = 0.002$). Furthermore, the mean sprint velocity for 0-10 and 10-20 m splits was significantly increased by caffeine supplementation (all $P < 0.05$). **Conclusions:** Acute caffeine supplementation enhanced the corrected 100-m sprint time by improving the sprint performance in the first 60 m following more explosive acceleration in the early stage of the acceleration phase. Thus, for the first time, we directly demonstrated caffeine's ergogenicity on 100-m sprint performance in athletics.

Key Words: ERGOGENIC AID, SINGLE SPRINT RUNNING, ATHLETICS, ACCELERATION PHASE, SPRINTER

INTRODUCTION

Pre-exercise caffeine (1,3,7-trimethylxanthine) supplementation acutely enhances performance in various sports, both aerobic and anaerobic (1). Worldwide, caffeine is one of the most consumed substances in competitive sports as an ergogenic aid to enhance sports performance. Indeed, caffeine has been found in more than 70% of athletes' urine obtained for doping analysis in national and world competitions, and urinary caffeine concentrations increased from 2004 to 2015 in some sports, such as athletics, weightlifting, and rowing (2).

To focus on athletics, the International Association of Athletics Federations (IAAF; currently called World Athletics, WA) proclaimed the effect of caffeine as an ergogenic aid to enhance sprint running performance in the consensus statement of the nutrition strategy for athletics (3,4). However, the rationale of caffeine's ergogenicity in this consensus did not indicate the effect of caffeine supplementation on sprint running in athletics but on other anaerobic sports. In other words, there is no study to support this consensus directly for sprint running performance. To date, some previous studies have investigated the effect of caffeine on running activity, but a number of them have limitations. Specifically, improving sprint performance in single (5-7) or multiple (8-10) sprint running trials up to 40 m was reported in some previous studies, but their experimental designs all simulated ball-game sports in aspects of the trial (e.g., experimental protocols and running distance) and types of participants (e.g., soccer players). In sprint events of the Olympics, the shortest distance is 100 m (although indoor athletic events include a sprint of 60 m), and only one sprint race is performed in each round (i.e., preliminary, semifinal, and final

rounds); nevertheless, no studies investigated caffeine's ergogenicity in a single sprint running for more than 60 m.

In the 100-m sprint race in athletics, the running velocity changes during the all-out running of approximately 10 sec; hence, we can divide the 100-m sprint change in velocity into three phases: the acceleration phase, the maximum speed (constant speed) phase, and the deceleration (speed maintenance) phase (11,12). Because the acceleration phase continues for approximately 30-50 m after the start of the 100-m sprint (11), the sprint running up to 40 m utilized by previous studies may be too short for sprinters in athletics to reach maximum velocity. Therefore, a field test of actual 100-m sprint running is needed to directly clarify the effect of caffeine on sprint running in athletics.

Caffeine supplementation enhances muscle activation, including the rate of force development (RFD; 13-15). The RFD is associated with jump and sprint performance (16,17). In addition, many previous studies reported that vertical jump height in jumps such as countermovement jumps (CMJs) and squat jumps (SJs) was increased by caffeine supplementation (5,6,14,15,18), and two meta-analyses suggested positive effects on jump performance (19,20). The heights of CMJs and SJs are associated with sprint time in 60-m sprint running and maximum velocity in 100-m sprint running (21-23). Therefore, we hypothesized that caffeine supplementation would enhance 100-m sprint running performance by increasing the running velocity for the first 60 m, including the maximum velocity. The purpose of this study was to investigate the acute effect of

caffeine as an ergogenic aid on 100-m sprint running performance in a field test. We also tried to determine the phase that is influenced by caffeine supplementation by investigating whether an improvement in 100-m sprint performance could be attributed to an improvement in sprint performance in the first 60 m.

METHODS

Experimental design and participants

In this study, which had a double-blind, counterbalanced, randomized, and crossover design, participants executed the field test of 100-m sprint running time trials (TTs). Fifteen male collegiate sprinters participated in this study. All included participants had a minimum of two $h \cdot day^{-1}$, five $days \cdot week^{-1}$ training habituation (including resistance training) and could complete all-out 100-m sprint running. Participants were excluded from this study if they reported (a) an injury making it difficult to run a 100-m sprint race; (b) a mental disorder or cardiovascular disease; (c) smoking status within the past year; or (d) allergy to caffeine or the prescribed diet in this study. Two participants dropped out before the TTs due to their injuries. Thirteen participants (mean ± SD of age: 20.6 ± 1.0 years; height: 175.5 ± 5.0 cm; weight: 65.9 ± 5.1 kg; personal best 100-m sprint time: 11.18 ± 0.38 sec; season's best 100-m sprint time: 11.28 ± 0.41 sec; habitual caffeine intake: 205 ± 162 $mg \cdot day^{-1}$) were enrolled in this study, and all of them completed the experimental trial. Habitual caffeine intake was estimated with the questionnaire of Bühler et al. (24). Participants participated in sprint training for at least three years, and most of them were included in the category of subelite sprinters classed in the previous study (25). Participants were

prohibited from caffeine and alcohol intake from 0:00 on the day before all experiments and fasted from 23:00 on the day before. All experiments were carried out with an interval of at least one week as a wash-out period (6-8). This study conformed to the Declaration of Helsinki and was approved by the Ethics Committee for Human Experiments at Ritsumeikan University (BKC-IRB-2021-012). Written informed consent was obtained from all participants.

Experimental procedures

Participants visited the laboratory three times (once for the preliminary study and twice for the TTs). In the preliminary experiment and the TTs of the caffeine condition, participants ingested 6 $mg \cdot kg^{-1}$ body weight anhydrate caffeine (Pure Caffeine, Myprotein, United Kingdom) in capsule form. This dose is within the range considered optimal and is commonly utilized in experiments on the acute effects of caffeine supplementation (1,26). In the TTs of the placebo condition, participants ingested 6 $mg \cdot kg^{-1}$ maltitol (Place-plus, Placebo Seiyaku, Japan) as the control condition. Caffeine and placebo were given in the same capsule form, and it was impossible to determine whether the participants had taken caffeine or placebo based on taste, smell, or appearance.

