



HAL
open science

Accuracy and Repeatability of the Polar ® RS800sd to evaluate stride rate and running speed

Christophe Hauswirth, Yann Le Meur, Antoine Couturier, Jeanick
Brisswalter, Thierry Bernard

► **To cite this version:**

Christophe Hauswirth, Yann Le Meur, Antoine Couturier, Jeanick Brisswalter, Thierry Bernard. Accuracy and Repeatability of the Polar ® RS800sd to evaluate stride rate and running speed. International Journal of Sports Medicine, 2009, 30 (5), pp.354-359. 10.1055/s-0028-1105936 . hal-01713133

HAL Id: hal-01713133

<https://insep.hal.science/hal-01713133>

Submitted on 20 Feb 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Accuracy and Repeatability of the Polar[®] RS800sd to evaluate stride rate and running**
2 **speed**

3
4
5 CHRISTOPHE HAUSSWIRTH¹, YANN LE MEUR^{1,2}, ANTOINE COUTURIER¹, JEANICK
6 BRISSWALTER², THIERRY BERNARD²

7
8 ¹ Research Mission, Laboratory of Biomechanics and Physiology, National Institute of Sport
9 and Physical Education, 75012 Paris, FRANCE.

10 ² Laboratory of university of Toulon-Var, unit sporting ergonomics and performance, Handibio,
11 83952 La Garde Cedex, FRANCE.

12 **Corresponding Author :**

13 Dr Christophe Hausswirth, PhD

14 Research Mission,

15 National Institute of the Sport and Physical Education (INSEP),

16 11 Avenue du Tremblay, 75012 Paris, FRANCE

17 Phone : + 33 1-41-74-43-85

18 Fax : + 33 1-41-74-45-35

19 E-mail : christophe.hausswirth@insep.fr

20 **Running title: Stride rate and running speed evaluation**

21 **Section of the journal : training & testing**

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22

Accuracy and Repeatability of the Polar® RS800sd to evaluate stride rate and running speed

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.

1 INTRODUCTION

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

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

1 examining self pacing have been limited to relatively global characterizations of exercise over
2 moderate or long distances.

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

15

16 **Material and methods**

17

18 **Subjects.** Eight well-trained triathletes volunteered to participate in this study after they were
19 informed of the nature and possible inconveniences associated with the experiment. The
20 subjects were familiar with all testing procedures and gave their written informed consent
21 before participation. Subjects mean (\pm SD) age, weight, height and $\dot{V}O_{2\max}$ were 31.7 ± 5.3 yrs,
22 69.7 ± 7.9 kg, 177.5 ± 6.8 cm and 62.6 ± 3.8 mlO₂.min⁻¹.kg⁻¹, respectively. All of them were
23 endurance trained triathletes, who trained 6-8 times per week. **Five of them were confirmed**
24 **runners with personal best under 37 minutes over 10 km running performance.**

25 **Instrumentation.**

1 • *Uniaxial accelerometry (anteroposterior axis)*. The s3 accelerometer (Polar RS800sd,
2 Kempele, Finland) is a very small (3,5 x 5 x 0,7 cm) and light weight (20g) commercial device
3 with a time-sampling mechanism that allows it to provide a chronological measure of the
4 frequency, intensity and duration of movement. It was necessary to hook this system to the
5 shoe laces to prevent any extraneous movement. This tool allows data to be analyzed over user-
6 defined intervals (ranging from 1 second to 1 minute). In this study, epoch duration was set at
7 30 seconds for each running speed. This epoch was selected, as this was the epoch duration that
8 would not likely be used in field-based studies, allowing data to be collected for up to 15 days
9 with no download. The unit was stored in the watch supplied wearied by the subjects during
10 running. Before each test, the s3 sensor was calibrated, as recommended by the manufacturer to
11 integrate each runner's stride characteristics. Each subject had to follow the pace (*i.e.* 12 km/h)
12 imposed by the treadmill including acceleration and deceleration phases for 5 minutes. Hence
13 the distance measured by each system was identical. The distance calculated by the RS800sd
14 system was then compared, corrected manually according to the distance calculated thanks to
15 the optical system mounted on the treadmill.

