MEASUREMENT SCIENCE REVIEW, **19**, (2019), No. 3, 79-85

sciendo

ISSN 1335-8871

MEASUREMENT SCIENCE REVIEW

Journal homepage: https://content.sciendo.com

Quality of One-channel Telemetric ECG Sensor Signal in Maximum Exercise Stress Tests

Boris Širaiy[1], Roman Trobec[1], Vladimir Ilić[2]

[1]*Josef Stefan Institute, Department of Communication Systems, Jamova cesta, 39, 1000, Ljubljana, Slovenia, boris.siraiy@ijs.si*

[2]*Faculty of Sport and Physical Education, University of Belgrade, Blagoja Parovića, 156, 11000, Belgrade, Serbia*

The aim of this study was to evaluate the quality of the ECG signal, obtained from a telemetric body-sensor device during a maximum stress test on an ergometer. Twenty-three subjects, 13 males, were included in the study (20.56±1.19 years). Two different sensor positions were verified on each subject by the concurrent use of two ECG sensors. Each subject participated in four exercise stress tests: two on a treadmill and two on a cycle ergometer. In the first test, both sensors were attached to self-adhesive skin electrodes on the body, while in the second test the sensors were additionally fixed with self-adhesive tapes. The measurements were compared on both ergometers, in terms of the ECG sensors' positions and the methods used for the sensors' fixation. The results showed a significant difference in the running speed that provides an assessable ECG signal between the non-fixed and the fixed sensors at position left inferior ($p = 0.000$), as well as between the positions left inferior and left superior in the first ($p = 0.019$), and in the second test ($p = 0.000$) on the treadmill. On the cycle ergometer the differences were significant between the positions left inferior and left superior in the first ($p = 0.000$), and the second test ($p = 0.003$), and between the tests with fixed and non-fixed sensors in the position left superior ($p = 0.011$). The study confirms that ECG sensors could be used for maximal exercise stress tests in laboratories, especially on a cycle ergometer, and that they present a great potential for future use of ECG sensors during physical activity.

Keywords: Cycle ergometer, ECG body sensors, exercise stress tests, healthcare, maximal physical activity, treadmill.

1. INTRODUCTION

Today's sport requires extreme efforts from athletes, and these efforts represent a high risk to their health. Numerous studies have reported the increased risk of cardiovascular events and sudden death during intense exercise – particularly in competitive sports [1], [2]. Training leads to changes in the heart's electrophysiological characteristics, e.g. sinus bradycardia, sinus arrhythmia [3], or grade 1 and grade 2 atrioventricular block [4]. Due to sports-related sudden cardiac arrest it is necessary to clearly delineate the pathological characteristics of the cardiovascular system, and its adaptation to physical effort, which can be detected by an ECG sensor. In many cases of sudden death there are found elevated levels of the ST segment [5], and there are many ventricular tachycardias present, which may pose a reason for ischemia of the left ventricle [6]. An exercise stress test (EST) with electrocardiogram (ECG) monitoring [7] provides the information necessary for a diagnosis and evaluation of heart arrhythmias and ischemic cardiac disease [8]. Understanding the purpose of individual exercise tests, which are typically conducted using a treadmill or a cycle ergometer, allows test supervisors to determine the appropriate methodology and to select the optimal test end points that maximize safety and obtain the required diagnostic and prognostic information. An EST is especially important and sensitive for people with symptoms of cardiac disease, but the positive predictive value of an EST in asymptomatic people is relatively low [9].

Even recreational athletes often avoid stress tests and check-ups with a medical doctor. Two studies conducted in France reported a daily incidence of three sudden deaths and four myocardial infarctions during physical activity in the general population [10], [11]. From the ethical, medical, and legal points of view it is justifiable to prevent sudden sports-related deaths [12], [13]. Considering the fact that 55-80 % of the athletes who died of sudden cardiac death had no prior symptoms of heart disease [14], the question is what else should be done for the prevention and detection of the people with increased risk of sudden cardiac death. Since an EST with ECG monitoring is usually performed in laboratory conditions, our goal is to determine whether it is possible to measure an ECG during regular sports activities, because it will offer a significant advantage for the prevention of cardiovascular accidents [15]. The body sensor we used in our research was already employed in preliminary research on

DOI: 10.2478/msr-2019-0013

cardiac patients [16], and to conduct a study during light physical activity [17]. This study presents an extension of the pilot study made with the same device [18].