At the first visit, a preliminary experiment was conducted to measure the change in plasma caffeine concentration over time after caffeine ingestion for each participant. The time to reach the peak plasma caffeine concentration (T_{max}) ranges from 30-120 min interindividually after caffeine ingestion (27,28). Thus, the timing of caffeine supplementation was based on 60 min

before each TT in this study but was adjusted according to the results of the preliminary experiment measuring the T_{max} such that the T_{max} was reached at the start of the TTs for the participants whose T_{max} might be delayed. Participants visited the laboratory at 8:00, and their height and weight were measured by body scales (WB-510, TANITA Co., Japan). Each participant's dose of caffeine was decided by the result of these measurements. Following the body measurements, participants took the prescribed meal, a jelly- and a block-type (i.e., a nutrition bar) breakfast, for a total of 380 kcal. At 9:00, as the timepoint before caffeine ingestion (PRE), 100-120 μL of blood was obtained from a fingertip with a micro blood sampling kit (Kantan-tube Eiken, Eiken Chemical, Japan). After PRE blood sampling, participants ingested 6 $mg \cdot kg^{-1}$ body weight caffeine, and micro blood sampling was performed at 30, 60, 90, and 120 min after caffeine ingestion. Each participant's plasma caffeine concentration over time after caffeine ingestion was analyzed by ELISA (Caffeine ELISA Kit, BioVision Inc., United States), and the T_{max} was investigated. The ELISA was run according to the manufacturer's instructions, and samples were run in duplicate.

At the second and third visits, participants performed TTs after caffeine or placebo supplementation. Two TT conditions were completed on the same day of the week with randomized conditions that were not affected by the participants' weekly cycle of daily training. All TTs were executed at Quince Stadium on the Biwako-Kusatsu Campus of Ritsumeikan University, an athletic field equipped with an all-weather track. Participants visited the laboratory at 8:00 and took the same prescribed meal as in the preliminary experiment. Following rest,

participants started a 60-min warm-up at 10:00 at the stadium. Participants conducted their routine warm-ups in each TT. Heart rate (HR) was measured every 10 min during the warm-up to assess the intensity of the warm-up. On the basis of the results of the preliminary experiments (see Fig. S1, Supplemental Digital Content, Blood caffeine concentration before and every 30 min after 6 $mg \cdot kg^{-1}$ caffeine ingestion in the preliminary experiment, http://links.lww.com/MSS/C723), one participant ingested caffeine or placebo 90 min before starting TTs, four participants ingested caffeine or placebo 120 min before starting TTs, and the others ingested caffeine or placebo 60 min before starting TTs.

TTs started at 11:00 after the warm-up. All participants wore their spiked shoes, which were the same for the two TTs. Participants started in a crouch position with a starting block and accelerated explosively with gunfire as the "go" signal. In this study, a laser system (LDM201.100, JENOPTIK, Germany) was employed to measure the running velocity during the 100-m sprint. The laser system is a reliable method to measure sprint running velocity (29). This device was set up 10 m behind the start line. The running velocity during the TT was recorded continuously, with the laser aimed at the participants' lower backs and with a 100-Hz sampling rate, while the participant executed the TT. Furthermore, participants' running actions were recorded by an iPad (iPad Air, Apple, United States) to calculate the mean step length and frequency during TTs. Videos were taken from the finish line of the 100 m so that running participants were always in the frame and near the middle of the frame when they passed through the finish line.

The raw running displacement data measured by the laser system were immediately downloaded as the continuous running velocity data. Noise in the displacement data was removed by a 1.0-Hz low-pass filter (4th Butter-worth). The sprint time, the mean velocity every 10 m, the maximum velocity, and the distance to the maximum velocity were calculated using filtered data. The results of TTs measured by the laser system started at the point where participants passed 0 m and finished at the point where they passed 100 m. Furthermore, the 100-m sprint time and the first 60-m sprint time during the TT were corrected to the same condition, the "sea level, 1013 hPa, 15ºC, 0% humidity, and 0.0 $m \cdot sec^{-1}$ wind" condition, by the 100-m drag adjustment calculator (http://jmureika.lmu.build/track/DensityAltitude.html; the details of the formula are given in Mureika [30,31]). The 60-m sprint time was corrected to the sea level and 0.0 $m \cdot sec^{-1}$ wind condition with the tool. Temperature, humidity, and barometric pressure were measured just before starting the TT (11:00). Altitude was set to 138 m because the locations for all TTs were the same. The wind variable utilized the result measured during the TT by an ultrasonic wind gauge (NMS 200, NISHI, Japan), which was set at 50 m. This device is utilized in official athletic competitions. The corrected 40-m sprint time from 60 to 100 m was calculated from the above results. The mean step length and frequency were obtained from the video taken during the TT. In this study, the mean step length was obtained by dividing the whole distance of the TT (i.e., 100 m) by the number of steps taken during the TT. The mean step frequency was obtained by dividing the number of steps taken during the TT by the 100-m sprint time.

Statistics

All data are expressed as the means ± the SDs. Comparisons of the sprint time (100 m before correction, 60 m, 100 m and 40 m during 60-100 m after correction), maximum velocity, distance to the maximum velocity, running actions (mean step length and frequency), environmental factors (excluding altitude, i.e., temperature, humidity, barometric pressure, and wind) during TTs, and the mean HR during the warm-up were performed using a paired Student's *t* test. The relationship between the amount of change from placebo to caffeine for the corrected 60-m sprint time and 100-m sprint time was analyzed using Pearson's correlation test. Planned a priori comparisons between caffeine and placebo for the mean sprint velocity every 10 m were tested by a paired Student's *t* test. In this study, a priori comparisons, not a two-way analysis of variance (ANOVA), were planned because it was possible that the condition (caffeine vs. placebo) effect was not identified for being offset by the distance (10 segments of distance every 10 m) effect. It was evident that the running velocity of each 10 m segment significantly changed given that running velocity changes markedly during 100-m sprint running, as mentioned above (11,12). Comparing conditions at 10 points would increase the chance of type I error; however, Healy et al. (32) reported that the faster sprinters were quicker over each section within a 100-m sprint, so the increase in type I error might be less than would be expected for independent outcomes. The Hedge's *g* effect size using the pooled SD was calculated as the effect size (ES) to determine the magnitude of the difference in measured variables between conditions. This ES was interpreted as small ($0.20 \leq g < 0.50$), medium ($0.50 \leq g < 0.80$), and large ($0.80 \leq g$) (33). Changes in HR every 10 min during the warm-up were analyzed using two-

way (two conditions×six times) ANOVA. In addition, to test the bias for the order of conditions, comparisons of sprint performance between the trial order were conducted with a paired Student's *t* test. The statistical significance level was set at $P < 0.05$. All statistical analyses were carried out using IBM SPSS software (Ver. 28, IBM, United States).

