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Research article

Field based reliability and validity of the Bioharness™ multivariable monitoring device

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Abstract

The Bioharness™ device is designed for monitoring physiological variables in free-living situations but has only been proven to be reliable and valid in a laboratory environment. Therefore, this study aimed to determine the reliability and validity of the Bioharness™ using a field based protocol. Twenty healthy males participated. Heart rate (HR), breathing frequency (BF) and accelerometry (ACC) were assessed by simultaneous measurement of two Bioharness™ devices and a test-retest of a discontinuous incremental walk-jog-run protocol (4 – 11 km·h^{-1}) completed in a sports hall. Adopted precision of measurement devices were; HR: Polar T31 (Polar Electro), BF: Spirometer (Cortex Metalyser), ACC: Oxygen expenditure (Cortex Metalyser). For all data, precision of measurement reported good relationships ($r = 0.61$ to 0.67, $p < 0.01$) and large Limits of Agreement for HR (>79.2 b·min^{-1}) and BF (>54.7 br·min^{-1}). ACC presented excellent precision ($r = 0.94$, $p < 0.01$). Results for HR ($r = \sim 0.91$, $p < 0.01$: CV <7.6) and ACC ($r > 0.97$, $p < 0.01$; CV <14.7) suggested these variables are reliable. BF presented more variable data ($r = 0.46$-0.61, $p < 0.01$; CV < 23.7). As velocity of movement increased (>8 km·h^{-1}) data became more erroneous. A data cleaning protocol removed gross errors in the data analysis and subsequent reliability and validity statistics improved across all variables. In conclusion, the Bioharness™ HR and ACC variables have demonstrated reliability and validity in a field setting, though data collected at higher velocities should be treated with caution. Measuring human physiological responses in a field based environment allows for more ecologically valid data to be collected and devices such as the Bioharness™ could be used by exercise professionals to begin to further investigate this area.

Key words: Multi-variable, physiological monitoring, ecological validity, new technology.

Introduction

Exercise Science research is ultimately completed to provide an improvement for the coach and performer to implement. Advances in human monitoring technology now permit multi-variable data to be recorded unobtrusively and analysed during or post sporting performance (Achten and Jeukendrup, 2003; Jobson et al., 2009). The integration of multiple "physiologically" related variables could provide more ecologically valid and accurate information on athletes and consequently improvements in performance, all of which coaches have requested (Brage et al., 2005; Carling et al., 2009; Foster et al., 2006; Williams and Kendall, 2007). Paradoxically though, the use of new technology by some exercise and coaching professionals is limited in some sports (Buchanan, 2008). Moreover, it has been reported that at times, inadequate dissemination or application of research to wider sport professionals creates a "gap" in understanding between exercise science research and actual coaching practice (Bishop, 2008; Bishop et al., 2006; Williams and Kendall, 2007). The limited and disjointed dissemination of information could be linked to the lack of valid and reliable field based research tools.

A new applied research tool, the Bioharness™ (version 1, Zephyr Technology, MD, USA), is promoted as a field based physiological measuring system, assessing variables such as heart rate, breathing rate, skin temperature and activity (i.e. accelerometry and posture) via an unobtrusive chest strap. To date, all 5 variables of the Bioharness™ were proven to be reliable and valid in a laboratory environment (Johnstone et al., 2012a; 2012b) whilst Hailstone and Kilding (2011) investigated the breathing frequency variable only. It is common practice for new applied physiological monitoring technology to be initially assessed in a controlled laboratory based environment and if acceptable levels of precision are identified, it is logical to go on to complete field/free movement activities (Grossman et al., 2006; Johnstone et al., 2012a; Leger and Thivierge, 1988; Rowlands et al., 2003; Trost et al., 2005). There is a plethora of sport specific field based testing protocols though many lack wider ecological validity with regards to movement patterns and velocities included within them (Carling et al., 2009). To capture a broad activity spectrum, combining and adapting recognised field based walking (Brown and Wise, 2007) and progressive running tests (Ledger et al., 1988; Ramsbottom et al., 1988) may be the better option, especially if assessing the capacity of a new physiological measuring device for a wide sporting audience.

In summary, there are gaps in the literature with regards to field based testing of applied technology and many prediction equations within field based devices are based from data collected from laboratory studies (Welk et al., 2000). Understanding the possible changes in precision of measurement from the laboratory to the field is an important step within the research process. Therefore, the aim of this paper was to assess the reliability and validity of each variable measured in the Bioharness™ in relation to criterion measures within a physically active field

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based setting.

Methods

General design

To assess the Bioharness™ in a field based environment, appropriate respective criterion measures and protocols were identified. Data collected used one synchronized timeline linked to a laptop computer. A discontinuous incremental walk-jog-run (WJR) protocol, over 20 m, was developed after considering intermittent activity patterns witnessed in athletic performance (Carling et al., 2009) and adapting other recognised field based protocols (Brown and Wise, 2007; Ledger et al., 1988; Ramsbottom et al., 1988). Reliability and validity of accelerometry (ACC), heart rate (HR) and breathing frequency (BF) were assessed. The validity experimental design only permitted analysis of ACC as one data set, though velocity specific analysis was permitted within the reliability testing. Due to technical limitations the other two Bioharness™ variables, skin temperature and posture were not assessed in this research.