Aims of the study

Because it was already recognised that the poor quality of telemetric ECG recordings can lead to misdiagnosis [19], the aim of this study was to evaluate ECG body-sensor signals during maximum EST, and to analyse the quality of the recorded ECG signal. Next aim was to determine whether varying positions of the sensor and different types of sensor fixation influenced the ECG signal. The use of a telemetric ECG during physical activity could be very beneficial for medical doctors and sports scientists, and also for professional and recreational athletes.

2. SUBJECT & METHODS

A. *Study population*

Twenty-three participants were included in the study, 13 males, age between 19 and 23 years (20.56 ± 1.19). All of them were students at the Faculty of Sport and Physical Education at the University of Belgrade. All the participants were healthy and without known previous cardiac problems. Prior to the tests the purpose of the study and its protocol were explained to each participant. A signed consent for participation in the study was collected from each participant.

B. *Experimental setup*

ECG measurements during the EST were made with wireless ECG body sensors Savvy (Saving d.o.o., Ljubljana, Slovenia) [20], which is a certified medical device, described in detail in the study of Trobec et al. [21]. The body sensor is light and non-obstructive for users, which allows long-term ECG measurements during exercise. The sensor is fixed on the body via two self-adhesive skin electrodes. An Android application, MobECG, which runs on a smartphone, captures and displays the measured data and saves it in the smartphone's memory for further processing.

The sensor positions should be close to the heart to obtain the appropriate amplitude of the ECG signal. In addition, its position should avoid large muscles, due to the signals from the electrical muscular activity (EMG) that could disturb the ECG [21]. Consequently, two positions were chosen, marked as LS (left superior) and LI (left inferior), respectively. In the LS position the sensor electrodes are at the positions V1 and V2 of standard precordial leads. In the LI position the sensor is translated by approximately 10 cm, below the xiphoid, where the influence of muscular disturbances is expected to be minimal (see the left-hand part of Fig.1.).

The ECG electrodes were positioned 5 cm apart [22]. Before the positioning, we cleaned the skin of the subjects with diluted ethanol. Then we attached four electrodes, two for the LS position and two for the LI position and connected the two ECG body sensors.

Two different types of standard self-adhesive Skintact ECG electrodes (Leonhard Lang GmbH, Innsbruck, Austria) were used for all the measurements: type PREMIER (T-60) (referred to in the following text as PT), recommended for general use in ECG measurements, and type ELITE (FS-VB01) (termed EFS), recommended for Holter measurements. The electrodes were in the original packaging and used according to the manufacturer's instructions. After the placement of the electrodes and sensors, every subject rested for 5 minutes before the start of the EST while the ECG was recording.

Fig.1. LS and LI positions of the sensors and electrodes in the first test (left) and in the second test (right), where both sensors are additionally fixed with Omniplast tape.

All the participants made two ESTs on each device, with two ECG sensors at different positions. In the first tests the ECG body sensors were just attached to the electrodes (see the left-hand part of Fig.1.), while in the second test the sensors were additionally fixed with self-adhesive tape. To fix the sensors, medical Omniplast 2.5 cm tape (Paul Hartmann AG, Heidenheim, Germany), specially designed to fix Holter electrodes, was used (see the right-hand part of Fig.1.). Both parts of the sensors were fixed together with one, approximately 40-cm-long strip of tape. Each subject participated in four tests, two with non-fixed and two with fixed electrodes on each ergometer.

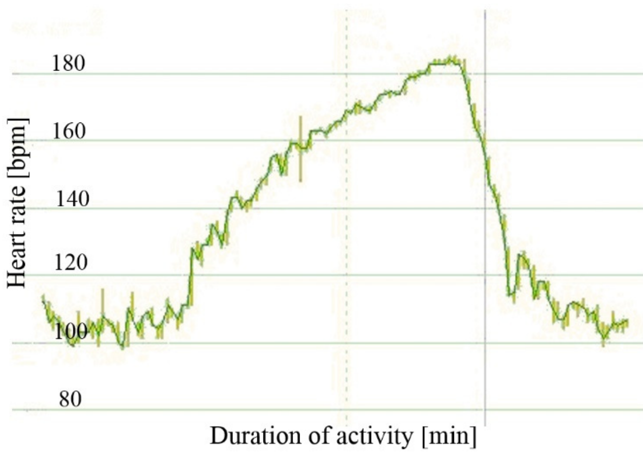

Fig.2. Typical heart-rate curve during the exercise test, obtained after the analysis of the ECG signal.