RESULTS

Sprint time

There was no significant difference between the caffeine and placebo conditions for the 100-m sprint time before correction (placebo: 11.36 ± 0.49 sec, caffeine: 11.22 ± 0.35 sec, $P = 0.058$, $g = -0.27$, data not shown). However, compared to placebo, the corrected 100-m sprint time was significantly shorter with caffeine supplementation (placebo: 11.40 ± 0.39 sec, caffeine: 11.26 ± 0.33 sec, $P = 0.007$, $g = -0.33$, Fig. 1A). The corrected 60-m sprint time during TTs was also significantly reduced with caffeine supplementation (placebo: 7.12 ± 0.20 sec, caffeine: 7.03 ± 0.17 sec, $P = 0.002$, $g = -0.42$, Fig. 1B). In addition, the change in the 100-m sprint time with caffeine supplementation was significantly associated with the change in the 60-m sprint time ($R = 0.88$, $P < 0.001$, Fig. 1C). However, there was no significant difference between caffeine and placebo for the corrected 40-m sprint time from 60-100 m (placebo: 4.27 ± 0.19 sec, caffeine: 4.23 ± 0.16 sec, $P = 0.075$, $g = -0.23$, Fig. 1D).

Sprint velocity

There were no significant differences between caffeine and placebo for the maximum velocity and distance to maximum velocity during TTs (all $P > 0.05$, Table 1). As a result of a priori comparisons for the mean sprint velocity every 10 m, the mean velocity for 0-10 m (placebo: 5.74 ± 0.14 m·sec^{-1}, caffeine: 5.83 ± 0.14 m·sec^{-1}, $P = 0.044$, $g = 0.64$) and 10-20 m (placebo: 8.55 ± 0.33 m·sec^{-1}, caffeine: 8.64 ± 0.28 m·sec^{-1}, $P = 0.015$, $g = 0.22$) splits was enhanced significantly (Fig. 2). However, there were no significant differences between caffeine and placebo for the mean sprint velocity of any other 10-m sections (i.e., more than 20 m, all $P > 0.05$; the supplementary table shows all the detailed data [see Table S1, Supplemental Digital Content, Variables of all sprint performances in placebo vs. caffeine supplementation, http://links.lww.com/MSS/C723]).

Step length and step rate

There were no significant differences between caffeine and placebo in terms of the mean step length ($P = 0.241$) or mean step rate ($P = 0.417$, Table 1).

Heart rate during the warm-up

Regarding HR during the warm-up every 10 min, the main effect of time was significantly changed ($F_{(2.80, 22.37)} = 14.71$, $P < 0.001$, $\eta_p^2 = 0.648$), but the main effect of the condition ($F_{(1, 8)} = 0.06$, $P = 0.820$, $\eta_p^2 = 0.007$) and the interaction effect ($F_{(3.35, 26.78)} = 0.54$ $P = 0.677$, $\eta_p^2 = 0.063$) were not significantly different. The difference in the mean HR during the warm-up

between caffeine and placebo was not significant (placebo: 93.7 ± 15.8, caffeine: 92.4 ± 15.5, P = 0.592, data not shown).

Environmental factors

There were no significant differences between caffeine and placebo for any environmental factors in TTs (all $P > 0.05$, Table 1).

Trial order effects

The mean velocity for 10-20 (P = 0.021), 20-30 (P = 0.026), 30-40 (P = 0.013), 50-60 (P = 0.049), and 60-70 m (P = 0.040) was significantly faster in the first trial. However, any other outcome of sprint performance, including sprint time, was not significantly changed (Table 2). Of note, seven participants ingested caffeine and six did placebo in the first trial; hence, this study was done with a counterbalanced design certainly.

DISCUSSION

The present study showed that acute caffeine supplementation shortened the corrected 100-m sprint time by 0.14 sec. To the best of our knowledge, this is the first study to directly determine the effect of caffeine as an ergogenic aid on the 100-m sprint performance in athletics. Caffeine's ergogenicity on the sprint performance in athletics still has been attributed to the IAAF (WA) consensus (3,4). In the statement, two previous studies have been cited as evidence. Glaister et al. (10) examined the effects of caffeine supplementation on 12×30-m repeated sprint running

performance at 35 sec intervals and reported that caffeine reduced the fastest sprint time relative to placebo. However, they did not investigate caffeine's ergogenicity with a single sprint running but with a 30-m sprint, which is shorter than a sprint race in athletics. Astorino & Roberson (34) reported the positive effects of caffeine on various anaerobic performances in a systematic review, but all of the literature included in their review examined the effects of caffeine on multiple or just 10-m single sprint running trials. Furthermore, the results of the present study showed caffeine's ergogenicity to have small but significant ESs on 100-m sprint times. Several previous studies have shown small to medium ESs on 20- and 30-m sprint times (5-7). The ES on 100-m sprint times in the present study was similar to or slightly smaller than that reported in these previous studies. However, as 0.01 sec can often be the difference between winning or losing in athletics, the difference of 0.14 sec determined in the present study would actually impact sprint races in athletics.

In the present study, the corrected first 60-m sprint time during TTs was reduced with caffeine supplementation, and the change was associated with the improvement in the 100-m sprint time. This result suggested that the reduced 100-m sprint time with caffeine supplementation was at least partly due to the improvement in the sprint performance up to 60 m. Previous studies reported that caffeine enhanced single or multiple sprint performance in various distances up to 40 m (5-10). In addition, caffeine supplementation enhanced the sprint velocity in the first 20 m of the 100-m sprint. This result indicated that caffeine positively acted on sprint performance in the acceleration phase of the 100-m sprint, especially in the early stage of the acceleration phase

(23). As the mechanisms of caffeine's effects on sports performance, central factors, such as effects on adenosine receptors in the central nervous system, and peripheral factors, such as direct effects on skeletal muscle, have been considered (35-37), but these effects are controversial. Further research is needed to elucidate the mechanisms of caffeine's ergogenicity on sprint performance. Although only speculative, the results of this study might be due to the effect of caffeine on muscle activation, particularly the RFD. During sprint running performance, explosive muscle activation with shorter time is needed because sprint performance is limited by the minimum time to generate the necessary force (38). Given this, the velocity of muscle activation is more important than the magnitude of muscle power in high sprint performance. Importantly, the starting performance during the sprint is associated with the RFD (17), and caffeine enhances the RFD (13-15). Therefore, caffeine may improve 100-m sprint performance in the early stage of the acceleration phase by increasing the RFD by affecting neural or muscular function.

