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ABSTRACT

The purpose of this study was to evaluate the accuracy and the reliability a new running computer system (RS800sd, Polar®, Kempele, Finland) which includes the measurement of running speed (RS) and stride rate (SR). Eight well-trained triathletes participated in this study. First, they completed an incremental continuous maximum test on a treadmill (from 12 km.h-1 to 18 km.h-1) at 0% grade. Secondly, the subjects took part in a second test to determine RS800sd intra-reproductibility to evaluate running speed. They ran twice during 5 minutes at a pace corresponding to their maximal lactate steady-state. During these two tests, RS and SR were recorded by the RS800sd system, by an optical sensor system (for RS) and a force-sensitive device (for SR). No difference was found between the RS800sd system and the reference systems both for RS (ICC=0.95) and SR (ICC=0.69). Moreover RS measures were statistically repeatable (r^2=0.97, P<0.01). This study provided evidence for the validity of the RS800sd system for measuring the kinematic characteristics of running (speed and frequency). Further investigations are needed to replicate these findings at lower running speeds, notably during walking to assess its capacity to evaluate physical activity in natural conditions.

INTRODUCTION

Paragraph number 1 Recent studies have highlighted a possible discrepancy between factors affecting efficiency during competition and those classically identified during experimental settings in laboratory. One of the main differences is related to the stability of power output and/or running speed in laboratory studies when compared with pacing strategies used during races in competition. Over the last decades technological improvements have enabled sport scientists and coaches to identify and understand the characteristics of physical performance in sport. Due to miniaturization, new devices such as powermeters [14], heart rate monitors [10] or gas analyzers [20] can now be worn by athletes in order to facilitate multiple measurements under field conditions. Therefore, technology has been massively used to understand skills and expertise in human locomotion such as running [15], cycling [1], swimming [28]

Paragraph number 2 In running events, descriptive kinematic parameters such as running speed (RS), stride rate (SR) and stride length (SL) are often investigated. Evidence suggests that they are identified as main factors for coaches designing training programs [2, 13]. Initially, the analysis of running characteristics was limited to laboratory sessions or restricted areas to determine descriptive kinematic analysis such as SL and SR. In this context, heavy scientific protocols have been set using photographic [19] or video analysis [11], photoelectric systems [2] or contact-sensors [7]. More recently, pacing strategies during running competitions and/or training have also been identified as being stochastic [33]. Even if the reproduction of this situation is difficult to reproduce in laboratory conditions, the variability of running pace has been investigated to underline the genesis of induced fatigue and its consequences on the overall performance [3]. The recording kinematic parameters continuously during a running race occurring during a marathon, running event of a triathlon or duathlon is still difficult for sport scientists. Mastroianni et al. [21] explained thereby that many studies examining self pacing have been limited to relatively global characterizations of exercise over moderate or long distances.

Paragraph number 3 In this context, objective physical activity monitoring technologies (*e.g.* accelerometers) have been developed to provide robust measures of physical activity [6, 9, 32]. This technology using accelerometers employed in population-based surveillance most of the time has begun to supplement usual data with step counts, which provide a simple, stable metric to monitor ambulatory physical activity. The accelerometer RS800sd (Polar Electro, Kempele, Finland) has been developed to enable such an evaluation from a performance point of view, in both competition and training. Thus, this device could be a practical mean for recording stride characteristics (SL/SR, RS) without discomfort for athletes, coaches and sport scientists. Firstly, the major purpose of this study was then to test the validity and the accuracy of the Polar® RS800sd on a treadmill ranging from low to high running intensity in well-trained triathletes. Secondly, the aim of this investigation was to evaluate the reproducibility of speed measurement during a repeated rectangular test with intervening recovery time.

