Portable High Resolution Accelerometers (HRA) for the Estimation of VO_2 in Highly Trained Inter-collegiate Distance Runners.

Abstract

Background: Accurate quantification of training load is important to optimize training in any sporting discipline. In running this is problematic, but high resolution accelerometers (HRA) may be of value. Since workload is proportional to VO_2 in running, the objective of this study was to determine the relationship of HRA and VO_2 in highly trained inter-collegiate runners. **Methodology**: Runners performed 2 incremental VO_2max trials while wearing HRA affixed to the lower back. RMS of high frequency unfiltered signal from three axes (VERT, LAT, A/P) and the Euclidean resultant (RES) were compared to VO_2. Also, test-rest correlations were determined for each axis and RES to determine reliability of this approach. **Principal Findings**: RMS of acceleration in g's for each axis were significantly correlated to VO_2 (0.868-0.945). Importantly, a single linear regression best described the strong VO_2 to RES relationship (R = 0.95) across the speed spectrum including both walking and high speed running. This single regression did not require correction for individual characteristics such as heart rate. High reliability was also observed with RES (ICC = 0.99; CV = 5.1). C**onclusions/Signficance**: Results of this study indicate that HRA can accurately and reliably predict VO_2 during treadmill locomotion in highly trained runners.

Introduction

Standardized quantification of mechanical (e.g. cycle ergometry) or metabolic (indirect calorimetry; VO_2) work has been performed in the laboratory setting for over a century (3). Often athletes and/or coaches may take principles determined from laboratory testing (e.g. lactate threshold) and apply them in the field. Historically though, in disciplines such as cycling and running, there has been no way to quantify work performed in the field as accurately and reliably as in the laboratory. Heart rate monitors have been used extensively in an effort to estimate metabolic work from estimates of oxygen consumption, but these devices have numerous limitations (reviewed in (1)). Recently, there has been a revolution in the discipline of cycling with the advent of portable on-board power meters (4, 15, 19, 39, 40). These devices provide laboratory quality data, and enable coaches and athletes to more effectively quantify training loads and evaluate training/racing efforts than with heart rate monitors. Also, portable power meters provide objective criteria (e.g. watts or Kj) for rational progressive training overload based on specific effort based criteria obtained from competition (39, 40).

In the discipline of running, there is currently no device that serves the same role as the power meter in cycling. It has been demonstrated that power can be derived from running on a track (6, 11), but due to changes in grade and difficulty in accurately quantifying distance, this cannot be extended to running on open, varied terrain. Efforts have been made to utilize global positioning system (GPS) devices to account for changes in grade and the resulting change in energy expenditure relative to speed (26), but these devices have lower resolution than true power meters, and some problems inherent to the technology have yet to be resolved (e.g. altitude errors, errors on curved courses) (10, 35). A possible candidate that might serve as a "power meter" for running, is the accelerometer. The use of accelerometers to measure human movement has increased greatly in recent years (9, 36, 41), but, from a physiological perspective, they have commonly been used as "activity monitors" for the course-grained measurement of gross movements. In many cases, the goal of using these low resolution accelerometers has been in attempt to objectively determine energy expenditure during free living non-formal activities (37). Due to the discretized nature of the data obtained from activity monitor accelerometers, numerous studies have been performed in attempts at developing regression equations to fit activity counts obtained from these devices to other measures of metabolic work (e.g. VO_2 and/or doubly labeled water) (38, 41, 42) . Although clinical/epidemiological studies are numerous, there have been few attempts to use this approach in athletic populations in order to objectively quantify external work of a dynamic activity such as running. Fudge et al. (14) did investigate the relationship between activity monitor accelerometers and VO_2 in trained runners, but determined that a correction for HR was necessary to obtain strong correlations. Further, some of the accelerometers tested would not show a strong correlation with VO_2 during running even with a correction for HR (14). So, although the utility of accelerometer based activity monitors for the measurement of "work" in running has been investigated with some success, it might be expected that resolution could be improved relative to this approach (i.e. higher resolution, greater accuracy), and in turn, with higher resolution, greater accuracy relative to other measures such as VO_2 might be obtained. Further, in an activity such as running, portable accelerometers might not only serve as ergometers to measure work, but some insight might be gained by using the high frequency signal from such a device to examine running mechanics collected during "real world" activities such as racing and training. Low resolution "activity monitors" do not provide this capability.