16 • *Optical sensor system*. During both tests, treadmill speed was recorded with a custom
17 made optical device. The device mainly consisted of an infra-red sensor connected to an USB
18 data acquisition board (DT9800, Data Translation, Marlboro, USA) and reflectors evenly spaced
19 on the treadmill strip. The signal was continuously acquired at a 1kHz sampling frequency and
20 processed in real time so that treadmill speed was displayed on a PC screen with a 0.1 km.h⁻¹
21 accuracy (Testpoint software, Measurement Computing Corporation, Norton, USA). Treadmill
22 speed signal was simultaneously stored on hard drive for further comparison with RS800sd.

23 • *Force-sensitive system*. SR was calculated from two force sensing resistors (Interlink
24 Electronics, Camarillo, USA) connected to a portable data logger device (ME6000, Mega
25 Electronics Ltd., Kuopio, Finland). These footswitches which were very reduce in size (1,5 x

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

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

6 ***Protocol***

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

13 *Maximal Running Test (MRT)*. Before the test, subjects performed a familiarization period
14 composed by 15 minutes à 10km.h⁻¹. After 15 minutes rest , the test began at 12 km.h⁻¹, at 0%
15 grade and the speed was increased by 1 km.h⁻¹ every 3 minutes until volitional exhaustion.
16 Subjects were requested to maintain the same position on the treadmill using a rope tied around
17 their waist level. Between each increment, there was a 30 seconds rest period to collect
18 capillary blood samples from ear lobes. Blood lactate was analyzed using the Lactate Pro
19 system previously validated by Pyne et al. [25]. Oxygen uptake ($\dot{V} O_2$) was also recorded every
20 5 seconds using the portable gas analyser Cosmed K4b² System (Cosmed, Roma, Italy) [20].
21 $\dot{V} O_2 \text{ max}$ was determined according to criteria described by Howley et al. [17] — that is, a
22 plateau in $\dot{V} O_2$ despite an increase in power output, a respiratory exchange ratio value of 1.15,
23 or a Heart rate (HR) over 90% of the predicted maximal HR. MLSS was assessed according to

1 the method previously described by Snyder et al. (1994) [30]. During the entire test mean
2 running speed (RS) and stride rate (SR) values were determined during 120 seconds for each
3 step using both the RS800sd and the optical and the force-sensitive capture systems. RS and
4 SR values were recorded at a sampling rate of 1Hz for the RS800sd system and at 1 and 1000
5 Hz for the optical and the force-sensitive capture systems respectively. The data recorded
6 during the first and the last thirty seconds of each 3 minutes interval were annuled in order to
7 ensure the steady-state of the speed imposed by the treadmill. During this test values of SR and
8 RS recorded using the different devices were compared at low and high pace (12 km.h⁻¹, 18
9 km.h⁻¹).

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

18 *Statistical analysis*. All the results are expressed as mean \pm standard deviation, and level of
19 significance was set as P<0.05. For both sessions, SR and RS values were compared between
20 periods and devices using a two way repeated measures ANOVA. The normality of all
21 distributions of the values were previously tested using the Shapiro-wilk test. A Tuckey post-
22 hoc test was used to determine any differences between the intervals. SR and RS reliability
23 was assessed by comparing the variability of different values of the same subject to the total
24 variation across all measurements and all subjects using the intraclass correlation coefficient
25 (ICC). Furthermore, the accuracy of the Polar RS800sd for RS and SR was determined

1 according to the method of Bland and Altman [4]. For this analysis, the measuring agreement
2 of this device was estimated by indicating the differences in speeds and SR between the two
3 methods measurement systems. The mean of the difference represented the bias between the
4 two measurement systems. This value plus and minus two standard deviations represented the
5 limits of agreement for speed and SR measurement using the Polar RS800sd system. The data
6 were presented graphically comparing the difference between the methods versus their average
7 values for both RS and SR.