The 100-m sprint time in the present study did not include the reaction time from the start signal to the onset of the movement, which is one of the performance elements in sprint races. In the present study, we utilized the laser system for recording TTs. It is difficult for the laser system in this study to record sprint performance elements such as reaction time. In previous studies, the reaction time of the start was positively associated with 100-m sprint time in top-level athletes (32,39,40). On the other hand, reaction time is shortened by caffeine ingestion because of caffeine's effect on the central nervous system (35). Thus, caffeine supplementation

can be expected to shorten the reaction time in a 100-m sprint race, suggesting that it may further enhance the sprint performance in athletics beyond what was indicated in the present study. In contrast, caffeine supplementation has the possibility of side effects such as anxiety or nervousness (41). In this study, we did not observe side effects that affected the participants' sprint performance. However, it is unclear whether side effects negatively affect the starting performance of sprinters. Therefore, further investigations about the ergogenicity of caffeine on the start of a sprint and the possibility of a false start are needed.

After caffeine ingestion, the blood caffeine concentration increases rapidly but reaches the T_{max} at 15-120 min (27,28). The half-life of caffeine is four to six hours, and blood caffeine concentrations are maintained close to the T_{max} for three to four hours (26). For this reason, the ingestion of caffeine one hour before exercise is the optimal dose timing (26). Importantly, the possibility of caffeine as an ergogenic aid for individuals who do not experience acute positive effects (identified as "nonresponders") by adjusting the timing of ingestion has been discussed (42). In this study, the timing of caffeine supplementation was 60 min before TTs for most participants, but for some participants, this was adjusted to delay the timing to be within the range that caffeine's ergogenicity was expected (e.g., 90-120 min before the TT). In fact, caffeine supplementation shortened the sprint time in all five participants whose T_{max} was > 60 min in the preliminary experiment (see Fig. S1, Supplemental Digital Content, Blood caffeine concentration before and every 30 min after 6 mg·kg^{-1} caffeine ingestion in the preliminary experiment, http://links.lww.com/MSS/C723). Collectively, at least in this study, the timing of caffeine ingestion to effectively evoke its ergogenic effects may be reasonable.

We eliminated the effects of environmental confounding factors in TTs, such as wind, altitude, temperature, humidity, and barometric pressure, by the calculation tool of previous studies (30,31). A tailwind during the sprint race supports running performance. In the 100-m sprint, a 2.0 $m \cdot sec^{-1}$ tailwind generally reduces sprint time by approximately 0.1 sec in the most mathematical models (29,30,43). We performed wind measurements during the 100-m sprint by the official methods of the Japan Association of Athletics Federation and WA. In the present study, the difference in wind between the caffeine and placebo conditions was only 0.1 $m \cdot sec^{-1}$ and was not statistically significant. However, the largest difference between the two TTs for all participants was 4.0 $m \cdot sec^{-1}$ (data not shown). Thus, wind was a confounding factor that markedly influenced the results without correction in TTs. Due to atmospheric conditions, the effect of altitude on sprint time also cannot be ignored, and sprinters have an advantage equivalent to a tailwind of 2.0 $m \cdot sec^{-1}$ as the altitude increases by 1,000 m (43). However, all TTs were completed at the same place; hence, altitude was an ignorable variable in this study. As the density of the atmosphere decreases with increasing levels of temperature or humidity (29), these higher levels act in the direction of faster sprint times. For the same reason, sprint performance improves with low barometric pressure. In this study, however, these variables, such as humidity and barometric pressure, can be negligible because the variation in sprint time due to correction in the range measured in the TTs was less than 0.01 sec. For temperature, a change of 10ºC produces a time variation of 0.01 sec (31), but the largest difference of temperature between the two TTs in all participants was 5.3ºC. Consequently, the variation in the correction is likewise less than 0.01 sec, suggesting that the variables had little or no effect on sprint times.

Based on the above, wind was the only environmental factor to affect sprint performance in the TTs. In the present study, significant changes in mean velocity by the trial order were found in the several 10-m segments before the correction but not in all sprint time after correcting environmental factors. The results might corroborate the notion that the environmental factors, particularly wind, impacted on sprint running performance. On the other hand, although the magnitude of correction based on Mureika (30,31) was mostly the same as the other wind-corrected mathematical models, one may doubt the validity of correction. Importantly, we also performed the mathematical model of wind correction based on Linthorne (43), resulting in a significant reduction in 100-m sprint time by caffeine supplementation (placebo: 11.38 ± 0.41, caffeine: 11.24 ± 0.33, P = 0.011) as shown in the present result. Altogether, despite no significant difference between caffeine and placebo for any environmental factor during the TTs, the correction of sprint performance was a critical process to precisely reveal the effect of caffeine on 100-m sprint performance with the large wind variation between the two TTs in all participants.

We did not direct the warm-up of participants; instead, participants conducted their routine warm-ups. Indeed, there were no differences between the effects of caffeine and placebo on HR during the warm-up. Moreover, one meta-analysis indicated that caffeine did not affect heart rate during submaximal intensity exercise (44). Taken together, the intensity of warm-ups before the TTs was similar between the two conditions in all participants, and warm-up was not a confounding factor in this study.

