HHS Public Access

Author manuscript

Int J Sports Med. Author manuscript; available in PMC 2015 October 26.

Published in final edited form as:

Int J Sports Med. 2013 June ; 34(6): 497–501. doi:10.1055/s-0032-1327661.

Measurement Accuracy of Heart Rate and Respiratory Rate during Graded Exercise and Sustained Exercise in the Heat Using the Zephyr BioHarness™

J.-H. Kim[1], **R. Roberge**[1], **J. B. Powell**[1], **A. B. Shafer**[2], and **W. Jon Williams**[3]

[1]NPPTL/NIOSH/CDC, Technology Research Branch, Pittsburgh, United States

[2]Exercise Science, Pittsburgh, University of Pittsburgh, United States

[3]NIOSH/CDC, Technology Research Branch, Pittsburhg, United States

Abstract

The Zephyr BioHarness™ was tested to determine the accuracy of heart rate (HR) and respiratory rate (RR) measurements during 2 exercise protocols in conjunction with either a laboratory metabolic cart (Vmax) or a previously validated portable metabolic system (K4b^2). In one protocol, HR and RR were measured using the BioHarness and Vmax during a graded exercise up to $\dot{V}O_{2max}$ (n = 12). In another protocol, HR and RR were measured using the BH and K4b^2 during sustained exercise (30 % and 50 % $\dot{V}O_{2max}$ for 20 min each) in a hot environment (30°C, 50 % relative humidity) (n = 6). During the graded exercise, HR but not RR, obtained from the BioHarness was higher compared to the Vmax at baseline and 30 % $\dot{V}O_{2max}$ ($p < 0.05$), but showed no significant difference at other stages with high correlation coefficients for both HR (r = 0.87–0.96) and RR (r = 0.90–0.99 above 30 % $\dot{V}O_{2max}$). During the exercise in the heat, there were no significant differences between the BioHarness and K4b^2 system. Correlation coefficients between the methods were low for HR but moderately to highly correlated (0.49–0.99) for RR. In conclusion, the BioHarness is comparable to Vmax and K4b^2 over a wide range of $\dot{V}O_2$ during graded exercise and sustained exercise in the heat.

Keywords

physiological monitoring; portable metabolic system; reliability

Introduction

Measurement of heart rate (HR) and respiratory rate (RR) is important in medical evaluations, exercise science studies, and various other field scenarios (e. g., sports; occupational activities). HR can be identified by manual means (i.e., palpation of the pulse),

Correspondence: Dr. W. Jon Williams, PhD, NIOSH/CDC Technology, Research Branch, 626 Cochrans Mill Road, 15236 Pittsburhg, United States, Tel.: + 1/412/386 4002, Fax: + 1/412/386 6864, aun7@cdc.gov.

Conflict of interest: The authors identify no conflicts of interest in the conduct of this study.

Disclaimer: The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of product names does not imply endorsement.

or through the use of a device that captures bioelectric signals generated by the heart. One popular technology for modern wireless HR monitors consists of a chest strap that contains sensors for capturing cardiac electrical impulses conducted across the skin. These impulses are then transmitted to a receiver for real-time display and/or downloading for later analysis. Estimation of RR by observation and counting is unreliable and variable, even among trained healthcare professionals [12]. This is due, in part, to the limitations of identifying shallow respirations and the interposition of various other modifiers such as talking, emotional states (e. g., sobbing, etc.) and movement (e. g., during exercise test, etc.). In response to these limitations, numerous methodologies have been developed that utilize various technologies to measure RR. These RR measurement technologies include contact devices that require the use of nasal prongs, facemasks or endotracheal tubes (e. g., capnography, fiber optic nasal sensors, nasal thermisters, nasal pressure tranducers, pyroelectric monitor strips, pneumotachography, etc.) to detect changes in such parameters as exhaled carbon dioxide, air temperature and air humidity [2, 7, 10, 12], but that may themselves alter the RR and pattern. Other technologies include pulse oximetry-derived plethysmograms, electrocardiogram-based respiratory rate derivation, respiratory inductance plethysmography, and thermal imaging of expired air, all of which can be impacted by motion artifact [2, 12].