Apparatus

Overview of the Bioharness monitoring device

The Bioharness™ (version 1) is worn against the skin by the participant via an elasticated strap attached around the chest. The monitoring device attaches on to the strap and acts a data logger or transmitter measuring five variables simultaneously, which are time stamped and exportable to Microsoft Excel. Further technical detail on the device has been reported in previous reliability and validity studies by the author (Johnstone et al., 2012a).

Participants

After securing local institutional ethical agreement, 20 male volunteers (Mean ± SD; age 21.5 ± 2.8 yrs, body mass 71.4 ± 7.9 kg, body stature 1.79 ± 0.1 m) who were physical active and injury free, consented to participate in the reliability (n = 10) and validity (n = 10) aspects of the study. Participants refrained from consuming alcohol and caffeine, kept hydrated and rested 24 hours prior to testing. On arrival to the testing area stature (Seca 214, Birmingham, UK) and body mass (Seca 761, Birmingham, UK) were measured (Stewart and Eston, 2007).

Precision of Bioharness

Validity of heart rate (HR), Breathing Frequency (BF) and Accelerometry (ACC)

One standard Bioharness™ device was concurrently compared with adopted criterion measures. Precision of the HR, BF and ACC were assessed by participants (n=10) completing the WJR shuttle protocol. Adopted criterion measures within this procedure were, for HR, the Polar T31 (Polar Electro, Kempele, Finland). For BF, a face mask (Hans Rudolf Inc, USA) was worn by participants in order to connect a Tripple-V spirometer which was attached to a portable metalyser (Metamax 3B; Cortex Medical, Germany; weight 650g). Oxygen (O_2) expenditure was assessed for ACC also using the aforementioned portable metalyser which was calibrated prior to testing according to the manufacturers specifications. The latter criterion (O_2 expenditure) is considered an indirect measure of ACC (Johnstone et al., 2012a, Rowlands et al., 2003). All equipment was fitted on to participants by one experienced researcher throughout all phases of data collection.

Reliability of HR, BF, ACC

Test-retest design

Using one standard Bioharness™ device, participants (n = 10) completed the same WJR shuttle protocol using a test-retest design. Re-tests were completed at the same time of day, between 48 and 72 hours apart, with participants instructed to follow same pre-test protocol before testing.

Simultaneous wearing of two Bioharness devices

Using two standard Bioharness™ devices, of similar age and usage, participants (n = 10) completed the WJR protocol. One device (B) was positioned in the normal position around the chest as described by manufacturer. The second device (A) was positioned directly above the first without being in contact with the former.

WJR Test protocol

Test protocol - General information

In a purpose built indoor sports hall (20.1 ± 2.5 °C) the protocol consisted of participants completing a discontinuous WJR 20 meter shuttle activity starting at 4km.h^{-1} and increasing to 11 km·h^{-1} mirroring a wide range of physical activity/exercise tasks in the wider sporting world. Two days before data collection commenced participants received a full briefing of the protocol at the location of test, including a familiarisation period with equipment to be worn and a partial dry-run practice of each stage without equipment.

Walking stage

With monitoring equipment fitted and data being collected, a 10 minute familiarisation period occurred. When the participant was ready, on the lead experimenters command, participants received a 10 second count down before completing a 6 minute walking stage (Brown and Wise, 2007). Initially walking was at a velocity of 4 km·h^{-1} for 3 minutes after which this increased to a velocity of 6 km·h^{-1} for a further 2 minutes. Maintaining the correct velocity for these walking stages was assured by the use of research team acting as pace makers. At the end of the walking stage participants had 1 minute of unrecorded active rest before the jog-run shuttle activity was started. Within this walking test phase, data were collected for the last 60 seconds of each of the respective active 4 km·h^{-1} and 6 km·h^{-1} stages.

Jog-run stage

Utilising the Multi Stage Shuttle Run (MSSR) (Ledger et al., 1988; Ramsbottom et al., 1988) participants completed 6 min 20 seconds of 20 metre shuttles, which equated to Level 1 to the end of Level 6 of the MSSR. Jog-run shuttles were completed in time with an audible beep (MSSR CD version; Coachwise Ltd, UK) relayed to participants via a laptop computer and speaker system. Participants increased velocity by 0.5 km·h^{-1} at ~1 minute intervals starting at 8 km·h^{-1} increasing through to 11

km·h^{-1} and data were collected for the duration of stage.

Data analysis

Data were exported to statistical software packages (Excel Microsoft Windows, USA; SPSS v17, SPSS Inc, Chicago, USA) for analysis. Concurrent validity for all variables were analysed against their respective criterion measures, identifying means and standard deviations (M ± SD) for the data. To fully understand the data generated, a range of reliability and validity statistics in combination with descriptive data has been previously been reported (Bland and Altman, 1986; Brunton et al., 2000; Hopkins, 2000; Hopkins et al., 2009).