There are some limitations in the present study despite various confounding factors being controlled in the field test. First, we were unable to correct for the effects of environmental factors on running velocity and motions. In the present study, caffeine significantly improved the corrected 100-m sprint time but not the time before correction. Only one previous study demonstrated the effect of caffeine supplementation on sprint running of more than 60 m (sprint training containing multiple 30-, 50-, and 100-m sprints); however, the mean velocity in each sprint did not change significantly with caffeine supplementation when compared with placebo supplementation (45). This previous study did not report the wind during sprint running, although the trials were performed on an outdoor athletic track. This previous study and the present study suggested that environmental factors, especially wind, as mentioned above, were confounding factors in investigating the net effect of caffeine on sprint running performance. The maximum velocity was negatively correlated with the whole 100-m sprint time (32,46). On the basis of this correlation, the significant difference between caffeine and placebo may be seen by excluding the effects of environmental factors on the maximum velocity. Moreover, there were no significant changes in step length or frequency. When sprint performance changes, these motions increase or decrease by changing the stance and flight distance/time (47). Hence, if environmental factors could be eliminated, step length/frequency may vary from the actual values.

In addition, the sample size may be small; accordingly, type II error may be caused by the sample size in some results. In the present study, the result of the corrected 40-m sprint time

from 60-100 m was not significant, but the *P* value was 0.075. If this change was significant, the result suggested that sprint performance in the deceleration phase was improved by caffeine supplementation. Similarly, the result of maximum velocity was not significant, but the *P* value was 0.062. If this change was significant, the result could be interpreted to suggest that the sprint performance with caffeine in the last 40 m did not change because of the greater reduction in running velocity in the deceleration phase despite passing 60 m with higher velocity than with placebo; namely, caffeine, in contrast to the ergogenicity aforementioned, negatively affected or did not affect sprint performance in the deceleration phase. Therefore, the statistically unchanged time in the last 40 m, from 60-100 m, needs to be discussed carefully.

Some participants were moderate to high caffeine users as classed previously (48). The effect of daily habitual caffeine consumption is now controversial. Evans et al. (9) indicated that high caffeine users would not obtain caffeine's ergogenicity. On the other hand, Grgic & Mikulic (48) reported the ergogenic effect of caffeine irrespective of daily habitual caffeine consumption. Furthermore, the latest meta-analysis concluded no influence of habitual caffeine intake on the ergogenic effect of acute caffeine supplementation (49). In line with this notion, there was no association between habitual caffeine intake and changes in the 100-m sprint time with caffeine supplementation (R = 0.21, P = 0.300, Fig. S2, Supplemental Digital Content, Relationship between habitual caffeine intake and changes in the corrected 100-m sprint time, http://links.lww.com/MSS/C723). Therefore, habitual caffeine intake by participants did not affect the ergogenicity of caffeine supplementation on sprint performance in this study.

As mentioned above, most participants in the present study were subelite sprinters (25). Thus, it is still unclear whether caffeine shortens 100-m sprint running time in elite sprinters (e.g., Olympic-level sprinters). A previous study found that caffeine supplementation enhanced national- or international-level jumpers' running velocities during the approach for those running in the long jump (50). Given this and the present study, caffeine supplementation may have an ergogenic effect on the 100-m sprint performance of elite sprinters; however, the truth needs to be investigated hereafter.

CONCLUSIONS

In conclusion, this study suggested that acute caffeine supplementation enhances the corrected 100-m sprint time by improving 60-m sprint performance following more explosive acceleration in the early stage of the acceleration phase in the actual 100-m sprint field test. This study is the first direct evidence to indicate caffeine's ergogenicity on sprint running in athletics. Further investigations to elucidate the mechanisms of caffeine's ergogenicity in sprint running performance are needed.

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FIGURE LEGENDS

Figure 1. The effect of caffeine supplementation on the corrected 100-m sprint time (A), the first 60-m sprint time (B), and the 40-m sprint time from 60-100 m during TTs (D). **Significantly different from placebo ($P < 0.01$). The significant positive linear relationship between the change in the corrected 60-m sprint time and the 100-m sprint time with caffeine supplementation (C). Values are presented as the means ± SDs. Each participant's result is presented in the plot (black circle).

Figure 2. The effect of caffeine supplementation on the mean sprint velocity measured every 10 m. *Significantly different from placebo ($P < 0.05$). Values are presented as the means ± SDs.

SUPPLEMENTAL DIGITAL CONTENT

SDC 1: Supplemental Digital Content.docx

Table S1. Variables of all sprint performances in placebo vs. caffeine supplementation

Figure S1. Blood caffeine concentration before and every 30 min after 6 $mg \cdot kg^{-1}$ caffeine ingestion in the preliminary experiment. Bars of the mean blood caffeine concentration are the SDs.

Figure S2. Relationship between habitual caffeine intake and changes in the corrected 100-m sprint time. Each participant's result is presented in the plot (black circle).