The BioHarness™ (Zephyr Technology Corporation, Annapolis, MD, US) is a U.S. FDA-approved wireless, ambulatory physiological monitoring device that consists of a 50 mm wide, adjustable fabric chest strap and attached transmitter unit (total weight 85 grams). The BioHarness determines HR via capture of cardiac electrical impulses by conductive fabric (anti-microbial silver lycra) skin electrodes that are relayed to the transmitter for electronic filtration and analysis. The BioHarness measures RR through an embedded proprietary capacitive sensor composed of layers of conductive fabric, foam and flexible mylar [6]. Based upon the principle of a strain gauge sensor (i.e., the resistance of a conductor is increased when the area of the conductor is increased) [2], thoracic expansion and contraction cause size differentials that induce changes in capacitance because of resultant changes in impedance (opposition of a circuit to electrical flow). The change in impedance is manifested as a change in waveform signal amplitude represented as a sine wave with downward and upward deflections indicating chest expansion (increased impedance) and contraction (decreased impedance), respectively. To our knowledge, no study has investigated the accuracy of BioHarness-determined HR and RR other than 2 limited manufacturer-directed studies (n = 4) which simply tested BioHarness at a short period of 5-minute static, walking and running exercises (Zephyr Application Notes and White Papers, Zephyr Technology Corp., Annapolis, MD, http://www.zephyr-technology.com/resources/whitepapers) and one recent study which only validated RR measurements relative to percentages of peak treadmill speed [8]. Therefore, the aim of this study was to determine the accuracy of the BioHarness measurements of HR and RR as compared to standard laboratory spirometry during a graded exercise test (GXT) and a previously validated portable metabolic system during a sustained period of exercise in the heat.

Materials and Methods

Subjects

12 healthy men were recruited whose demographics were as follows: mean (standard deviation), age: 25.5 years (4.1), height: 180.1 cm (6.5), weight: 78.8 kg (13.9), and Body Mass Index: 24.2 $kg.m^2$ (3.2). Prior to participation in the 2 protocols, all subjects underwent a medical examination by a licensed physician including a urine screening test for drugs-of-abuse (Triage™, Biosite Inc., San Diego, CA) and both oral and written informed consent was obtained from each subject. The study was approved by the NIOSH Human Subjects Review Board and performed in accordance with the ethical standards of the International Journal of Sports Medicine [9].

Test procedure

The first part of the study was carried out in a physiology laboratory under ambient laboratory conditions (22°C, 40–50 % relative humidity [RH]), and 12 subjects exercised while wearing cotton t-shirts, athletic shorts, and athletic shoes. The subjects also wore a BioHarness while connected by a mouthpiece to a standard metabolic cart with open-circuit spirometry and 12-lead electrocardiogram (Vmax Spectra System, VIASYS, Yorba Linda, CA) while participating in a Graded Exercise Test (GXT) up to their maximal (peak) rate of oxygen consumption ($\dot{V}O_{2max}$). The second part of the testing (heat exposure test: HET) was carried out in an environmental chamber (32°C, 50 % RH; heat index = 35°C) a minimum of 7 days after the GXT. 6 subjects were randomly selected from the original pool of 12 subjects for participation in the HET. These 6 subjects wore the same athletic clothing and shoes as in the GXT and engaged in continuous treadmill exercise at 2 different $\dot{V}O_2$ stages (30 % and 50 % $\dot{V}O_{2max}$ with no rest period between stages). Each stage lasted 20 min for a total of 40 min of exercise. During this part of the testing, the BioHarness was worn concurrently with a previously validated, portable cardiopulmonary breath-by-breath gas exchange analyzer (Model K4 b^2, COSMED, Rome, Italy) that employs a bidirectional digital turbine flowmeter fitted to a facemask [14]. Thus, with the present study design, we tested the accuracy of the BioHarness-determined HR and RR responding to an incremental exercise stress from rest to exhaustion, and a sustained exercise in heat stress conditions to mimic its application in the field.

Statistical analysis

The data were first summarized as a 1-min average value by % $\dot{V}O_{2max}$ in the GXT and by time in the HET for subsequent statistical analysis. Paired-sample Wilcoxon signed rank test and Spearman correlation coefficients for non-parametric variables were performed to determine the systematic mean difference and the degree of monotonic relationship between the methods, respectively. Additionally, Bland-Altman plots were created using SigmaPlot (v.12, Systat Software Inc., San Jose, CA) to quantify disagreements of the individual measurements of the variables between the methods (95 % limits of agreement [LoA] = mean difference ± 1.96 SD). Statistical significance was accepted when $p < 0.05$, and all analyses were performed using a statistical software package (SPSS v.18, IBM, Somers, NY).