Characteristics of the data set were considered and appropriate statistical procedures were followed thereafter. After plotting the predicted against the residuals for HR and BF, data were considered to be non-uniform (i.e. heteroscedastic) so were transformed logarithmically (log) in order to provide a true interpretation (Atkinson and Nevill, 1998; Hopkins, 2000; Hopkins et al., 2009). It was decided that descriptive data for these variables would be reported in absolute values while reliability and validity statistics are presented log transformed. The combined data presentation approach was determined in order for comparison with other studies to occur, the majority of which have reported absolute data.

Adopting a composite of reliability and validity statistics may provide a more informed view to assess agreement between methods (Harper-Smith et al., 2010). The following statistical analysis was calculated for each variable; Descriptive statistics including absolute mean bias and 95% Confidence Intervals/limits (CI/CL). Validity statistics (log transformed) included; Mean bias, 95% Limits of Agreement (LoA), Pearson's Product Moment Correlation Coefficient (PCC), Coefficient of Determination (CoD). Reliability statistics included; Mean difference, Coefficient of Variation (CV), Intra Class Correlation Coefficients (ICC). Within the descriptive statistics, the mean bias and associated 95% CI/CL provides an indication of raw difference between the data sets. Correlation coefficients, such as PCC/ICC (*r*), provide a good indication of the relationship between data sets. Boundaries for the correlation statistics are not confirmed, though amalgamated thoughts of Leger and Thivierge (1988) and Hopkins (2000) suggest; r > 0.9 Excellent or very strong, r = 0.7 – 0.9 Very large , r = 0.7 – 0.5 Good to moderate, r < 0.5 Moderate to minor. CoD (r^2), linked to the correlation analysis, express the variance in one variable that can be attributed to the second variable (Atkinson and Nevill, 1998; Bland and Altman, 2003; Brunton et al., 2000, Winter et al., 2001). Correlation statistics should not be reported in isolation as they can be blind to bias (Bland and Altman 2003). As noted elsewhere (Finni et al., 2007), the LoA method (Bland and Altman, 1986) is used to compare the agreement between methods. Summarising the differences between the two methods is a corner stone of the process. It is expected that the differences outside of ±2 SD from the mean difference are not practically important. If 95% of data are within 2 SD it is considered an acceptable 'limit of agreement' and methods or equipment is thought to be interchangeable (Bland and Altman, 2003). LoA cannot be used when units between two methods are not comparable hence ACC data is not analysed in this way. An acceptable reliability boundary for CV (< 10%) has been cited in some papers though this is not accepted unanimously in the literature (Atkinson and Nevill, 1998; Currell and Jeukendrup, 2008; Hopkins, 2000).

Previously reliability and validity research has removed data sets when data is clearly erroneous in the belief that a technical breakdown has occurred with the system (Leger and Thivierge, 1988). Analysis completed which includes erroneous data sets would possibly reduce the practical usefulness of the results especially if the erroneous data was linked to only two or three participants. The reporting of data removal (i.e. cleaning) has been used as an additional validity statistic with high volumes of data being removed reducing the credibility of the device. Based on estimated maximal values of each physiological variable (McArdle et al., 2009) and considering other literature (Field and Miles, 2010; Johnstone et al., 2012a; 2012b, Ledger et al., 1988) the following data set removal criteria was established; If absolute mean of a data set difference was ± 20 b·min^{-1} for HR, or ±7 br·min^{-1} for BF, from the criterion the participants data from the specific velocity stage was removed.

Results

Validity of the Bioharness^{TM}

Precision of measurement results for HR

When considering all data (n =10 participants) collected HR data (Table 1) produced good to moderate relationships (r = 0.61; p < 0.01) with a relatively low mean bias though LoA were large. When data with clear technical error was removed (HR n = 9 participants remain) the relationship became stronger, mean bias and LoA reduced. At 4 – 6 km·h^{-1} relationships in HR data are very large with a small mean bias and LoA. Above 8 km·h^{-1} precision reduced with relationships becoming moderate to minor, and LoA became large (> ± 97 b·min^{-1}). After data cleaning at 8 – 10.5 km·h^{-1} (n=9) and 11 km·h^{-1} (n = 8) results improved with very large to moderate relationships seen, smaller mean bias and LoA.

Precision of measurement results for BF

When all BF data (n = 10) are considered (Table 1) good to moderate relationships (r = 0.67; p < 0.01) are noted though LoA were large. Velocity specific precision at 4 – 6 km·h^{-1} presented moderate relationships but large LoA remained (> ± 43.4 br·min^{-1}). At higher velocities (> 8 km·h^{-1}), statistics presented reduced precision. Cleaned data (n = 9) improves results with good relationship (r > 0.60; p < 0.01), reduced mean bias (< -1.43 br·min^{-1}) though LoA remains high (> ± 36.7 br·min^{-1}).

Precision of measurement results for ACC

ACC data (Table 2) produced excellent data relationships between oxygen uptake (mL·kg^{-1}·min^{-1}) and VMU counts (r > 0.90; p < 0.01) at both second-to-second and over a mean 10 second assessment.

Table 1. Precision of HR (b·min^{-1}) and BF (br·min^{-1}) data in comparison to respective criterion measure.