Figure 1

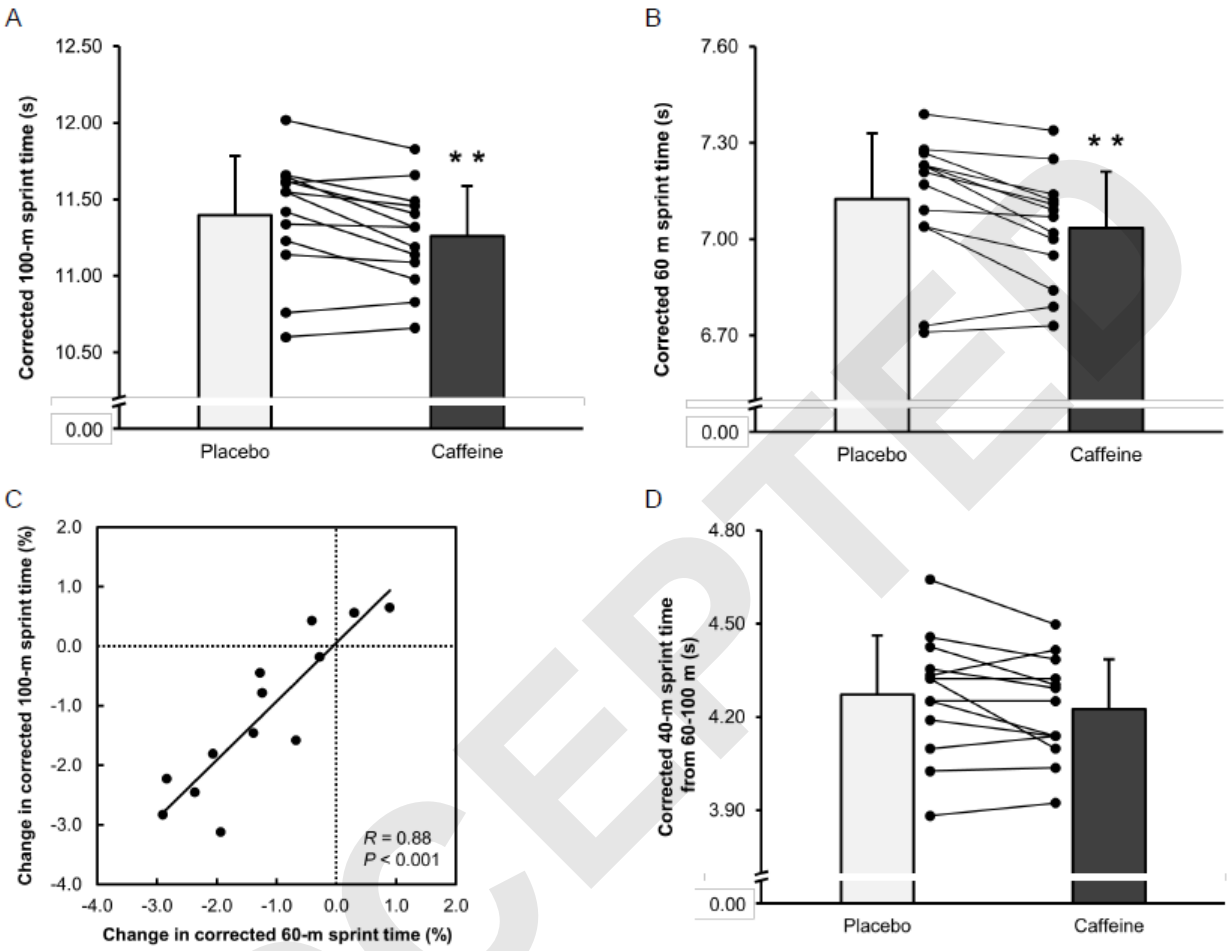

Figure 2

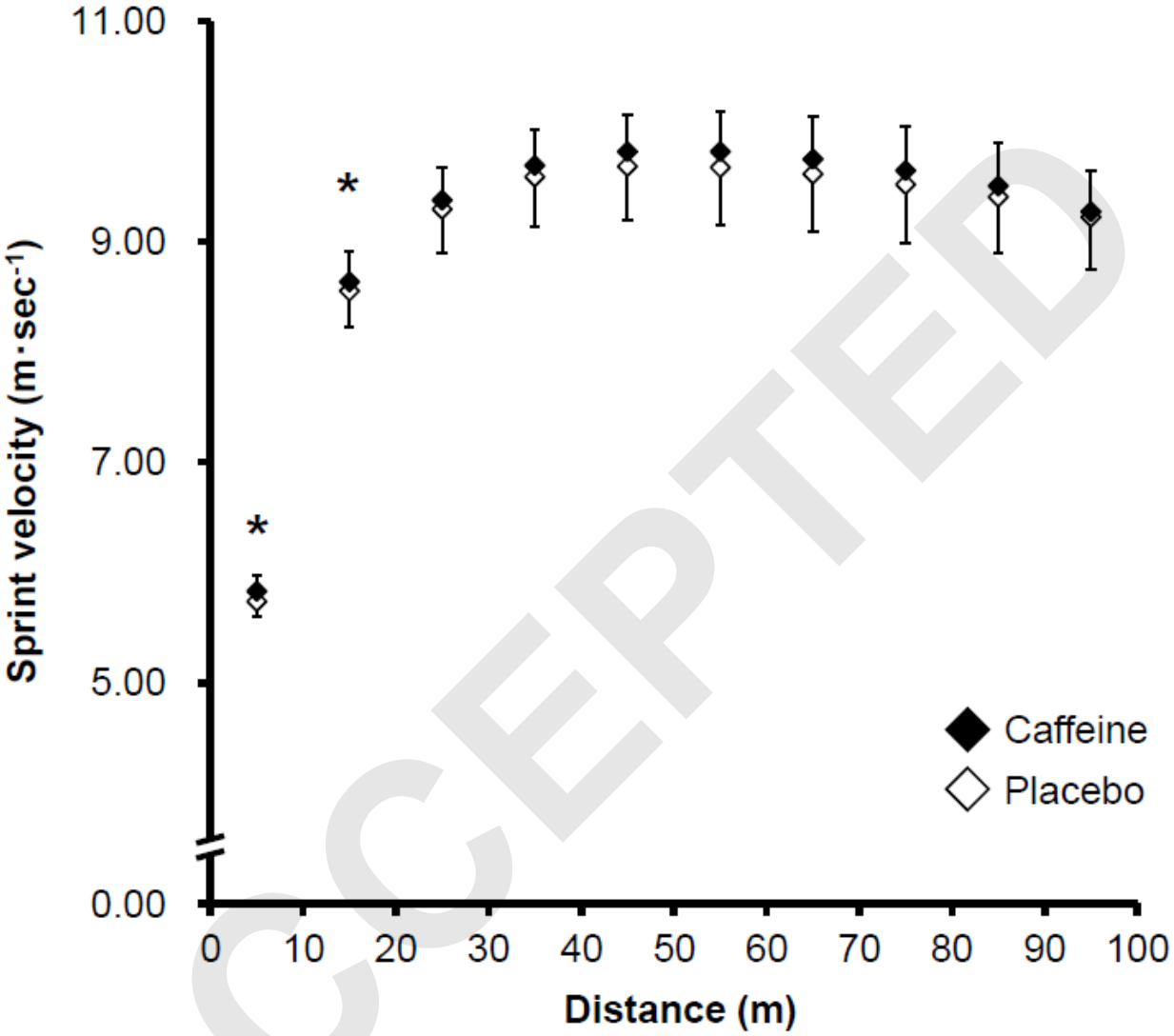

Table 1. Variables of sprint performance and environmental factors in placebo vs. caffeine supplementation.