8

9 **Results**

10

11 *Maximal Running Test (MRT).*

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

20

21 *Repeatability test (RT)*

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

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

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

5

6 **Discussion**

7

8 **Paragraph** The aim of this study was to evaluate the accuracy and the reliability of a new
9 running computer system (RS800sd, Polar[®], Kempele, Finland) for measuring running speed
10 and stride rate. The first obvious finding of this study indicated that running speed
11 measurements using the RS800sd system were not statistically different compared to those
12 obtained with the optical sensor system (*i.e.* reference system). The results showed a validity at
13 95% of the RS800sd system for RS measurements for the same subjects over a range of speeds
14 from 12 to 18 km.h⁻¹. Moreover, these measures were statistically repeatable ($r=0.92$, $P<0.01$).
15 The second main finding of this study was the proof of performance of the stride rate
16 measurement within the new s3 accelerometer. The data from the MRT assessment indicated
17 that the accuracy of the RS800sd did not differ from the criterion of the force-sensitive system
18 (error of 1.4%).

19

20 *Running Speed Measurement*

21

22 **Paragraph** The speed values recorded with the RS800sd system were significantly different for
23 each interval ($p<0.05$). This is a positive finding because many researches studies have
24 demonstrated that vertical axis accelerometers often fail to evaluate high RS. Brage et al. [6]
25 suggested that accelerometers may reach the upper limit of their dynamic range with increasing

1 speed. This could explain some of leveling-off observed at high RS. As speed increased, the
2 relative duration of the contact phase of the stride decreases and the rebound becomes
3 assymmetric. To restore the vertical momentum (constant across running speeds), average
4 contact phase acceleration must increase with shorter contact duration. In this perspective,
5 Bouten and al. [5] reported for the triaxial Tracmor that the oxygen uptake was better predicted
6 from registrations in the anterior-posterior direction, despite the major acceleration component
7 occurring along the longitudinal axis. This anterior-posterior axis may be required to
8 differentiate intensity in the running range with accelerometry. The accuracy of the s3 sensor to
9 evaluate RS from 12 to 18 km.h⁻¹ could be explained by its horizontal axis. At fast speeds,
10 horizontal power increased indeed from 12 to 18 km.h⁻¹ of running, whereas vertical power is
11 almost constant in this interval [8]. Hence, as horizontal power predominates during running,
12 the RS800sd system seems to be particularly adapted to the biomechanical characteristics of
13 running. Moreover, as its output rose approximately linearly until 18 km⁻¹, the dynamic range
14 of this system appeared large enough to ensure RS measurement without leveling-off.

15 **Paragraph** Mostly, the continuous recording of pace and heart rate (HR) are widely used to
16 control training intensity. Usually, HR is the most common parameter used by coaches to
17 program training, despite a large discomfort produced by wearing of the elastic belt. Managing
18 training programs based on HR is obvious but also questionable because its concordance with
19 RS can be altered by physiological modifications during prolonged exercises (e.g. dehydration,
20 environmental conditions, stress...) [24]. Consequently, measuring RS is a more reliable means
21 for keeping an objective control of absolute intensity during training sessions when
22 environmental conditions remain stable. The results of the present study demonstrated the
23 accuracy of the RS800sd for RS evaluation (error of 4.9%). The results were significantly
24 better than those observed in the pedometer / accelerometer literature. For example, Brage et al.
25 [6] observed that the Computer Science and Applications Model 7164 output rose

1 approximately linearly with speed until 8 or 9 km.h⁻¹, but at higher velocities its output leveled
2 off and showed a tendency to drop close to 16 km.h⁻¹. Nevertheless, recent studies
3 demonstrated a greater accuracy for global positioning system (GPS) technique to measure RS.
4 Townshend et al. [32] demonstrated that the speed determined by GPS was highly correlated
5 with actual speed (r=0.9994). Mean error was only 0.01 m.s⁻¹. A second method (using
6 differential GPS, DGPS) involves placing a stationary receiver at a known location that
7 compares its position with that given by the satellites, sending correctional information to the
8 roving receiver. Some authors [29] showed that the accuracy of speed assessment using the
9 DGPS mode could even been improved as compared to non-differential GPS. GPS technique
10 presents all the same some limits. Speed can only be measured in an environment in which
11 access to the satellites is not obstructed by urban canyons, tall skyscrapers, tunnels, caves,
12 compact trees. Moreover, RS measurements cannot be completed by SR ones using the GPS
13 technique. At last, the differential GPS equipment remains still cumbersome to be transported
14 by athletes [32].