Variable	Velocity	Data	Predicted M (SD)	Criterion M (SD)	Mean bias (95%CI)	Mean bias (95%LoA)	PCC *r*	CoD r^2
HR (b·min^{-1})	All velocities	All	123.3 (38.4)	125.9 (34.4)	-2.56 (1.40)	-2.56 (79.20)	.61*	37%
		Clean	122.6 (34.0)	122.6 (34.6)	-.02 (.50)	.02 (11.50)	.98*	96%
	4-6 km·h^{-1}	All	92.6 (11.9)	91.3 (10.9)	1.26 (.40)	1.26 (9.60)	.92*	85%
		Clean	-	-	-	-	-	-
	8-10.5 km·h^{-1}	All	143.7 (30.4)	142.3 (21.6)	1.45 (1.6	1.45 (97.40)	.58*	34%
		Clean	141.8 (22.0)	142.5 (21.2)	-.64 (.70)	-.64 (12.20)	.93*	87%
	11 km·h^{-1}	All	146.3 (18.3)	170.4 (11.5)	-24.08 (6.40)	-24.10 (20.40)	.57*	33%
		Clean	173.2 (14.2)	175.3 (9.6)	-2.08 (1.90)	-2.08 (12.70)	.67*	45%
BF (br·min^{-1})	All velocities	All	29.1 (7.2)	32.7 (11.5)	-3.57 (.40)	-3.57 (54.70)	.67*	45%
		Clean	29.0 (7.4)	30.2 (8.2)	-1.19 (.30)	-1.19 (34.40)	.82*	67%
	4-6 km·h^{-1}	All	23.9 (4.1)	24.9 (6.6)	-.96 (.50)	-.96 (43.40)	.59*	35%
		Clean	23.4 (3.7)	24.0 (5.0)	-.60 (.40)	-.60 (36.70)	.60*	36%
	8-10.5 km·h^{-1}	All	30.5 (5.8)	35.3 (10.7)	-4.79 (.87)	-4.79 (57.30)	.48*	23%
		Clean	30.6 (5.9)	32.4 (6.2)	-1.81 (.42)	-1.81 (33.50)	.70*	49%
	11 km·h^{-1}	All	37.0 (6.1)	43.5 (11.4)	-6.53 (1.81)	-6.53 (73.70)	-.21	44%
		Clean	38.6 (4.9)	40.1 (5.9)	-1.43 (.45)	-1.43 (17.10)	.83*	69%

Tabular report of validity statistics: Descriptive statistics, Standard Deviation (SD), Mean Bias, 95% Confidence Intervals (CI), Log transformed mean bias, 95% Limits of Agreement (LoA), Pearson's Product Correlation Coefficient (PCC) and Coefficient of Determination (CoD) across whole data set. * $p < 0.01$

Table 2. Relationship of ACC data to the respective criterion measure (oxygen uptake, mL·kg^{-1}·min^{-1}).

	PCC *r*
Activity (VMU/ct·sec^{-1})	.91 *
Activity (VMU/ct·mean 10 sec^{-1})	.94 *

A tabular report of validity statistics: Pearson's Product Correlation Coefficient (PCC) for ACC Vector Magnitude Units (VMU) versus oxygen uptake, ml.min.kg^{-1}. * $p < 0.01$

Reliability of the Bioharness™ during simultaneous wearing of two devices

Reliability of HR during simultaneous protocol

When all data (n = 10) were considered (Table 3) low CV (7.6) and excellent relationship (r= 0.91; $p < 0.01$) are noted. At 4 - 6 km·h^{-1} excellent relationship (r = 0 .99; $p < 0.01$) and low CV (< 2) are seen though as velocity increased, the strength of the data relationships decrease and CV increases. Data cleaning at 8 km·h^{-1} and 11 km·h^{-1} (n = 9) improves reliability statistics, mirroring the raw values noted at 4 km·h^{-1}.

Reliability of BF during simultaneous protocol

In comparison to HR, the BF results (Table 4) for all data (n = 10) were weaker though after data was cleaned, CV decreased and r values improved, as they did for HR data (n = 8). Even with relatively small change in mean, at lower intensity BF data presents indifferent reliability statistics with moderate-to-high CV (> 14) and weak relationships in data (r < 0.38). Data cleaning (8 km·h^{-1} n = 7; 11 km·h^{-1} n = 9) improves these statistics with CV < 10, and r values between 0.52 and 0.89.

Velocity specific reliability of ACC data during simultaneous protocol

ACC data (Table 5) presents consistent reliability statistics with small change in means and narrow 95% CL. The relationship in data remains significant though reduces from excellent (r = 0.93) to good/moderate (r = 0.66) as velocities increase, while CV is relatively constant through this same period.

Reliability of Bioharness™ during the test-retest protocol

Reliability results for test-retest for all HR

For all HR data (n =10) very strong reliability statistics are noted with excellent relationships in data and low CV (Table 6). At 4 - 6 km·h^{-1}, HR data (Table 6) notes small change in mean, low CV (5.9) and very strong relationships in data (r = 0.97, $p < 0.01$). At higher velocities, change in mean and CV increase slightly and relationships decrease to good to moderate. Data cleaning (n = 8) improves reliability statistics though change in

Table 3. Reproducibility of the HR (b·min^{-1}) variable during simultaneous wearing of two devices.