The measured ECG data were continuously stored in the mobile-phone memory and transferred after the completion of the measurements to a personal computer. The subsequent ECG analysis was made with medically certified Holter interpretation software QuickReader® AFT-1000 (Holter Supplies, Paris, France) that provides automatic medical analysis, and an efficient visual inspection of the interpretation results. All the ECG measurements were grouped in folders, named with depersonalized identifications of the analysed subjects. A screenshot of a typical heart-rate (HR) signal in beats-per-minute (BPM), and QRS detection is shown in Fig.2.

The computerized heart-rate analysis was successful for most of the time during the ESTs, with a typical example in the left-hand panel of Fig.3., shown with a 2D waterfall plot. Most of the difficulties with the correct QRS detection appeared in the vicinity of the limit of the subjects' tolerance. Therefore, all the measurements and the results were also visually examined by a medical doctor. During the visual inspection we also found erroneously detected QRS complexes, using the Holter interpretation software, often because of the excessive artefacts that come from the intense activity (right-hand part of Fig.3.).

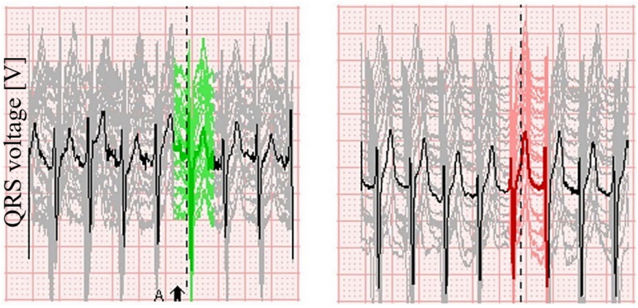

Fig.3. Templates of the detected QRS complexes made automatically by the Holter interpretation software QuickReader. An example of two identical QRS complexes: in the left-hand panel correctly interpreted as a correct QRS (green colour), in the right-hand panel wrongly interpreted as a non-correct QRS (red colour).

C. *Exercise stress test protocol*

The RAMP protocol with linear intensity increments to the point of exhaustion was used in all the ESTs [23]. The RAMP protocol on the treadmill starts with the speed of 5 km/h for females and 7 km/h for males. The running speed increases by 1 km/h after every minute, until the point of exhaustion. On the cycle ergometer, the RAMP protocol starts with a load of 50 W for females and 75 W for males. The cycling speed of 60-70 rpm was the same for all the subjects during the whole test. The load increases by 25 W after every minute, until the point of exhaustion.

D. *Measurement protocol*

Every participant made four ESTs on two different ergometers over four different days. Two ESTs with fixed and non-fixed ECG sensors were made on a treadmill and two on a cycle ergometer. Before performing the ESTs, the electrodes and sensors were positioned at the LI and LS positions and the participants sat down and waited for 5 minutes, while the ECG was recorded. After 5 minutes the participant started with the EST on the treadmill or on the cycle ergometer. When the EST was finished the participant sat down and rested for 5 minutes, while the ECG was still recording. The next day the participant took part in a second test on the same device. In the second test both sensors were fastened with self-adhesive tape. The ECG recording protocol was the same as on the previous day. The next pair of ESTs, on a second device, under the same protocol, was performed in the next 2 days. The study was conducted in accordance with the ethical standards of the Faculty of Sport and Physical Education (IRB approval No. 02-1359/18-2), University of Belgrade, and the Helsinki Declaration.

E. *Statistical analysis*

Descriptive statistics were calculated for all the measurements and their parameters, e.g. the speed of running on the treadmill, the maximum load on the cycle ergometer, the percentage of correctly detected heart beats, etc. Because the descriptive statistics indicate differences between the ECG measurements, an ANOVA analysis was used to obtain more detailed results.

Using the ANOVA, we compared the ECG signals from the first and second tests (non-fixed versus fixed sensors), and from two different positions. First, Mauchly's test of sphericity was made for both devices. The sphericity is violated if $p < 0.05$; in this case the Greenhouse-Geisser or Huyhn-Feldt correction of degrees of freedom was used [24]. If the Greenhouse-Geisser result is <0.75, the Greenhouse-Geisser correction is used, or else, for >0.75, the Huyhn-Feldt correction of degrees of freedom is used [24]. If the ANOVA shows the differences between the measurements, a Least Significant Difference (LSD) post-hoc analysis is made. The significance level of the statistical analysis was set to $p < 0.05$ [25]. The statistical analysis was conducted using IBM SPSS Statistics 20 software.