Results

All subjects completed GXT (n = 12) and 6 of them also completed HET (n = 6). The descriptive summary and results for statistical analysis during GXT and HET are presented in Table 1, 2, respectively.

During the GXT, overall HR readings during higher intensity exercise were not significantly different between the BioHarness and Vmax. However, BioHarness recorded significantly higher HR than Vmax at lower metabolic rates (Baseline and 30 % $\dot{V}O_{2max}$; $p < 0.05$). Spearman correlation coefficients showed that the measurements by the 2 systems were highly correlated overall with r-values ranging from 0.87 to 0.96 for HR and from 0.80 to 0.97 for RR, and a moderate correlation with a coefficient of 0.50 for RR at 30 % % $\dot{V}O_{2max}$. The Bland-Altman plots indicated a bias of 0.5 (LoA: + 16.3, −15.3) for HR and −0.6 (LoA: + 4.4, −5.6) for RR (Fig. 1a, b). Only one individual measurement (of total 72) was outside the LoA limits for both HR and RR. In terms of agreement, systemic bias between the 2 systems for both HR and RR was very small as indicated by the fact that most of the measurement differences are symmetrical around the bias line. During HET, there were no significant differences between the BioHarness and K4 b^2 for any measured physiological parameter ($p > 0.05$) (Table 2). Spearman correlation coefficients were low for HR (with the exception of baseline [0.89]), whereas RR was moderately to highly correlated, with r-values ranging from 0.49 to 0.99 (Table 2). The Bland-Altman plots indicated a bias of 0.3 (LoA: + 17.8, −17.2) for HR and 0.2 (LoA: + 8.5, −8.2) for RR (Fig. 1c, d). 5 and 4 of the individual measurements for HR and RR, respectively (of total 56), were outside LoA limits. HR and RR measurements between the 2 systems agreed fairly well within LoA; however, the individual data were widely dispersed from the bias line, with more values observed beyond one standard deviation compared to those during GXT.

Discussion

The purpose of the present study was to test the accuracy of the HR and RR measurements obtained from the BioHarness as compared to the Vmax metabolic cart and also to the K4 b^2 portable metabolic measurement system, (such as would be used in field studies), in order to determine its possible utility under various study scenarios. During the GXTs, the Vmax and BioHarness data were concordant, especially with respect to RR determinations, with no significant differences overall, coupled with strong correlation coefficients (Table 1, Fig. 1b). The Bio-Harness recorded slightly lower HR than the Vmax at early stages of GXT, with a mean difference between 3.2 and 4.4 beats·min^{-1} associated with somewhat greater individual HR variability. This difference in HR frequency was attributable to one subject, and resulted in statistically higher HR readings at rest ($p = 0.01$) and during exercise at 30 % $\dot{V}O_{2max}$ ($p = 0.04$). However, HR measurements were not statistically different at any other stage, as indicated by an average mean difference of 2.3 beats·min^{-1}. This variance in HR is unlikely to be related to the RR in as much as it has previously been shown that HR and RR variability are mutually independent of one another [17]. In addition, HR and RR measurements by both systems were strongly correlated, indicating that overall measurement errors are consistent. These results are in close agreement with previously stated accuracy criteria (HR errors of ≤ 5 beats·min^{-1} and correlations of ≥ 0.90) [16] for a

HR monitor compared to EKG. The Bland-Altman plot showed overall bias of 0.5 and LoA between 16.3 and − 15.3 (Fig. 1a) for HR and overall bias of − 0.6 and LoA between 4.4 and − 5.6 for RR (Fig. 1b). These results are comparable to a recently validated HR monitoring device that showed overall bias between 1.8 and − 1.9 and LoA between 14.7 and − 15.7 (during rest to running at 9.6 $km \cdot h^{-1}$) [11] and a transthoracic impedance plethysmography unit that showed a bias of − 1.2 and LoA between 7.5 and − 9.9 (in a triage setting) [12].

Studies by Hailstone and Kilding [8] examined the accuracy of the BioHarness system in subjects performing a GXT. The focus of the research was to determine whether the anaerobic threshold could be identified using RR data from the BioHarness. Although the data from the BioHarness was demonstrated to be similar to that obtained from a standard metabolic cart at exercise intensities < 70 % $\dot{V}O_{2max}$, a significant difference was noted during higher exercise intensities. This is in contrast to our findings in which the BioHarness underestimated HR but not RR at lower exercise intensities but HR and RR were strongly correlated to our metabolic cart at higher intensities under mild laboratory conditions (22°C, 50 %RH). We attribute the discrepency to inter-instrument differences; however, the actual cause of the difference remains unclear.