Material and methods

Subjects. Eight well-trained triathletes volunteered to participate in this study after they were informed of the nature and possible inconveniences associated with the experiment. The subjects were familiar with all testing procedures and gave their written informed consent before participation. Subjects mean (± SD) age, weight, height and $\dot{V}O_{2max}$ were 31.7 ± 5.3 yrs, 69.7 ± 7.9 kg, 177.5 ± 6.8 cm and 62.6 ± 3.8 $mlO_2.min^{-1}.kg^{-1}$,respectively. All of them were endurance trained triathletes, who trained 6-8 times per week. Five of them were confirmed runners with personal best under 37 minutes over 10 km running performance.

Instrumentation.

- *Uniaxial accelerometry (anteroposterior axis).* The s3 accelerometer (Polar RS800sd, Kempele, Finland) is a very small (3,5 x 5 x 0,7 cm) and light weight (20g) commercial device with a time-sampling mechanism that allows it to provide a chronological measure of the frequency, intensity and duration of movement. It was necessary to hook this system to the shoe laces to prevent any extraneous movement. This tool allows data to be analyzed over user-defined intervals (ranging from 1 second to 1 minute). In this study, epoch duration was set at 30 seconds for each running speed. This epoch was selected, as this was the epoch duration that would not likely be used in field-based studies, allowing data to be collected for up to 15 days with no download. The unit was stored in the watch supplied wearied by the subjects during running. Before each test, the s3 sensor was calibrated, as recommended by the manufacturer to integrate each runner's stride characteristics. Each subject had to follow the pace (*i.e.* 12 km/h) imposed by the treadmill including acceleration and deceleration phases for 5 minutes. Hence the distance measured by each system was identical. The distance calculated by the RS800sd system was then compared, corrected manually according to the distance calculated thanks to the optical system mounted on the treadmill.
- *Optical sensor system.* During both tests, treadmill speed was recorded with a custom made optical device. The device mainly consisted of an infra-red sensor connected to an USB data acquisition board (DT9800, Data Translation, Marlboro, USA) and reflectors evenly spaced on the treadmill strip. The signal was continuously acquired at a 1kHz sampling frequency and processed in real time so that treadmill speed was displayed on a PC screen with a 0.1 $km.h^{-1}$ accuracy (Testpoint software, Measurement Computing Corporation, Norton, USA). Treadmill speed signal was simultaneously stored on hard drive for further comparison with RS800sd.
- *Force-sensitive system.* SR was calculated from two force sensing resistors (Interlink Electronics, Camarillo, USA) connected to a portable data logger device (ME6000, Mega Electronics Ltd., Kuopio, Finland). These footswitches which were very reduce in size (1,5 x

1,5 x 0,02 cm) were mounted on the sockliner of the right shoe, under the heel and the base of the first metatarsus. Subsequent analyses were performed using the Origin 6.1 software (OriginLab, Northampton, USA).

Recordings of all measurements were referenced to the time-synchronization, so that the retrieved data could be matched temporally.

Protocol

Each subject completed two experimental sessions separated by at least 3 days. The first one was an incremental treadmill test to determine maximal oxygen uptake ($\dot{V}O_2$ max) and the speed corresponding to the maximal lactate steady state (MLSS). The second one was a rectangular test performed at the maximal lactate steady state intensity to evaluate the repeatability of speed and stride rate measurement. During all the experimental protocol strenuous physical was restricted.