3. Results

The presented results focus on the statistical analysis of the ECG measurements, giving emphasis on the quality of the ECG signal during the ESTs.

ECG measurements

Maximal speed of running was 15.22±1.57 km/h, while maximal load on bicycle ergometer was 210.87±44.48 W. Table 1. and Table 2. present descriptive statistics of the treadmill and the cycle ergometer tests for all the positions and the electrodes' fixation options, with the percentage of ECG signal of sufficient quality. All the available parameters, listed in Table 1., are presented as a mean and a standard deviation (± SD). The results reflect the substantial differences between the positions and the fixation methods.

Because the results from Table 1. show differences between the measured parameters, we proceed with the ANOVA analysis. Based on the tests of sphericity, the appropriate correction of degrees of freedom was used for every test, as shown in Table 2. All the results with significant differences between each of the relevant parameters are marked by an asterisk.

Table 1. Descriptive statistics of the treadmill (upper table) and the cycle ergometer test (bottom table).

	Sensor position & fixation	Detected QRS	False positive QRS	False negative detection	Correct software detection	Load with still assessable HR [km/h]	Percentage of acceptable signal
Mean	ALL	1797.20	166.61	122.11	44.49	11.25	73.01
	LS	1647.57	169.70	99.22	70.48	9.13	58.88
	LI	1823.13	178.96	145.43	33.52	11.48	73.34
	LSP	1709.74	147.35	82.22	65.09	9.43	62.18
	LIP	2008.35	170.43	161.57	8.87	14.96	97.64
±SD	ALL	521.61	226.27	191.55	86.80	3.73	22.87
	LS	568.94	255.78	172.75	121.07	3.11	18.56
	LI	428.66	261.99	249.67	54.24	3.95	22.42
	LSP	476.81	197.07	140.15	100.10	2.43	17.19
	LIP	558.48	195.70	188.53	30.72	1.94	7.48

	Sensor position & fixation	Detected QRS	False positive QRS	False negative detection	Correct software detection	Load with still assessable HR [W]	Percentage of acceptable signal
Mean	ALL	1994.20	43.12	38.62	4.50	191.03	90.60
	LS	1808.39	16.57	1.09	15.48	160.87	75.92
	LI	2115.91	52.13	51.30	0.83	210.87	100
	LSP	1881.74	9.35	7.78	1.57	181.52	87.79
	LIP	2170.74	94.43	94.30	0.13	210.87	100
±SD	ALL	355.45	150.86	148.38	31.44	54.29	17.49
	LS	314.87	63.59	1.65	62.51	59.75	22.26
	LI	349.57	169.11	169.03	2.74	44.48	0.00
	LSP	340.26	31.30	31.51	2.25	52.88	18.32
	LIP	296.82	236.12	235.84	0.46	44.48	0.00

Legend: LS and LI - two positions for non-fixed ECG sensors; LSP and LIP - two positions for fixed ECG sensors; ALL – average of LS, LI, LSP and LIP, SD – standard deviation; QRS – depolarization waves of the ECG

Next, we proceeded with the LSD post-hoc analysis in order to obtain the details of these differences (see Table 3.). The post-hoc LSD analysis showed significant differences between the Detected QRS in the positions LIP and LS, and between the LIP and LSP on the treadmill, and also between the positions LS and LI, LS and LIP, LI and LSP, and between LSP and LIP on the cycle ergometer. Correct software detection was significantly different between the positions LI and LS, LI and LIP, and LIP and LSP on the treadmill. The load with the still-assessable HR was significantly different between the positions LI and LS, LIP and LI, LIP and LS and between LIP and LSP on the treadmill, and between positions LS and LI, LS and LSP, LS and LIP, LSP and LI, and LSP and LIP on the cycle ergometer.

Table 2. ANOVA test of within-subject effects based on the sphericity analysis.