There were no significant differences in HR and RR measurements between the BioHarness and K4 b^2 systems during the second part of the study (HET) (Table 2). Nevertheless, HR measures were poorly correlated overall, whereas RR showed a slight decrease in correlation coefficient values compared to those during GXT (Table 2). Although the biases between the 2 systems for HR (0.3) and RR (0.2) were minor and smaller than those during GXT, LoA was much wider at 17.8 and − 17.2 for HR and 8.5 and − 8.1 for RR during HET, indicating a greater variability in measurements (Fig. 1b, c). This increased variability during HET may be partially related to increased motion artifact. In addition, given that moisture content on the BioHarness chest strap affects electrical impulse conduction (BioHarness™ User Guide, Zephyr Technology Corp., Annapolis, MD,) differences in moisture (sweat) accumulation on the BioHarness chest strap during a sustained period of exercise in the heat may be responsible for some of the observed variability. Yet, the BioHarness provided reasonably accurate measurements of RR during a sustained period of exercise while showing less accurate, but comparable, results from previous studies that tested a portable plethysmographic device indicating a correlation coefficient of 0.92 (ranging from rest to running at 8.9 $km \cdot h^{-1}$) [18] and 0.98 (walking/running at 50 % $\dot{V}O_{2max}$ in protective clothing) [5]. It is also perhaps not surprising that lower variability for RR than HR was noted for all phases of the current study insofar as while both RR and HR increase abruptly with exercise onset [4, 15], respiration follows a more gradual increase as exercise continues [4] and reaches a steady state that is related to the metabolic demands of exercise [13]. Finally, despite the environmental chamber being lined with stainless steel on its inner and exterior surfaces, no interference with data transmission to a computer located outside of the chamber occurred, a problem we have previously encountered with other systems.

Limitations of the current study include the small number of subjects studied (n = 6 for chamber study and n = 12 for GXT). Nonetheless, in our subjects, between-subject variability was small in terms of functional and demographic characteristics, which could have reduced the likelihood of detecting a true difference (β-error) caused by small samples.

The present study did not include a test on the repeatability of each device tested as suggested to perform in a method comparison study [3], but replicated testing is rarely performed in human subject testing. Lastly, the results from HET need to be interpreted with caution as the protocol compared the BioHarness with a previously validated portable device for its use in a field scenario, but not for validation against a standard laboratory device.

In conclusion, the BioHarness was found to provide reasonably accurate HR and RR measurements comparable to a standard laboratory metabolic system over a wide range of $\dot{V}O_2$ measured during GXTs and to be comparable to a previously validated portable metabolic system during sustained, low and moderate (30 % and 50 % $\dot{V}O_{2max}$) intensity exercise in the heat. Measurement of RR in field-type studies is problematic [1] and the BioHarness offers a relatively unobtrusive manner for obtaining this information accurately. Further investigation into the performance of BioHarness over various types and intensities of exercise in the field is warranted.

Acknowledgments

The authors would like to thank the subjects who generously volunteered their time to participate in this study. The authors would also like to thank Christina Baxter, PhD, of the Technical Support Working Group, Department of Defense, for supplying the investigators with the BioHarness units used in the study. The authors also wish to thank Ronald Shaffer, PhD, Jay Parker, MS, Bill Monaghan, MS, Steven Small (Zephyr Technology Corp.), and Aitor Coca, PhD for their manuscript reviews and suggestions.