Variable	Velocity	Data	Device A M (SD)	Device B M (SD)	Change in Mean	95% CL	CV	ICC
HR (b·min^{-1})	All velocities	All	140.4 (33.3)	143.7 (34.0)	3.32	2.94 to 3.71	7.6	.91*
		Clean	140.7 (33.4)	141.0 (33.4)	.39	.22 to .56	2.9	.98*
	4-6 km·h^{-1}	All	97.9 (15.4)	97.7 (15.5)	-.29	-.40 to -.18	1.6	.99*
		Clean	-	-	-	-	-	-
	8-10.5 km·h^{-1}	All	150.7 (22.7)	155.2 (23.0)	4.54	4.06 to 5.01	6.8	.82*
		Clean	151.7 (22.4)	152.8 (22.2)	1.14	.88 to 1.39	3.4	.95*
	11 km·h^{-1}	All	172.1 (22.9)	174.8 (14.4)	2.63	1.20 to 4.05	14.4	.51*
		Clean	174.6 (13.2)	173.4 (12.9)	-1.29	-1.74 to -.84	2.6	.99*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), Change in mean, 95% Confidence Limits (CL), Coefficient of Variation (CV) and Intra Class Coefficient (ICC) * $p < 0.01$

Table 4. Reproducibility of the BF (br·min^{-1}) variable during simultaneous wearing of two devices.

Variable	Velocity	Data	Device A M (SD)	Device B M (SD)	Change in Mean	95% CL	CV	ICC
BF (br·min^{-1})	All velocities	All	32.2 (12.4)	29.6 (7.3)	-2.57	-2.88 to -2.55	23.7	.46*
		Clean	30.1 (6.8)	29.8 (6.8)	-.38	-.50 to -.27	9.0	.86*
	4-6 km·h^{-1}	All	26.8 (3.3)	25.5 (4.5)	-1.32	-1.57 to -1.07	14.0	.38*
		Clean	27.0 (2.7)	26.0 (3.9)	-.98	-1.19 to -.77	9.8	.52*
	8-10.5 km·h^{-1}	All	30.2 (7.9)	29.6 (7.3)	-.54	-.84 to -.24	22.8	.39*
		Clean	30.5 (7.0)	30.4 (6.8)	-.17	-.31 to -.03	8.4	.89*
	11 km·h^{-1}	All	48.1 (20.1)	35.9 (6.9)	-12.21	-13.59 to 10.82	33.6	.22*
		Clean	36.6 (8.2)	36.7 (6.7)	.07	-.35 to .49	8.4	.87*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), Change in mean, 95% Confidence Limits (CL), Coefficient of Variation (CV) and Intra Class Coefficient (ICC) * $p < 0.01$

mean remains ~ -5 b·min^{-1}.

Velocity specific test-retest reproducibility of BF data

When considering all data (n = 10) BF variable presents an indifferent set of statistics. A low change in mean (< 1 br·min^{-1}), high CV and erratic relationships in data are seen (Table 7). Cleaned data (n = 8) at 8 – 10.5 km·h^{-1} presented the strongest relationships ($r = 0.91$, $p < 0.01$) and lowest CV (6.6) within the data set.

Velocity specific test-retest reproducibility of ACC data

ACC results (Table 8) notes consistent data at all velocities. Very strong relationships in data at 4 – 6 km.h^{-1} ($r = 0.84$, $p<.01$) then diminish as velocity increases though CV remains stable.

Data removal

The trend for the volume of data removal through the cleaning process as velocity increased can be seen in Figure 1. The figure demonstrates more data is removed at higher exercise intensities. No data was removed from the ACC data set.

Discussion

General findings

This is the first investigation reporting the reliability and validity of the Bioharness^{TM} device in an applied field based scenario. This multi-variable technology is designed to allow physiological monitoring during free movement, therefore understanding precision and variance of data in this environment is important, especially for the exercise scientists seeking to monitor performers in more ecologically valid scenarios. Overall results (Table 1- 8) suggest that HR and ACC variable are reliable and valid but with the BF variable presenting indifferent data which has also been noted previously in a laboratory environment (Johnstone et al., 2012a; 2012b). Further specific variable and velocity specific analysis identifies differences in the data sets which are discussed in the following sections.

Accelerometry

When data for each specific variable was considered, the ACC variable presents the strongest reliability and validity, with good data relationships and relatively low variance reported, concurring with previous laboratory based testing (Johnstone et al., 2012a, Johnstone et al., 2012b). Assessment of the validity of the ACC used indirect methods, therefore it was not possible to ascertain how precision of measurement varied with increasing velocities. Reproducibility at different velocities (Table 5 and 8) identified that CV was relatively consistent with a tendency for the variability of ACC data to increase at higher velocities, which is consistent with previous accelerometry research (Johnstone et al., 2012b; Trost et al., 2005). Use of piezoelectric technology within accelerometers is now well established (Chen and Bassett, 2005) and the non-reliance of this variable on a skin-based contact for data production may explain the positive reliability and validity results in this field environment.

Heart rate and breathing frequency

In comparison to ACC and considering all data, HR and BF variables presented less precision and more variance. When HR is investigated specifically (Table 1, 3, 6), it appears this variable produced a good level of precision and reproducible data at walking pace (i.e. 4-6 km·h^{-1}) though was less conclusive as velocities increased.