	Treadmill		Cycle Ergometer	
Parameter	F-value	p-value	F-value	p-value
Detected QRS	F(2.018, 44.392) = 3.559	0.036*	F(2.669, 58.720) = 21.821	0.000*
False positive QRS	F(2.124, 46.730) = 0.107	0.909	F(1.528, 33.681) = 2.017	0.158
False negative detection	F(3, 66) = 0.927	0.433	F(1.540, 33.870) = 2.580	0.103
Correct software detection	F(1.822, 40.084) = 4.615	0.018*	F(1.006, 22.124) = 1.264	0.273
Load with still assessable HR	F(3, 66) = 22.282	0.000*	F(3, 66) = 16.636	0.000*

Table 3. Pairwise LSD comparison test.

	Treadmill			Cycle Ergometer		
Parameter			p-value			p-value
Detected QRS	LIP	LS	0.037	LS	LI	0.000
					LIP	0.000
		LSP	0.029	LI	LSP	0.002
				LSP	LIP	0.000
Correct software detection	LI	LS	0.049			
		LIP	0.031			
	LIP	LSP	0.012			
Load with still assessable HR	LI	LS	0.019	LS	LI	0.000
	LIP	LI	0.000		LSP	0.011
					LIP	0.000
		LS	0.000	LSP	LI	0.003
		LSP	0.000		LIP	0.003

In order to see an alternative practical view of the statistics, the results can be obtained with a tabular presentation for the different activity levels. The final speed on the treadmill was, for females, between 12 and 16 km/h, and for males, between 15 and 19 km/h. The maximum load on the cycle ergometer was, for females, between 150 and 225 W, and for males, between 200 and 325 W. The percentages of the ECG signal that had acceptable quality at different speeds of running on the treadmill, and load on the cycle ergometer, are shown in Table 4. and Table 5., respectively. Note that the percentage was calculated only from the number of participants that reached the selected activity level (#partic).

The results from Table 4. show that for the treadmill the signal was acceptable in the range between 90 % and 100 %. We see again that the fixed electrodes in position LIP provide the best results on both devices. On both devices, the LI position is better than the LS position. Note that on the treadmill, the measurements that were not acceptable at the maximum running speed were recorded using the EFS electrodes. On the cycle ergometer, the positions LI and LIP are advantageous, with all recorded measurements being acceptable (Table 5.).

Table 4. Percentage of the ECG signal of acceptable quality at different running speeds [km/h] on the treadmill.

Treadmill					
Running speed	#partic	LS	LI	LSP	LIP
5	23	100	100	100	100
6	23	100	100	100	100
7	23	91.3	100	100	100
8	23	78.3	87	82.6	100
9	23	43.5	60.9	43.5	100
10	23	17.4	52.2	43.5	100
11	23	13	52.2	26.1	95.7
12	23	13	47.8	17.4	95.7
13	20	14.3	38.1	14.3	95.2
14	19	15	40	10	90
15	17	11.8	47.1	11.8	94.1
16	13	16.7	41.7	0	100
17	3	50	100	0	100
18	1	100	100	0	100
19	1	100	100	0	100

Table 5. Percentage of the ECG signal of acceptable quality at different loads [W] on the cycle ergometer.

Cycle Ergometer					
Maximal load	#partic	LS	LI	LSP	LIP
50	23	100	100	100	100
75	23	100	100	100	100
100	23	95.7	100	100	100
125	23	78.3	100	87	100
150	23	56.5	100	82.6	100
175	19	42.1	100	73.7	100
200	15	46.7	100	60	100
225	13	28.6	100	42.9	100
250	5	33.3	100	33.3	100
275	2	50	100	50	100
300	1	100	100	100	100
325	1	100	100	100	100

4. DISCUSSION

This research confirms that a wireless ECG body sensor can be used for non-obstructive measurements of an ECG during cycling and running on ergometers in laboratory conditions or during fitness training. The aim of this study was to test the hypothesis of whether wireless ECG body sensors can be used for an EST. The results show that the ECG body sensor is very useful for an EST on a cycle ergometer. On a treadmill the ECG sensor provides adequate results for running speeds up to 15 km/h, on average, but often a running speed above this value also provides an adequate ECG signal, mostly dependent of the sensor's position and the fixation method.