References

1. Adams, W. [Accessed on November 14, 2011] Measurement of breathing rate and volume in routinely performed daily activities. California Environmental protection Agency Air Resource Board Research Division Contract No, A033-205. 1993. Available from: http://www,arb,ca,gov/research/apr/past/a033-205.pdf
2. Al-Khalidi F, Saatchi R, Burke D, Elphick H, Tan S. Respiration rate monitoring methods: A review. Ped Pulmonol. 2011; 46:523–529.
3. Bland JM, Altman DG. Measuring agreement in method comparison studies. Stat Methods Med Res. 1999; 8:135–160. [PubMed: 10501650]
4. Caruana-Montaldo B, Gleeson K, Zwillich CW. The control of breathing in clinical practice. Chest. 2000; 117:205–225. [PubMed: 10631221]
5. Coca A, Roberge RJ, Williams WJ, Landsittel DP, Powell JB, Palmiero A. Physiological monitoring in firefighter ensembles: wearable plethysmographic sensor vest versus standard equipment. J Occup Environ Hyg. 2010; 7:109–114. [PubMed: 20017053]
6. Cubitt, C. [Accessed on September 6, 2011] Zephyr Technology Premarketing Notification. 2009. Available from: http://www.accessdata.fda.gov/cdrh_docs/pdf10/K100040.pdf
7. Dodds D, Purdy J, Moulton C. The PEP transducer: a new way of measuring respiratory rate in the non-intubated patient. J Accid Emerg Med. 1999; 16:26–28. [PubMed: 9918282]
8. Hailstone J, Kilding AE. Reliability and validity of the Zephyr BioHarness to measure respiratory responses to exercise. Meas Phys Educ Exerc Sci. 2011; 15:293–300.
9. Harriss D, Atkinson G. Update–ethical standards in sport and exercise science research. Int J Sports Med. 2011; 32:819–821. [PubMed: 22065312]
10. Larsson C, Staun P. Evaluation of a new fibre-optical monitor for respiratory rate monitoring. J Clin Monit Comput. 1999; 15:295–298. [PubMed: 12568135]
11. Lee CM, Gorelick M, Mendoza A. Accuracy of an infrared LED device to measure heart rate and energy expenditure during rest and exercise. J Sports Sci. 2011; 29:1645–1653. [PubMed: 21995327]

12. Lovett PB, Buchwald JM, Sturmann K, Bijur P. The vexatious vital: neither clinical measurements by nurses nor an electronic monitor provides accurate measurements of respiratory rate in triage. Ann Emerg Med. 2005; 45:68–76. [PubMed: 15635313]
13. McArdle, W.; Katch, F.; Katch, V. Exercise Physiology: Energy, Nutrition, and Human Performance. 5. Philadelphia: Lippincott Williams & Wilkins; 2001.
14. McLaughlin JE, King GA, Howley ET, Bassett DR Jr, Ainsworth BE. Validation of the COSMED K4 b2 portable metabolic system. Int J Sports Med. 2001; 22:280–284. [PubMed: 11414671]
15. Miyamoto T, Oshima Y, Ikuta K, Kinoshita H. The heart rate increase at the onset of high-work intensity exercise is accelerated by central blood volume loading. Eur J Appl Physiol. 2006; 96:86–96. [PubMed: 16307281]
16. Terbizan D, Dolezal B, Albano C. Validity of seven commercially available heart rate monitors. Meas Phys Educ Exerc Sci. 2002; 6:243–247.
17. West BJ, Griffin LA, Frederick HJ, Moon RE. The independently fractal nature of respiration and heart rate during exercise under normobaric and hyperbaric conditions. Respir Physiol Neurobiol. 2005; 145:219–233. [PubMed: 15705537]
18. Witt JD, Fisher JR, Guenette JA, Cheong KA, Wilson BJ, Sheel AW. Measurement of exercise ventilation by a portable respiratory inductive plethysmograph. Respir Physiol Neurobiol. 2006; 154:389–395. [PubMed: 16503424]