Maximal Running Test (MRT). Before the test, subjects performed a familiarization period composed by 15 minutes à 10km.h^{-1}. After 15 minutes rest , the test began at 12 km.h^{-1}, at 0% grade and the speed was increased by 1 km.h^{-1} every 3 minutes until volitional exhaustion. Subjects were requested to maintain the same position on the treadmill using a rope tied around their waist level. Between each increment, there was a 30 seconds rest period to collect capillary blood samples from ear lobes. Blood lactate was analyzed using the Lactate Pro system previously validated by Pyne et al. [25]. Oxygen uptake ($\dot{V}O_2$) was also recorded every 5 seconds using the portable gas analyser Cosmed K4b² System (Cosmed, Roma, Italy) [20]. $\dot{V}O_2$ max was determined according to criteria described by Howley et al. [17] — that is, a plateau in $\dot{V}O_2$ despite an increase in power output, a respiratory exchange ratio value of 1.15, or a Heart rate (HR) over 90% of the predicted maximal HR. MLSS was assessed according to the method previously described by Snyder et al. (1994) [30]. During the entire test mean running speed (RS) and stride rate (SR) values were determined during 120 seconds for each step using both the RS800sd and the optical and the force-sensitive capture systems. RS and SR values were recorded at a sampling rate of 1Hz for the RS800sd system and at 1 and 1000 Hz for the optical and the force-sensitive capture systems respectively. The data recorded during the first and the last thirty seconds of each 3 minutes interval were annuled in order to ensure the steady-state of the speed imposed by the treadmill. During this test values of SR and RS recorded using the different devices were compared at low and high pace (12 $km.h^{-1}$, 18 $km.h^{-1}$).

Repeatability test (RT). After a three-day recovery period, the subjects took part in a second test in order to evaluate the repeatability of RS and SR measurements. The subjects had to run two times for 5 minutes at a pace corresponding to their maximal lactate steady-state. The treadmill speed was monitored with the optical system. The speed values measured during each running bout were compared to evaluate the repeatability of pace calculated by the RS800sd. Similarly to the MRT mean RS and SR data were calculated by the average of the values recorded during the middle 120 seconds of each interval. These data were collected at a sampling rate of 1 Hz by both systems as undertaken in the MRT protocol.

Statistical analysis. All the results are expressed as mean ± standard deviation, and level of significance was set as $P<0.05$. For both sessions, SR and RS values were compared between periods and devices using a two way repeated measures ANOVA. The normality of all distributions of the values were previously tested using the Shapiro-wilk test. A Tuckey post-hoc test was used to determine any differences between the intervals. SR and RS reliability was assessed by comparing the variability of different values of the same subject to the total variation across all measurements and all subjects using the intraclass correlation coefficient (ICC). Furthermore, the accuracy of the Polar RS800sd for RS and SR was determined according to the method of Bland and Altman [4]. For this analysis, the measuring agreement of this device was estimated by indicating the differences in speeds and SR between the two methods measurement systems. The mean of the difference represented the bias between the two measurement systems. This value plus and minus two standard deviations represented the limits of agreement for speed and SR measurement using the Polar RS800sd system. The data were presented graphically comparing the difference between the methods versus their average values for both RS and SR.

Results

Maximal Running Test (MRT).

Values of stride rate and running speed during the incremental test are presented table 1. During this test RS or SR values were unaffected by the system of measurement at low and high pace (P>.05, respectively for RS and SR, ICC = 0.97 and 0.97). In addition, as shown in **Fig**. **1**, the confidence interval for the bias (*i.e.* mean difference between the two systems) for RS was 0.39 to -0.63 $km.h^{-1}$. Almost all the individual values were within the limits of agreement, and for each of the exercise intensities, only two individual values (out of 56) were outside the limits of agreement. Thus, 95% of the measurements were less than two standard deviations.

Repeatability test (RT)

Values of stride rate and running speed during the reproductibility test are presented table 2. SR and RS measurements appeared consistent for a same subject during the repeatability test while the pace imposed by the treadmill was strictly the same during the two running legs (P>.05, respectively for RS and SR, ICC = 0.95 and 0.69). For SR, results revealed that 95.4%

of the values were also within the range of values authorized for the agreement although the confidence interval for the bias was very narrow (0.03 Hz) (**Fig. 2**)

In addition, there was a high correlation between SR results obtained by use of RS800sd or the force-sensitive system ($r^2=0.973$, $P<0.001$).