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

21 **Paragraph** The instantaneous recording of RS also represents an interesting opportunity for
22 coaches and sport scientists to accurately determine pacing strategies adopted in competition by
23 athletes. As this study demonstrated that the recording of RS with RS800sd is reproducible at
24 96%, using the RS800sd enables the identical reproduction of the speed achieved during
25 competition in training. The light weight of the Polar RS800sd (20g) enables indeed

1 measurement without disturbing the running pattern of athletes. A thorough investigation of the
2 literature revealed that the analysis of pacing strategies studying are being a more and more
3 investigated area because of their strong impact on performance and direct link to
4 neuromuscular and central fatigue [27]. The continuous measurement of RS in competition
5 offersan attractive variable to appreciate pacing strategies in competition.

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

14

15 *Stride Rate Measurement*

16

17 **Paragraph** The second major result of this investigation was the accuracy of SR values
18 recorded with the s3 accelerometer. This study demonstrated a level of accuracy at 98.6% of
19 SR values recorded with this device ($P < 0.001$). Those results were positive in comparison to
20 the values obtained using other commercial pedometers/accelerometers. Eslinger et al. [12]
21 observed that the Actical accelerometer tended to overestimate intervals at speeds higher than
22 9.6 km.h^{-1} . A possible explanation for this overestimation could be a lack of specificity in terms
23 of discrimination between actual steps and spurious accelerometer movement caused by the
24 bouncing of the accelerometer on the waist belt. As the RS800sd system was hooked to the

1 shoe laces to prevent any extraneous movement, this could explain the accuracy of this system
2 to evaluate SR.

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

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

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

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

21

22

23

24

25 **References**

- 1 1. *Atkinson G, Davison R, Jeukendrup A, Passfield L.* Science and cycling: current
2 knowledge and future directions for research. *J Sports Sci* 2003; 21: 767-87
- 3 2. *Bernard T, Vercruyssen T, Grego F, Hausswirth C, Lepers R, Vallier JM, Brisswalter J.*
4 Effect of cycling cadence on subsequent 3 km running performance in well trained triathletes.
5 *Brit J of Sport Med* 2003; 37: 154-159
- 6 3. *Billat VL, Slawinski J, Danel M, Koralzstein JP.* Effect of free versus constant pace on
7 performance and oxygen kinetics in running. *Med Sci Sports Exerc* 2001; 33: 2082-8
- 8 4. *Bland JM, Altman DG.* Statistical methods for assessing agreement between two
9 methods of clinical measurement. *Lancet I*, 1986; 307-310
- 10 5. *Bouten CV, Westerterp KR, Verduin M, Janssen JD.* Assessment of energy expenditure
11 for physical activity using a triaxial accelerometer. *Med Sci Sports Exerc* 1994; 26: 1516–1523
- 12 6. *Brage S, Wedderkopp N, Franks PW, Andersen LB, Froberg K.* Reexamination of
13 validity and reliability of the CSA monitor in walking and running. *Med Sci Sports Exerc* 2003;
14 35: 1447-54
- 15 7. *Brisswalter J, Legros P.* Comparaison du coût énergétique dans une population de
16 coureurs de moyennes, de longues distances. *Science & Sports* 1992; 7: 43-49
- 17 8. *Cavagna GA, Thys H, Zamboni A.* The sources of external work in level walking and
18 running. *J Physiol* 1976; 262: 639-657
- 19 9. *Crouter SE, Schneider PL, Karabulut M, Bassett DR Jr.* Validity of 10 electronic
20 pedometers for measuring steps, distance, and energy cost. *Med Sci Sports Exerc* 2003; 35:
21 1455-60
- 22 10. *Crouter SE, Albright C, Bassett DR Jr.* Accuracy of polar S410 heart rate monitor to
23 estimate energy cost of exercise. *Med Sci Sports Exerc* 2004, 36: 1433-9
- 24 11. *Elliott BC, Roberts AD.* A biomechanical evaluation of the role of fatigue in middle-
25 distance running. *Can J Appl Sport Sci* 1980; 5: 203-7