	Placebo	Caffeine	*P* value	ES
Performance in TT				
Maximum velocity ($m \cdot sec^{-1}$)	9.77 ± 0.49	9.90 ± 0.36	0.062	0.25
Distance to maximum velocity (m)	48.2 ± 6.8	50.4 ± 5.6	0.294	0.32
Mean step length (m)	1.96 ± 0.09	1.97 ± 0.08	0.241	0.14
Mean step frequency ($steps \cdot sec^{-1}$)	4.50 ± 0.16	4.53 ± 0.13	0.417	0.16
Environmental factors				
Temperature (ºC)	31.7 ± 2.4	31.5 ± 3.1	0.843	-0.07
Humidity (%)	54.3 ± 9.7	55.5 ± 9.3	0.733	0.11
Barometric pressure (hPa)	997.1 ± 2.0	997.0 ± 2.2	0.908	-0.04
Wind ($m \cdot sec^{-1}$)	0.6 ± 1.9	0.5 ± 0.9	0.839	-0.08

Values are presented as mean SD.

Table 2. Variables of sprint performance and environmental factors in the first vs. the second trial.

	First trial	Second trial	*P* value	ES
Performance in TT				
100-m sprint time before correction (sec)	11.22 ± 0.37	11.36 ± 0.47	0.087	-0.28
Corrected 100-m sprint time (sec)	11.29 ± 0.36	11.37 ± 0.37	0.185	-0.19
Corrected 60-m sprint time (sec)	7.06 ± 0.21	7.10 ± 0.18	0.320	-0.16
Corrected 40-m sprint time during 60-100 m (sec)	4.23 ± 0.16	4.27 ± 0.19	0.130	-0.20
Maximum velocity ($m \cdot sec^{-1}$)	9.90 ± 0.38	9.76 ± 0.48	0.059	0.27
Distance to maximum velocity (m)	50.8 ± 4.3	47.8 ± 7.6	0.140	0.43
Mean velocity every 10 m ($m \cdot sec^{-1}$)				
0-10 m	5.78 ± 0.16	5.79 ± 0.13	0.860	-0.06
10-20 m	8.63 ± 0.31	8.56 ± 0.31	0.021*	0.24
20-30 m	9.39 ± 0.33	9.28 ± 0.36	0.026*	0.29
30-40 m	9.72 ± 0.36	9.56 ± 0.41	0.013*	0.37
40-50 m	9.82 ± 0.37	9.68 ± 0.45	0.062	0.32
50-60 m	9.83 ± 0.39	9.67 ± 0.51	0.049*	0.30
60-70 m	9.76 ± 0.39	9.60 ± 0.52	0.040*	0.29
70-80 m	9.66 ± 0.41	9.51 ± 0.52	0.050	0.29
80-90 m	9.52 ± 0.42	9.40 ± 0.49	0.111	0.24
90-100 m	9.30 ± 0.38	9.20 ± 0.46	0.252	0.21
Mean step length (m)	1.97 ± 0.07	1.96 ± 0.09	0.639	0.05
Mean step frequency ($steps \cdot sec^{-1}$)	4.53 ± 0.14	4.49 ± 0.15	0.204	0.25

Values are presented as the mean ± SD of the mean. * Significantly different ($P < 0.05$).

Figure S1. Blood caffeine concentration before and every 30 min after 6 mg·kg^{-1} caffeine ingestion in the preliminary experiment. Bars of the mean blood caffeine concentration are the SDs.

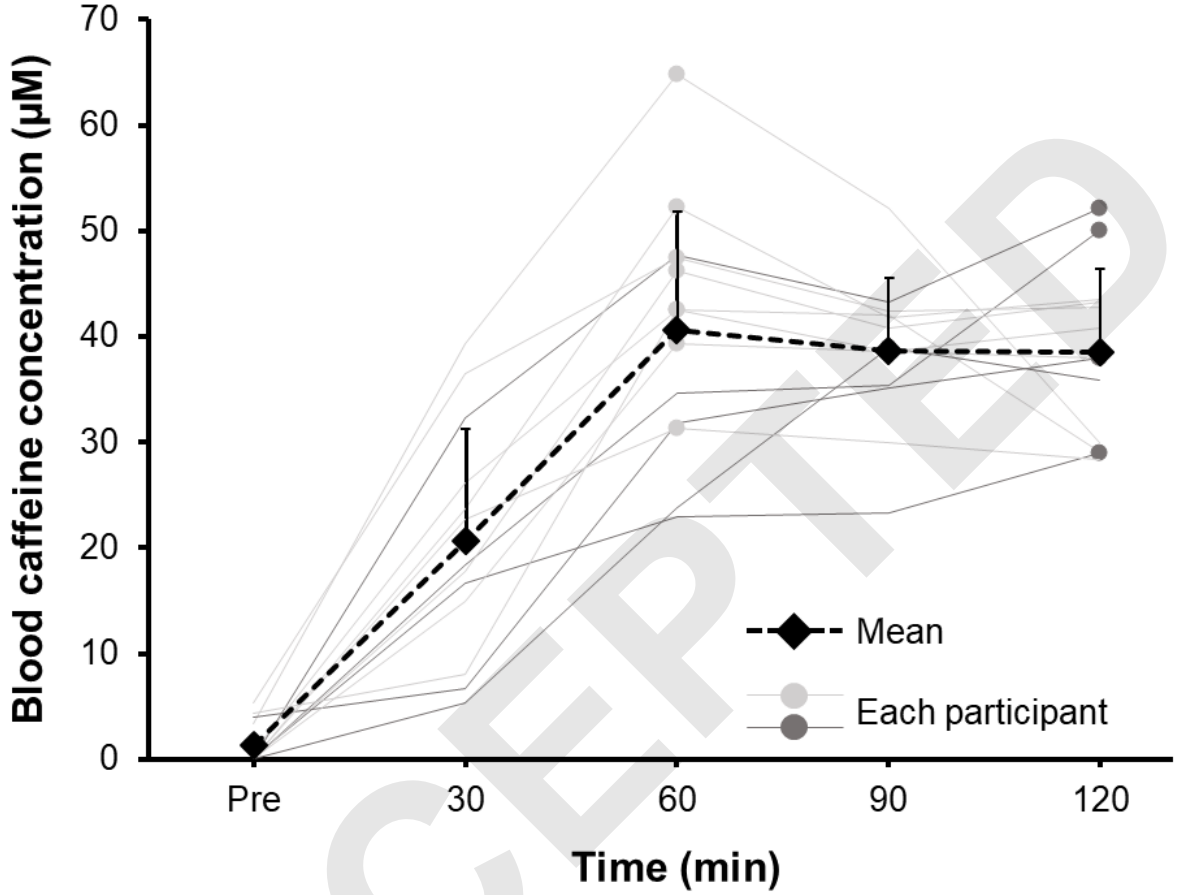

Figure S2. Relationship between habitual caffeine intake and changes in the corrected 100-m sprint time. Each participant's result is presented in the plot (black circle).