Discussion

Paragraph The aim of this study was to evaluate the accuracy and the reliability of a new running computer system (RS800sd, Polar®, Kempele, Finland) for measuring running speed and stride rate. The first obvious finding of this study indicated that running speed measurements using the RS800sd system were not statistically different compared to those obtained with the optical sensor system (*i.e.* reference system). The results showed a validity at 95% of the RS800sd system for RS measurements for the same subjects over a range of speeds from 12 to 18 km.h^{-1}. Moreover, these measures were statistically repeatable ($r=0.92$, $P<0.01$). The second main finding of this study was the proof of performance of the stride rate measurement within the new s3 accelerometer. The data from the MRT assessment indicated that the accuracy of the RS800sd did not differ from the criterion of the force-sensitive system (error of 1.4%).

Running Speed Measurement

Paragraph The speed values recorded with the RS800sd system were significantly different for each interval ($p<0.05$). This is a positive finding because many researches studies have demonstrated that vertical axis accelerometers often fail to evaluate high RS. Brage et al. [6] suggested that accelerometers may reach the upper limit of their dynamic range with increasing speed. This could explain some of leveling-off observed at high RS. As speed increased, the relative duration of the contact phase of the stride decreases and the rebound becomes assymetric. To restore the vertical momentum (constant across running speeds), average contact phase acceleration must increase with shorter contact duration. In this perspective, Bouten and al. [5] reported for the triaxial Tracmor that the oxygen uptake was better predicted from registrations in the anterior-posterior direction, despite the major acceleration component occurring along the longitudinal axis. This anterior-posterior axis may be required to differentiate intensity in the running range with accelerometry. The accuracy of the s3 sensor to evaluate RS from 12 to 18 $km.h^{-1}$ could be explained by its horizontal axis. At fast speeds, horizontal power increased indeed from 12 to 18 $km.h^{-1}$ of running, whereas vertical power is almost constant in this interval [8]. Hence, as horizontal power predominates during running, the RS800sd system seems to be particularly adapted to the biomechanical characteristics of running. Moreover, as its output rose approximately linearly until 18 km^{-1}, the dynamic range of this system appeared large enough to ensure RS measurement without leveling-off.

Paragraph Mostly, the continuous recording of pace and heart rate (HR) are widely used to control training intensity. Usually, HR is the most common parameter used by coaches to program training, despite a large discomfort produced by wearing of the elastic belt. Managing training programs based on HR is obvious but also questionable because its concordance with RS can be altered by physiological modifications during prolonged exercises (e.g. dehydration, environmental conditions, stress…) [24]. Consequently, measuring RS is a more reliable means for keeping an objective control of absolute intensity during training sessions when environmental conditions remain stable. The results of the present study demonstrated the accuracy of the RS800sd for RS evaluation (error of 4.9%). The results were significantly better than those observed in the pedometer / accelerometer literature. For example, Brage et al. [6] observed that the Computer Science and Applications Model 7164 output rose approximately linearly with speed until 8 or 9 km.h^{-1}, but at higher velocities its output leveled off and showed a tendency to drop close to 16 km.h^{-1}. Nevertheless, recent studies demonstrated a greater accuracy for global positioning system (GPS) technique to measure RS. Townshend et al. [32] demonstrated that the speed determined by GPS was highly correlated with actual speed (r=0.9994). Mean error was only 0.01 m.s^{-1}. A second method (using *differential* GPS, DGPS) involves placing a stationary receiver at a known location that compares its position with that given by the satellites, sending correctional information to the roving receiver. Some authors [29] showed that the accuracy of speed assessment using the DGPS mode could even been improved as compared to non-differential GPS. GPS technique presents all the same some limits. Speed can only be measured in an environment in which access to the satellites is not obstructed by urban canyons, tall skyscrapers, tunnels, caves, compact trees. Moreover, RS measurements cannot be completed by SR ones using the GPS technique. At last, the differential GPS equipment remains still cumbersome to be transported by athletes [32].

Paragraph While pace is recognized as a central parameter to control during training for maximizing performance in aerobic sports [3], the present device could improve the adjustment of intensity particularly during interval training sessions. The present study demonstrated the instrument reliability of RS measurement (r=0.95, P<0.05). Such reliability levels could help the athlete to reproduce exactly the same pace during repeated single running bouts of a training session.