Table 5. Reproducibility of the ACC (VMU/ct·sec^{-1}) variable during simultaneous wearing of two devices.

Variable	Velocity	Data	Device A M (SD)	Device B M (SD)	Change in Mean	95% CL	CV	ICC
ACC (VMUct.sec^{-1})	All velocities	All	.91 (.39)	.86 (.36)	-.05	-.05 to -.04	12.4	.97*
		Clean	.29 (.11)	.29 (.10)	-.003	.01 to .00	10.3	.93*
	4-6 km·h^{-1}	All	1.09 (.20)	1.03 (.19)	-.05	-.06 to -.05	12.6	.80*
		Clean	1.16 (.18)	1.11 (.17)	-.04	-.06 to -.03	11.8	.66*
	8-10.5 km·h^{-1}	All	.91 (.39)	.86 (.36)	-.05	-.05 to -.04	12.4	.97*
		Clean	.29 (11)	.29 (.10)	-.003	.01 to .00	10.3	.93*
	11 km·h^{-1}	All	1.09 (.20)	1.03 (.19)	-.05	-.06 to -.05	12.6	.80*
		Clean	1.16 (.18)	1.11 (.17)	-.04	-.06 to -.03	11.8	.66*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), Change in mean, 95% Confidence Limits (CL), Coefficient of Variation (CV) and Intra Class Coefficient (ICC) * $p < 0.01$

Table 6. Reproducibility of the HR (b·min^{-1}) variable during a test-retest protocol.

Variable	Velocity	Data	Device A M (SD)	Device B M (SD)	Change in Mean	95% CL	CV	ICC
HR (b·min^{-1})	All velocities	All	146.1 (35.4)	141.1 (33.4)	-4.26	-4.82 to -3.69	8.0	.92*
		Clean	143.1 (34.4)	138.8 (32.7)	-4.2	-4.56 to -3.92	4.6	.97*
	4-6 km·h^{-1}	All	99.5 (16.8)	99.7 (16.8)	-1.82	-2.41 to -1.23	5.9	.89*
		Clean	-	-	-	-	-	-
	8-10.5 km·h^{-1}	All	157.0 (25.0)	151.9 (22.5)	-5.09	-5.89 to -4.28	8.7	.73*
		Clean	156.5 (22.7)	151.4 (21.5)	-5.13	-5.55 to -4.71	4.1	.93*
	11 km·h^{-1}	All	179.9 (17.7)	175.1 (18.5)	-4.80	-6.44 to -3.16	7.4	.54*
		Clean	177.6 (12.0)	172.0 (13.3)	-5.58	-6.34 to -4.82	2.8	.85*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), Change in mean, 95% Confidence Limits (CL), Coefficient of Variation (CV) and Intra Class Coefficient (ICC) * $p < 0.01$

Larger LoA are noted at velocities > 8 km·h^{-1} though reliability statistics remained relatively strong until the highest velocity, all of which mirrors laboratory based results on this device (Johnstone et al., 2012a; 2012b). For similar HR technology tested within a laboratory environment, a slightly lower CV is reported (Kent et al., 2009) but it is documented that there is a decrease in precision at velocities > 9 km·h^{-1} (Kingsley et al., 2004; Terbizan et al., 2002), which is constant with these research findings.

BF data were the weakest of all variables assessed (Table 1, 4 and 7). Relatively large LoA, moderate-to-low relationships and high CVs were seen in data throughout all velocities which reflect previous laboratory based assessments (Johnstone et al., 2012a; 2012b). In comparison, the Lifeshirt monitoring device, which uses similar BF technology, reported CV of ~10 though this was after averaging data in the last 30 seconds of a treadmill based protocol (Kent et al., 2009). Physiologically, when measured directly, BF has been noted as having a relatively high test-retest variance (Johnstone et al., 2012b; Kent et al., 2009), therefore the indirect assessment method of respiratory inductive plethysmography technology may add another layer of variance on to an already inconsistent variable.

Interestingly, the Bioharness™ BF variable has been tested previously (Hailstone and Kilding, 2011) and contrary to this research the variable was reported to be valid and reliable within a treadmill based protocol. Without identifying the version of the Bioharness™ device and using different statistical techniques, the authors reported no significant differences at different physical intensities, identifying ~2 br·min^{-1} as an acceptable difference. Critically, Hailstone and Kilding (2011) specific data capture and analysis procedure seemingly only took a short (15 second) sample of respiratory data. The 15 seconds of data was then cleaned, though no overview of the cleaning process was provided, and then averaged before statistical procedures were applied. It is hypothesised that the current research presents a more comprehensive view of the BF variable with data sampled for 2 minutes at 4 – 6 km·h^{-1}, 5 minutes at 8 – 10.5 km·h^{-1}, 1 minute at 11 km·h^{-1} all of which is presented in raw and clean data, without averaging. Different data handling methods can influence results, a standard data processing method should be considered in future research in order to clearly compare devices and research (Boudet and Chamoux, 2000; Kent et al., 2009). Exercise professionals and coaches using the Bioharness™ would want to know the data precision as it is reported from the device, so it is felt this current research may be providing a more realistic view of precision and reproducibility.