In this study we analysed approximately 61 hours of ECG signals, and the statistical analysis showed the differences between the non-fixed and the fixed ECG sensors in both positions on the treadmill, and on the cycle ergometer at the position LS, while at the position LI the results were at the maximum level with a non-fixed and a fixed sensor. We found significant differences between the results of the Detected QRS and the Load with the still-assessable HR on both ergometers, and in the Correct software detection on the treadmill. The post-hoc analysis precisely detected the significant differences between the results. The analysis of the results confirmed that the ECG signal was better detected on both devices with the sensor in position LI. The final analysis on the treadmill showed the percentage of the ECG signal at position LIP, which was of acceptable quality at the level of 97.64 %, while on the cycle ergometer both tests, with the non-fixed and the fixed sensor at position LI, provided ECG signal at the 100 % level. As we expected, the results at position LS were not as good, because muscle activity [21], and shoulder movement influenced the results at position LS much more than at position LI. The ECG signal at position LS on the treadmill was acceptable in the range between 58.88 % and 62.18 %, and on the cycle ergometer signal was acceptable in the range between 75.92 % and 87.79 %. These results show significant improvement of the results presented in the study by Takalokastari et al. [26], where it was shown that on the treadmill during running 60 % of the signal was of moderate or good quality, while on the cycle ergometer 73 % of the signal was of moderate or good quality. They reported that 79 % of the ECG signal on the treadmill was of moderate or good quality in the Nordic walking test. In that study various types of ECG devices with different electrode positions were used. The studies by Shen et al. [27], and by Valchinov et al. [28] reported that the ECG signal was of adequate quality during resting, walking, or jogging, but there were some small motion artefacts present during running or jumping activities. In our preliminary pilot study [18] it was shown that the particular wireless ECG body sensor can correctly detect ECG signal on a cycle ergometer; however, on the treadmill the test signal was of adequate quality for running speeds of up to 13.5 km/h, while in the presented study it was of adequate quality up to 14.96 km/h. The pilot study showed that the applied methodology used for the sensor's fixation on the treadmill was not appropriate, because both parts of the sensor were fixed separately, and the ECG signal was not optimally detected. In the presented study an improved methodology of sensor fixation was used, i.e. a wider fixation tape was stretched over both electrodes. These results confirm the hypothesis that it is possible to measure ECG signal with ECG body sensors during sports activities and that sensor position and fixation influence the results. This leads to the conclusion that attention must be paid to the position of the ECG sensor and the sensor's fixation before physical activity.

The diagnostic ability of the ECG body sensor, used in this study, has been compared in various previous pilot studies with other similar devices [21] and with standard 12-lead ECG [21]. Even that the standard 12-lead ECG is a golden standard for detecting arrhythmias and myocardial ischemia or infarction [29], ECG body sensor, even so simple, can also detect most of the arrhythmic events, e.g. atrial or ventricular fibrillation, exstrasystole, tachycardias, bradycardias, etc.

However, if using a single-channel only, it has serious limitations in detection of ischemia, e.g. it is not possible to accurately assess ST denivelations. In cases with suspected myocardial ischemia, further analysis with 12-lead ECG is obligatory.

Because the primary goal of this study was not to detect cardiac disease but to find out whether the sensor provides optimal ECG measurement during maximal physical activity, where the noise of the ECG signal is the highest because of the muscle activity [21], and because of the maximal speed of running [30], we chose a homogeneous group of healthy young participants with a small age spread who were at the highest level of physical condition. Future laboratory studies should include a more heterogeneous age group of participants with potential cardiac problems. However, another analysis in the field tests should also be made to see if this sensor can be used during physical activity in regular conditions.

The analysed measurement methodology cannot completely replace the EST in the laboratory, but the obtained results can provide basic information about the heart rhythm's status. In the case of any detected abnormality the users can be directed to further diagnostics with a standard stress test and medical personnel.

5. CONCLUSION

The presented results are a motivation for further study, measuring the ECG during regular sports activities or in field tests. With such a telemetric approach it might be possible, to the best of our knowledge for the first time, to routinely measure ECG signals in real conditions, e.g. when users are cycling or running in nature, during a significant activity. In the presented study an appropriate method of sensor fixation was found; however, for tests during regular activities alternative types of fixation, e.g. an ECG sensor on a belt, should be verified in order to prevent extensive movement of the sensor during sports activities.

ACKNOWLEDGMENT

This work was supported in part by the Slovenian Research Agency under Grant P2-0095, and by the Ministry of Science of Serbia under Grant 41022.

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Received November 06, 2018
Accepted May 27, 2019