Paragraph The instantaneous recording of RS also represents an interesting opportunity for coaches and sport scientists to accurately determine pacing strategies adopted in competition by athletes. As this study demonstrated that the recording of RS with RS800sd is reproducible at 96%, using the RS800sd enables the identical reproduction of the speed achieved during competition in training. The light weight of the Polar RS800sd (20g) enables indeed measurement without disturbing the running pattern of athletes. A thorough investigation of the literature revealed that the analysis of pacing strategies studying are being a more and more investigated area because of their strong impact on performance and direct link to neuromuscular and central fatigue [27]. The continuous measurement of RS in competition offersan attractive variable to appreciate pacing strategies in competition.

Paragraph. In this context, the use of the RS800sd system could help triathletes to adjust their RS during the cycle-to-run transition. Bernard et al. [2] found that triathletes prefer to run at a high pace after cycling at 80 and 100 rpm because of high SR (1.51-1.52 Hz). The knowledge of RS but also of SR could subsequently help triathletes to better optimize their stride patterns after the cycling stage and, consequently to improve their pacing strategies. In this perspective, providing bio-feedback to the runners concerning his SR could allow a means of better adjusting his running technique according to the task demands of cycling via the commercialisation of cadence-meters.

Stride Rate Measurement

Paragraph The second major result of this investigation was the accuracy of SR values recorded with the s3 accelerometer. This study demonstrated a level of accuracy at 98.6% of SR values recorded with this device ($P<0.001$). Those results were positive in comparison to the values obtained using other commercial pedometers/accelerometers. Eslinger et al. [12] observed that the Actical accelerometer tended to overestimate intervals at speeds higher than 9.6 $km.h^{-1}$. A possible explanation for this overestimation could be a lack of specificity in terms of discrimination between actual steps and spurious accelerometer movement caused by the bouncing of the accelerometer on the waist belt. As the RS800sd system was hooked to the shoe laces to prevent any extraneous movement, this could explain the accuracy of this system to evaluate SR.

Paragraph When considering the effect of selected descriptor of running mechanics on economy under controlled running speeds, SR is one of the few variables that has been shown to affect economy using direct experimental device. A basic curvilinear relationship between SL and economy has been well-documented [16]. The Bland-Altman method to confront SR measurement using both force-sensitive system and s3-sensor demonstrated indeed a very narrow bias (**Fig. 2**); only 4.6% of the values had a greater difference than 0.026 Hz (*i.e.* 1.56 strides.min^{-1}). These results demonstrated the accuracy of the RS800sd system in SR recording in the same subjects in a range from 80 to 95 strides.min^{-1} which corresponded to the range of values adopted by runners in endurance events [18]. Thus, the RS800sd enables coaches and sport scientists to appreciate the ability of athletes to adjust their SR in relation to speed variations faced with their own fatigue or changes in circuit gradient.

Paragraph. For any given running speed, it is generally known that metabolic efficiency is optimized through one specific combination of SL and SR. Clearly, individuals do modify their running styles. Saito et al. [26] showed that trained runners increased their speed to 7 m.s^{-1} by lengthening their stride, whereas untrained runners increased SL only up to 5.5 m.s^{-1}; any further increase in running speed was achieved primarily by increasing SR. In the same way, Nelson and Gregor [22] observed that a group of distance runners shortened their strides at a given speed by an average of 7 cm during the 4 year of their varsity careers. The simple process of shortening or lengthening the stride has an important effect on all the active musculature. Each muscle is forced to work on a slightly different region of its force-velocity curve and, as a consequence, changes in efficiency can be anticipated [26]. Thus, the RS800sd could be used during training to accelerate the adoption of a higher SR for a given speed by providing instantaneous bio-feedback to the athlete.