Data cleaning and variance

The cleaning protocol on HR and BF data was completed in an attempt to present a comprehensive picture of the device, highlighting and removing gross technical error from the data through the employment of recognised procedures (Field and Miles, 2010; Leger and Thivierge, 1988). With both raw and clean data sets presented, the exercise professional can ascertain further information on stability of each variable in the device. With regards to the latter point, the majority of data sets were removed errors at velocities > 8km·h^{-1} (Figure 1) and primarily from specific individuals, rather than across all participants. In comparison to the HR variable, the BF variable had more data sets removed with a peak occurring at 8 - 10.5 km·h^{-1}. When cleaned data is assessed, both HR and BF variable improved the reliability and validity, though the latter variable still presented weaker results confirming previous comments about respiratory measurement within this device.

Table 7. Reproducibility of the BF (br·min^{-1}) variable during a test-retest protocol.

Variable	Velocity	Data	Device A M (SD)	Device B M (SD)	Change in Mean	95% CL	CV	ICC
BF (br·min^{-1})	All velocities	All	30.6 (7.2)	30.4 (7.5)	-.11	-.33 to .11	18.1	.61*
		Clean	31.0 (6.9)	31.5 (6.5)	.51	.39 to .64	7.7	.90*
	4-6 km·h^{-1}	All	24.4 (4.1)	23.4 (5.0)	-.99	-1.50 to -.48	25.1	-.18
		Clean	23.4 (3.0)	24.5 (3.9)	1.09	.81 to 1.37	10.1	.65*
	8-10.5 km·h^{-1}	All	31.4 (6.6)	31.6 (6.6)	.22	-.03 to .48	15.9	.63*
		Clean	32.2 (6.0)	32.7 (5.7)	.55	.41 to .69	6.6	.91*
	11 km·h^{-1}	All	37.9 (4.2)	37.8 (3.8)	-.11	-.71 to .49	12.0	-.12
		Clean	38.3 (3.2)	37.6 (3.2)	-.67	-1.11 to -.23	7.3	.30*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), Change in mean, 95% Confidence Limits (CL), Coefficient of Variation (CV) and Intra Class Coefficient (ICC) * $p < 0.01$

Table 8. Reproducibility of the ACC (VMU/ct·sec^{-1}) variable during a test-retest protocol.

Variable	Velocity	Data	Device A M (SD)	Device B M (SD)	Change in Mean	95% CL	CV	ICC
ACC (VMUct.sec^{-1})	All velocities	All	.85 (.36)	.87 (.36)	.02	.02 to .03	14.7	.92*
		Clean	.29 (.10)	.31 (.11)	.02	.01 to .02	15.8	.84*
	4-6 km·h^{-1}	All	1.02 (.17)	1.05 (.18)	.02	.01 to .03	14.5	.53*
		Clean	1.10 (.16)	1.12 (.16)	.02	.00 to .04	13.2	.39*
	8-10.5 km·h^{-1}	All	.85 (.36)	.87 (.36)	.02	.02 to .03	14.7	.92*
		Clean	.29 (.10)	.31 (.11)	.02	.01 to .02	15.8	.84*
	11 km·h^{-1}	All	1.02 (.17)	1.05 (.18)	.02	.01 to .03	14.5	.53*
		Clean	1.10 (.16)	1.12 (.16)	.02	.00 to .04	13.2	.39*

Tabular report of reliability statistics: Descriptive statistics, Standard Deviation (SD), Change in mean, 95% Confidence Limits (CL), Coefficient of Variation (CV) and Intra Class Coefficient (ICC) * $p < 0.01$

There are possible reasons for increased data variance from the Bioharness™, especially at higher velocities, for HR and BF. Data production for HR and BF, using chest mounted electrodes and respiratory inductive plethysmograghy respectively, are reliant on a constant close connection with the performer's body. It is posited that physical activity at higher velocities are associated with possible breaks in connection with the performers body, increasing movement artefacts linked to chest strap instability or electromyogram noise, all of which may intermittently corrupt data (Astrand et al., 2003; Boudet and Chamoux, 2000; Cho et al., 2009; Witt et al., 2006). Also, sampling frequency for these two variables may not be sufficient at higher velocities leading to increased errors/artefacts, as in comparison, commercial fixed wire ECG devices sample data at >1000 Hz (Gamelin et al., 2006; Lopes and White, 2006).

The total variability of a device is the combination of biological variation and technical variation (Hailstone and Kilding, 2011) and an outcome of the research design (i.e. test-retest and simultaneous wearing) provided an opportunity to consider these two sources of variation. The simultaneous data collection for each variable may logically mean that biological variance is removed. A limitation for the latter was it meant that one of the two Bioharness™ devices were not in the manufacturers recommended optimal position possibly allowing for increased artefacts to influence data collection (Cho et al., 2009; McArdle et al., 2005; Welk, 2005; Witt et al., 2006).

Reliability statistics for ACC and HR were stronger (i.e. less variance) from the simultaneous wearing of two Bioharness™ devices in comparison to the test-retest protocol (Tables 3, 5, 6, 8). With relatively free movement permitted, it is more likely differences in ACC data will occur between trials. Other accelerometry research where simultaneous data collection has occurred concurs with this research, noting correlation coefficients between 0.72 – 0.92, when devices are positioned on contra-lateral hips (Trost et al., 2005). Variation in data from simultaneous wearing of the ACC could be attributed to the positioning of the device on the chest as the ACC is calibrated to a specific anatomical location (Welk, 2005).