- 1 12. *Eslinger DW, Probert A, Gorber SC, Bryan S, Laviolette M, Tremblay MS.* Validity of
2 the Actical accelerometer step-count function. *Med Sci Sports Exerc* 2007; 39: 1200-1204
- 3 13. *Eston RG, Lemmey AB, McHugh P, Byrne C, Walsh SE.* Effect of stride length on
4 symptoms of exercise-induced muscle damage during a repeated bout of downhill running.
5 *Scand J Med Sci Sports.* 2000; 10: 199-204
- 6 14. *Gardner AS, Stephens S, Martin DT, Lawton E, Lee H, Jenkins D.* Accuracy of SRM
7 and power tap power monitoring systems for bicycling. *Med Sci Sports Exerc* 2004 36: 1252-8
- 8 15. *Hauswirth C, Lehénaff D.* Physiological demands of long distance running. *Sports Med*
9 2001, 31: 678-689
- 10 16. *Högberg P.* How do stride length and stride frequency influence the energy-output
11 during running ? *Arbeitsphysiologie* 1952; 14: 437-41
- 12 17. *Howley ET, Bassett DR Jr, Welch HG.* Criteria for maximal oxygen uptake: review and
13 commentary. *Med Sci Sports Exerc*, 1995; 27: 1292-301
- 14 18. *Hunter I, Smith G.* Preferred and optimal stride frequency, stiffness and economy:
15 changes with fatigue during a 1-h high-intensity run. *Eur J Appl Physiol* 2007; 100: 653-661
- 16 19. *Jones FP, Hanson JA.* Fatigue effects on patterns of movement. *Ergonomics* 1971; 14:
17 391-410
- 18 20. *Mac Naughton LR, Sherman R, Roberts S, Bentley DJ,* Portable gas analyser Cosmed
19 K4b² compared to a laboratory based mass spectrometer system, *J Sports Med Phys Fitness*
20 2005; 45: 315-23
- 21 21. *Mastroianni GR, Zupan MF, Chuba DM, Berger RC, Wile AL.* Voluntary pacing and
22 energy cost of off-road cycling and running. *Appl Ergon* 2000; 31: 479-85
- 23 22. *Nelson RC, Gregor RJ.* Biomechanics of distance running: a longitudinal study. *Res Q*
24 1976; 47: 417-28

- 1 23. *Nummela AT, Leena L, Paavolainen M, Sharwood KA, Lambert MI, Noakes TD, Rusko*
2 *HK.* Neuromuscular factors determining 5 km running performance and running economy in
3 well-trained athletes. *Eur J Appl Physiol* 2006; 97: 1-8
- 4 24. *O'Toole ML, Douglas PS, Hiller WD.* Use of heart rate monitors by endurance athletes:
5 lessons from triathletes. *J Sports Med Phys Fitness* 1998; 38: 181-7
- 6 25. *Pyne DB, Boston T, Martin DT, Logan A.* Evaluation of the Lactate Pro blood lactate
7 analyser. *Eur J Appl Physiol* 2000; 82: 112-6
- 8 26. *Saito M, Kobayani K, Miyashita M, Hoshikawa T.* Temporal patterns in running. In:
9 Nelson RC, Morehouse CA, eds. *Biomechanics IV*. Baltimore: University Park Press, 1974;
10 106-111
- 11 27. *St Clair Gibson A, Lambert EV, Rauch LH, Tucker R, Baden DA, Foster C, Noakes TD.*
12 The role of information processing between the brain and peripheral physiological systems in
13 pacing and perception of effort. *Sports Med* 2006; 36: 705-22
- 14 28. *Smith DJ, Norris SR, Hogg JM.* Performance Evaluation of swimmers : scientific tools.
15 *Sports Med* 2002; 32: 539-554
- 16 29. *Snutz Y, Herren R.* Assessment of speed of human locomotion using a differential
17 satellite global positioning system. *Med Sci Sports Exerc* 2000; 32: 642-646
- 18 30. *Snyder AC, Woulfe T, Welsh R, Foster C.* A simplified approach to estimating the
19 maximal lactate steady state. *Int J Sports Med* 1994; 5: 255-261
- 20 31. *Taylor CR,* Force development during sustained locomotion: a determinant of gait speed
21 and metabolic power. *J Exp Bio* 1985; 253-262
- 22 32. *Townshend AD, Worringham CJ, Stewart IB.* Assessment of speed and position during
23 human locomotion using nondifferential GPS. *Med Sci Sports Exerc* 2008; 40: 124-132

- 1 33. *Tucker R, Lambert MI, Noakes TD. An analysis of pacing strategies during men's*
2 *world-record performances in track athletics. Intern J of Sports Physiol and Perf* 2006; 1: 233-
3 245
4
5