Paragraph The accuracy of the RS800sd system in measuring SR and SL enables the athlete to adjust his/her own characteristics and to the task demands. Nummela et coll. [23] demonstrated for example a decrease in SL during a 5-km running race for well-trained distance runners. According to these authors, fatigue is determined by the neuromuscular capacity to produce a force which can be evidenced by kinematic parameters (SL/SR, flying and contact times). Although the RS800sd did not measure flying and contact times, the knowledge of SL and SR enables coaches and scientists to appreciate the ability of an athlete to maintain identical speeds and to adapt his/her stride according to muscular fatigue during a race. The use of the RS800sd system could allow coaches to better design training programs via the understanding of biomechanical changes induced by fatigue on stride pattern.

Paragraph In conclusion, we have demonstrated in the present study the validity (accuracy and reliability) of a new accelerometer device for measuring kinematic characteristics while running (speed and frequency)for only 8 trained triathletes performing in laboratory condition. This new device is then practical and useful both for laboratories and field testing, thanks to its practicality and light weight. Further investigations are needed to test the validity of the Polar RS800sd system at speed above 19 $km.h^{-1}$ and for measuring unsteady activity with sudden change in acceleration. Other population could be tested and the number of subjects could be increased to improve the accuracy of the results obtained. Moreover, it would be interesting to evaluate the RS800sd system at lower speeds, notably during walking, to assess its capacity to evaluate physical activity in a free-living conditions.

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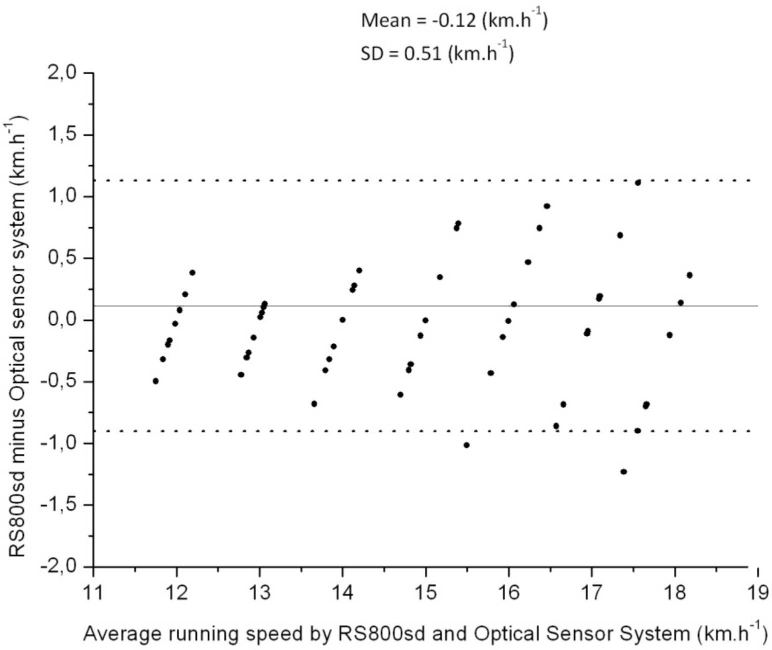

Fig. 1 Bland–Altman plot depicting the calculated bias between the two devices of measurement and the limits of agreement for speed running measurement using the RS800sd system (n=56).