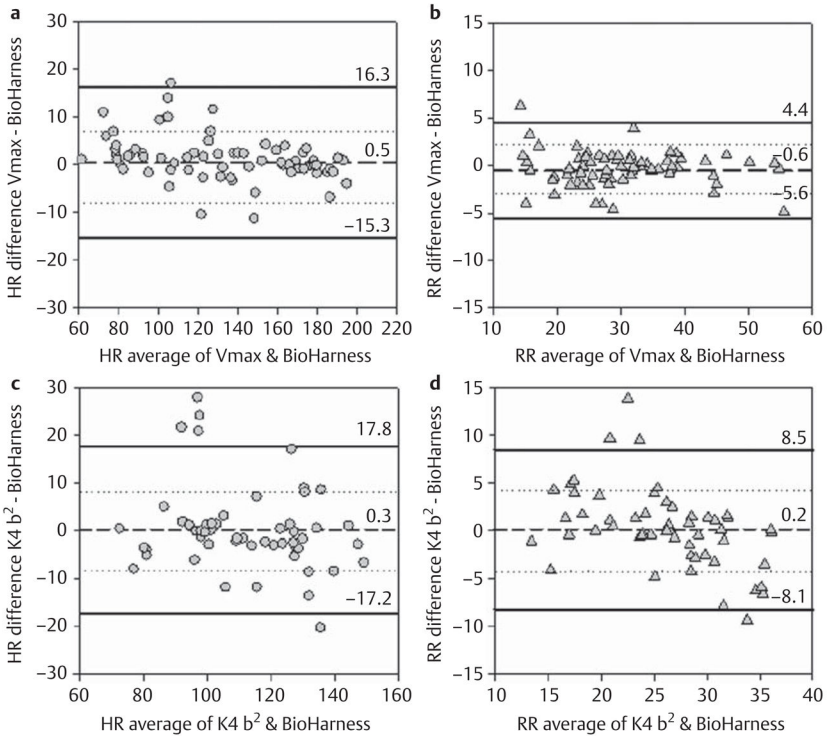

Fig. 1.

Bland-Altman plots for HR and RR measurements during GXT **a, b** and HET **c, d**. Center broken line: mean difference (bias) between the 2 methods. Upper and lower dot lines: mean difference ± 1 SD. Upper and lower solid lines: mean difference ± 1.96 SD (95 % limits of agreement).

Table 1

Summary of HR and RR measurements during Graded Exercise Testing (GXT).

	Heart Rate				Respiratory Rate			
	Vmax	**BioHarness**	**p**	**r_s**	**Vmax**	**BioHarness**	**p**	**r_s**
Baseline	76.9 (8.0)	80.1 (7.1)	0.01	0.87	17.6 (5.4)	18.2 (4.3)	0.70	0.80
30 % $V\dot{O}_{2max}$	100.1 (11.3)	104.5 (11.0)	0.04	0.88	26.1 (4.3)	24.9 (5.1)	0.10	0.50
50 % $V\dot{O}_{2max}$	125.0 (13.4)	123.6 (11.9)	0.53	0.92	26.7 (4.3)	25.4 (4.5)	0.12	0.95
70 % $V\dot{O}_{2max}$	145.3 (13.7)	142.0 (13.8)	0.70	0.90	31.1 (5.1)	31.3 (5.4)	0.88	0.90
90 % $V\dot{O}_{2max}$	171.2 (8.2)	171.8 (7.4)	0.35	0.96	36.6 (7.8)	36.3 (7.8)	0.70	0.99
$V\dot{O}_{2max}$	183.5 (9.1)	182.7 (8.0)	0.29	0.92	42.4 (9.6)	41.9 (8.7)	0.30	0.97

Values are mean (SD) (n = 12)

$V\dot{O}_{2max}$: 46.1 (6.3) ml/kg/min

p: p-value from Paired-Sample Wilcoxon Signed Rank Test

r_S: Spearman correlation coefficient

Table 2

Summary of HR and RR measurements during Heat Exposure Test (HET).

	Heart Rate				Respiratory Rate			
	K4 b^2	**BioHarness**	**p**	**r_s**	**K4 b^2**	**BioHarness**	**p**	**r_s**
Baseline	81.0 (4.4)	78.5 (5.9)	0.25	0.89	16.7 (1.5)	16.8 (3.4)	0.75	0.77
5 min	96.7 (10.2)	99.2 (6.6)	0.92	0.26	23.1 (2.9)	23.8 (3.2)	0.69	0.49
10 min	98.8 (7.9)	102.3 (5.3)	0.60	0.44	25.0 (6.3)	24.7 (3.7)	0.60	0.94
15 min	102.0 (11.6)	104.2 (5.3)	0.83	0.23	24.6 (5.8)	24.9 (3.0)	0.97	0.71
20 min	103.7 (11.8)	106.1 (5.4)	0.75	0.09	26.7 (8.3)	26.4 (5.0)	0.97	0.99
25 min	123.2 (11.0)	125.0 (8.3)	0.92	0.54	28.2 (7.9)	28.4 (5.8)	0.46	0.83
30 min	129.7 (7.2)	130.2 (8.4)	0.92	0.60	29.5 (7.6)	30.4 (4.1)	0.75	0.94
35 min	134.9 (8.2)	131.1 (8.1)	0.17	0.09	29.6 (8.4)	30.4 (2.1)	0.25	0.94
40 min	137.5 (9.5)	133.6 (8.2)	0.35	0.37	30.9 (7.5)	29.9 (2.5)	0.89	0.54

Values are mean (SD) (n = 6)

p: p-value from Paired-Sample Wilcoxon Signed Rank Test

r_S: Spearman correlation coefficient

Int J Sports Med. Author manuscript; available in PMC 2015 October 26.