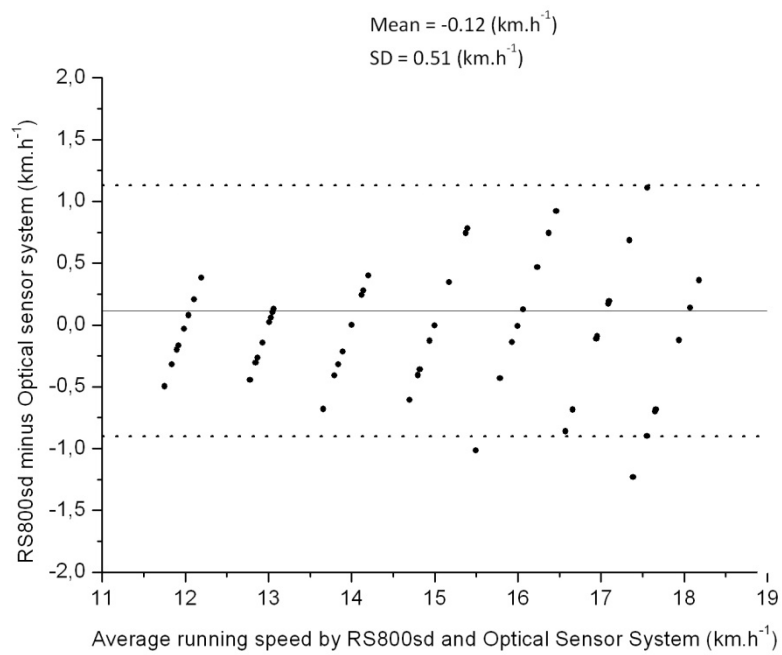


Fig. 1 Bland–Altman plot depicting the calculated bias between the two devices of measurement and the limits of agreement for speed running measurement using the RS800sd system (n=56).

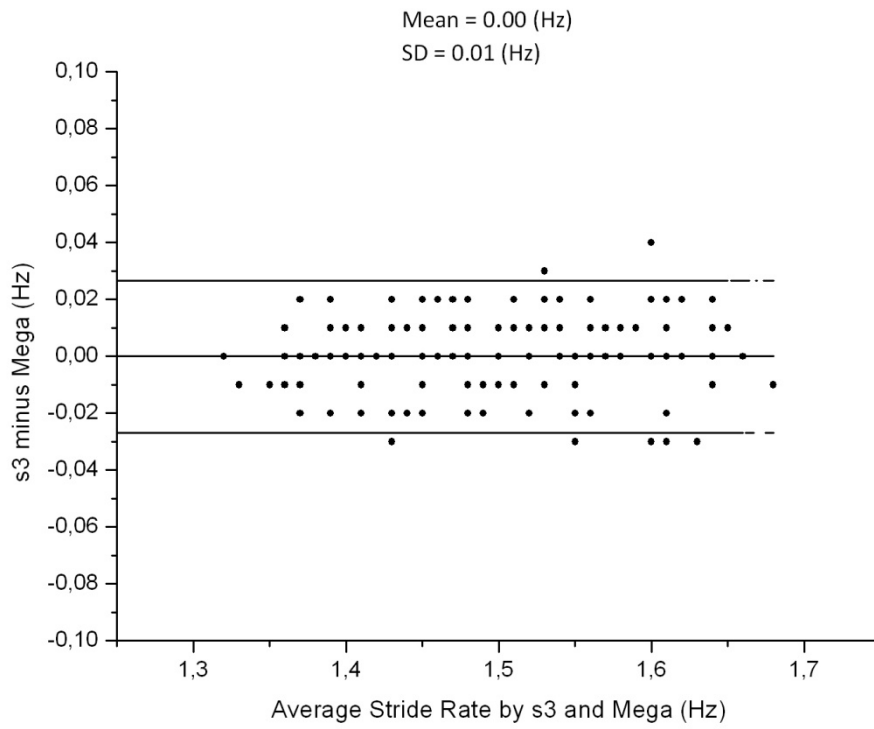


Fig. 2 Bland–Altman plot depicting the calculated bias between the two devices of measurement and the limits of agreement for stride rate measurement using the s3 accelerometer (n=153).

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).