Day-to-day variation of heart rate can vary, in absolute terms, between 3 – 8 b·min^{-1} with higher variance reported for sub-maximal activity in comparison to maximal activity (CV ~4.1 sub-max; ~1.6 max) (Achten and Jeukendrup, 2003; Astrand et al., 2003; Lamberts et al., 2004; Michaels and Cadoret, 1967). CV results for the simultaneous HR data collection (Table 3) fall within this range during walking and also at the other higher velocities when technical error is removed and, this may provide further indirect evidence that the HR variable is reliable. These positive results from the simultaneous wearing of the device also suggest there is some flexibility, as seen with other established chest mounted HRM, with the anatomical location and fitting of the Bioharness™ around the chest and subsequent capturing HR data.

Moreover, it does not seem that the same flexibility of placement may exist for BF variable as data comparisons between simultaneous and test-retest was inconclusive (Table 4 and 7). Though it is clear that each data set continued to produce comparatively weak reliability statistics which could be linked to the positioning

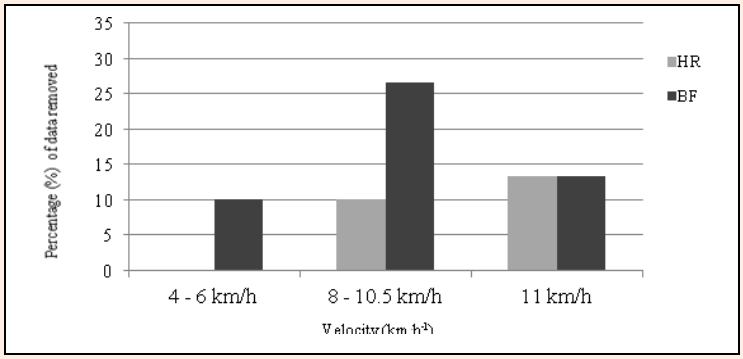

Figure 1. Profile of HR and BF data removal (%) at different velocities during data cleaning process.

and technical set up of the device (Johnstone et al., 2012a; 2012b, McCool et al., 2002), changes in breathing mechanics as velocity of movement increases (McArdle et al., 2005; Powers and Howley, 2007) and/or, as mentioned, that the notion that respiratory rate is normally variable (Kent et al., 2009).

Laboratory testing versus field testing

The relationship between measurements in a controlled environment when compared to more free movement based trials commonly identifies lower precision in the latter condition with the external environment adding a further dimension to movement patterns in participants (Charmari et al., 2004; Vanhelst et al., 2009; Welk et al., 2004). Comparing equivalent data collected on the Bioharness™, a trend of less precision and more variable data within a field based environment is seen in comparison to laboratory testing (Johnstone et al., 2012a; 2012b). Considering the most consistent variable during testing, ACC demonstrated a trend of greater variance in the field environment in comparison to a laboratory treadmill based event, a trend of which has been noted elsewhere (Bartlett et al., 2007; Hendelman et al., 2000; Welk, 2005; Welk et al., 2000). The WJR protocol allowed relatively free movement with non-specified turning episodes every 20 metres, involving acceleration and deceleration, therefore different running mechanics and physiological effort may well occur (Vanhelst et al., 2009), all of which can add to variability of data collected. Knowing how performers' data sets may change from a controlled to a field environment is an informative process for the exercise scientist who works in both scenarios.

Conclusion

The Bioharness™ ACC and HR variables demonstrate relative reliability and validity in the field based environment, though the use of some variables in wider sporting activities may be currently restricted due to the increased data errors at high velocities. BF variable appears to present more variable data and may need further development to be effective in the wider active or sporting environment. Any improvements to the device should be balanced with the maintenance of its unobtrusive and lightweight structure. It is clear that there is scope for more applied research to be completed, using up-to-date technology within a variety of physical activities, which will allow a clearer understanding of the key performance variables to be gained (Bartlett, 2006).

Future research may need to confirm the precision and reproducibility of data from the Bioharness™ within a female population and also with increased participants numbers, though this paper mirrors participants number seen in similar literature (Crouter et al., 2004; Gamelin et al., 2006; Kingsley et al., 2004; Terbizan et al., 2002). It has been highlighted that elite coaches want real life ecologically valid, applied research that can be utilised for performance enhancement (Achten and Jeukendrup, 2003; Gore et al., 1993) and this research provides an insight in to the Bioharness™ monitoring device for coaches and exercise scientists alike.

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Key points

- Field based monitoring technology should be assessed for reliability and validity in both the laboratory and applied setting in order to fully understand the data quality.
- Providing increased transparency in data collection and processing allows the exercise professional a comprehensive view of new technology.
- Of the three Bioharness™ variables assessed, heart rate and accelerometry provided the most valid and reliable data.
- The Bioharness™ and other similar new monitoring technology, may allow for further insight in to physical performance during ecologically valid experimental and "in-competition" athletic scenarios.

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