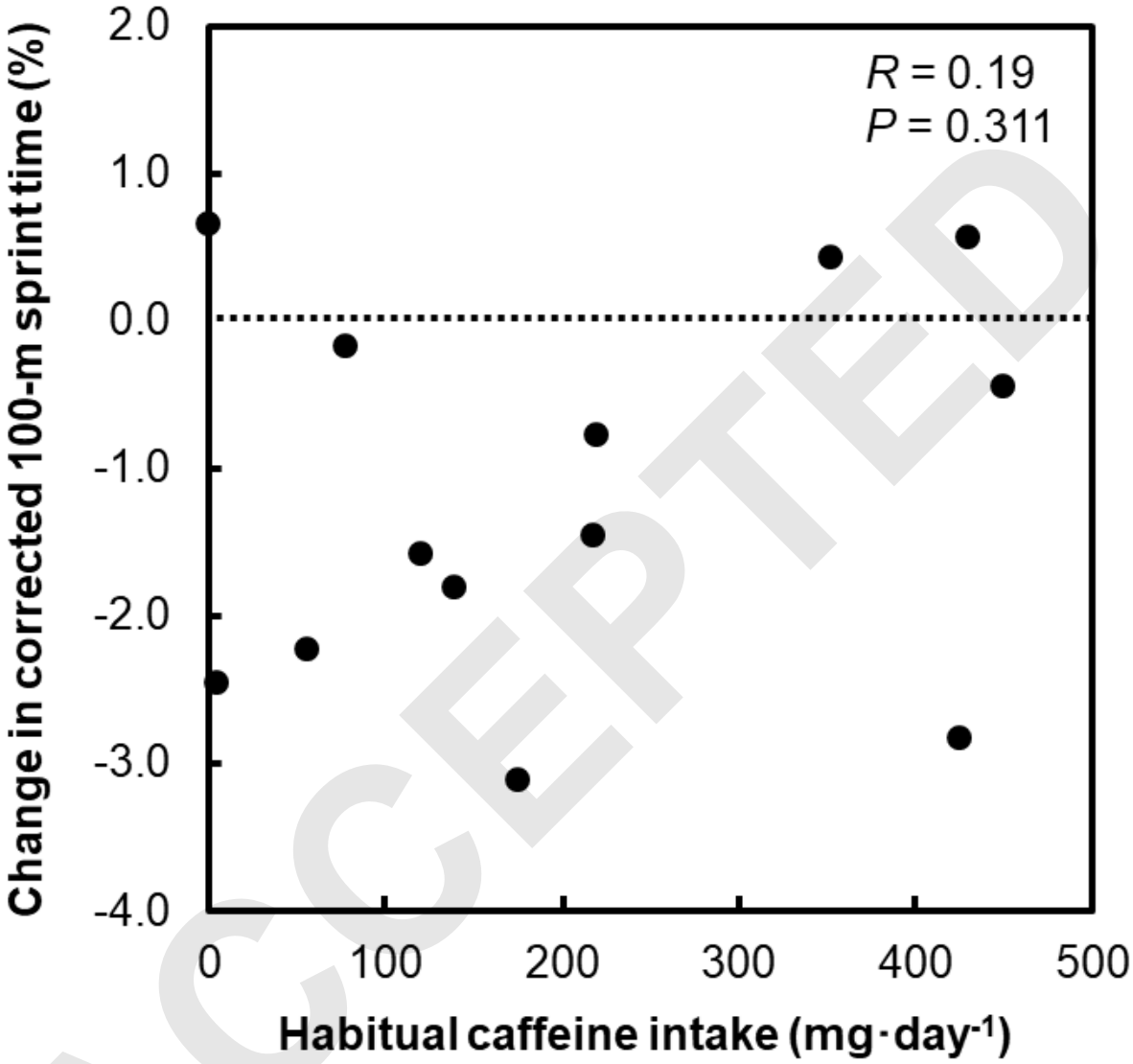

Table S1. Variables of all sprint performances in placebo vs. caffeine supplementation

	Placebo	**Caffeine**	***P* value**	**ES**
100-m sprint time before correction (sec)	11.36 ± 0.49	11.22 ± 0.35	0.058	-0.27
Corrected 100-m sprint time (sec)	11.40 ± 0.39	11.26 ± 0.33	0.007**	-0.33
Corrected 60-m sprint time (sec)	7.12 ± 0.20	7.03 ± 0.17	0.002**	-0.42
Corrected 40-m sprint time during 60-100 m (sec)	4.27 ± 0.19	4.23 ± 0.16	0.075	-0.23
Maximum velocity ($m \cdot sec^{-1}$)	9.77 ± 0.49	9.90 ± 0.36	0.062	0.25
Distance to maximum velocity (m)	48.2 ± 6.8	50.4 ± 5.6	0.294	0.32
Mean velocity every 10 m ($m \cdot sec^{-1}$)				
0-10 m	5.74 ± 0.14	5.83 ± 0.14	0.044 *	0.64
10-20 m	8.55 ± 0.33	8.64 ± 0.28	0.015 *	0.22
20-30 m	9.30 ± 0.39	9.38 ± 0.29	0.121	0.18
30-40 m	9.59 ± 0.46	9.69 ± 0.32	0.131	0.21
40-50 m	9.68 ± 0.48	9.82 ± 0.33	0.088	0.25
50-60 m	9.68 ± 0.52	9.82 ± 0.37	0.075	0.25
60-70 m	9.61 ± 0.53	9.75 ± 0.38	0.085	0.24
70-80 m	9.52 ± 0.53	9.65 ± 0.40	0.123	0.22
80-90 m	9.41 ± 0.51	9.51 ± 0.40	0.211	0.18
90-100 m	9.22 ± 0.47	9.27 ± 0.38	0.586	0.10
Mean step length (m)	1.96 ± 0.09	1.97 ± 0.08	0.241	0.14
Mean step frequency ($steps \cdot sec^{-1}$)	4.50 ± 0.16	4.53 ± 0.13	0.417	0.16

Values are presented as mean SD. Significant differences (*$P < 0.05$, **$P < 0.01$).