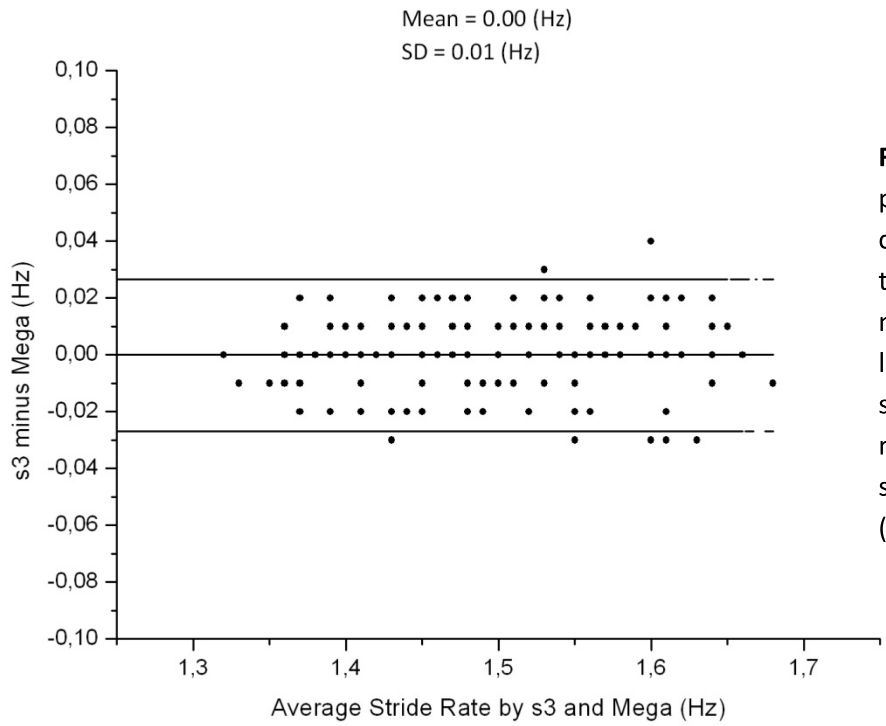

Fig. 2 Bland–Altman plot depicting the calculated bias between the two devices of measurement and the limits of agreement for stride rate measurement using the s3 accelerometer (n=153).

Optical sensor system Running speed (km.h^{-1}) Means ± SD	RS800sd Running speed (km.h^{-1}) Means ± SD	Force-sensitive system Stride rate (Hz) Means ± SD	RS800sd Stride rate (Hz) Means ± SD
12.0 ± 0.07	11.96 ± 0.27	1.49 ± 0.07	1.50 ± 0.08
13.0 ± 0.05	12.98 ± 0.27	1.50 ± 0.04	1.49 ± 0.07
14.0 ± 0.06	13.90 ± 0.38	1.54 ± 0.06	1.53 ± 0.04
15.01 ± 0.07	15.12 ± 0.59	1.48 ± 0.07	1.50 ± 0.04
16.0 ± 0.03	16.08 ± 0.60	1.46 ± 0.06	1.47 ± 0.05
17.02 ± 0.03	16.82 ± 0.52	1.47 ± 0.06	1.47 ± 0.06
18.0 ± 0.08	17.49 ± 0.64	1.48 ± 0.07	1.48 ± 0.08

Table 1. Running speed and stride rate during incremental maximum running test. Comparison between RS800 and optical sensor or force-sensitive systems.

Subjects	Running speed Leg 1 ($km.h^{-1}$) Means ± SD	Running speed Leg 2 ($km.h^{-1}$) Means ± SD	Stride rate Leg 1 (Hz) Means ± SD	Stride rate Leg 2 (Hz) Means ± SD
1	14.8 ± 0.2	15.3 ± 0.4	1.44 ± 0.03	1.41 ± 0.02
2	15.1 ± 0.1	15.2 ± 0.1	1.54 ± 0.01	1.50 ± 0.04
3	15.4 ± 0.2	15.5 ± 0.2	1.49 ± 0.03	1.47 ± 0.04
4	14.0 ± 0.2	14.6 ± 0.3	1.48 ± 0.05	1.46 ± 0.03
5	13.3 ± 0.5	13.3 ± 0.2	1.56 ± 0.02	1.52 ± 0.03
6	15.5 ± 0.1	15.4 ± 0.1	1.45 ± 0.03	1.45 ± 0.02
7	14.6 ± 0.1	14.8 ± 0.1	1.40 ± 0.03	1.42 ± 0.01
8	16.0 ± 0.3	16.3 ± 0.2	1.50 ± 0.04	1.49 ± 0.03

Table 2. Running speed and stride rate reproducibility during rectangular submaximum running test (RS800sd measurements).