Accelerometers have been used in the field of biomechanics for decades (8, 29) for the purposes of gait analysis. In contrast to "activity monitors" used for metabolic/activity studies, these devices generally collect data at higher frequencies in continuous, as opposed to discretized fashion and as such, provide higher resolution. The high resolution accelerometers (HRA) provide some advantages over traditional approaches (e.g. force plate analysis or inverse dynamics), in particular, HRAs are portable, light, and generally can be used to either stream data at high frequency in real time, or datalog similarly high frequency signals collected during “real world” activities of locomotion that would not be possible using other means. Although HRA used for gait analysis have previously been limited by data storage capacity and portability, with the recent innovation of microelectromechanical system (MEMS) accelerometers, the aforementioned advantages may be exploited to a greater extent.

Since the current technology exists to measure acceleration in a high frequency, high resolution manner using portable devices, it would seem that this might be an interesting way to determine work/energy expenditure in running, while at the same time collecting data with regard to the gait characteristics of the individual. As a first step, the validity of such high resolution accelerometers (HRA) should be compared to an objective physiological measure such as VO_2 and/or running speed. Therefore, it was the objective of this study to examine the potential utility of HRA to quantify workload in trained intercollegiate cross country runners by determining 1) the relationship of the HRA signal with VO_2 and speed and 2) the test – retest reliability of HRA across a wide range of walking/running speeds. It was anticipated that since course-grained activity monitor based accelerometers have demonstrated reasonable correlations with VO_2, and high frequency accelerometers have demonstrated validity and reliability against force plates, HRA units should provide good correlations with VO_2 and be indicative of the mechanical work in treadmill locomotion in trained runners. Further, examples are provided where raw signal from HRA can provide insight into the mechanics of running on an individual basis.

METHODS

Subjects

Nine male NCAA Intercollegiate Division 1 runners (Table 1) gave written informed consent to take part in this study, which was approved by the local Human Subject Review Board.

Experimental Design

Subjects completed two continuous, incremental exercise tests on a motorized treadmill (True ZX-9, St. Louis, MO) with at least 6 days separating each trial. Exercise tests were performed to volitional exhaustion while high resolution triaxial acceleromety (HRA) and metabolic gasses were collected to determine relationships between, HRA, VO_2, walking and running speed. In addition, validity and reliability of the unfiltered, HRA was determined. After the first trial, two subjects could not complete a second trial due to injury. Data for these subjects was therefore not included in the reliability analysis, but was used for correlations and regression curve fits.

Procedure

Subjects reported to the laboratory on the day of examination after a 3 hr fast and having refrained from strenuous exercise, alcohol, and caffeine for 24 hours prior to the day of testing. Height and body mass were measure upon arrival at the laboratory (Mettler-Toledo, OH).

Incremental exercise test to volitional exhaustion

In each of the two tests, subjects began walking at 2km/h and speed was increased 2km/h every two minutes until volitional exhaustion. The treadmill grade was held constant at 1% to simulate normal over-ground walking/running. During tests, metabolic data was collected on a breath-by-breath basis using portable open circuit spirometry (Jaeger Oxycon Mobile, CA). VO_{2max} was determined as the highest 30s average of the test.

Metabolic Measurements

Indirect calorimetry was used to collect breath-by-breath measurements of VO_2 and VCO2 using electrochemical oxygen measuring cell (SBx) in an Oxycon Mobile (Cardinal Health, OH) and averaged over 5 sec. Heart rate was collected continuously via telemetry using a Polar coded transmitter belt (Polar t-31, Polar Electro, Oulu, Finland). The oxygen and carbon dioxide sensors were calibrated prior to each test for: ambient conditions (temperature and barometric pressure), volume and gas content against precision analyzed gas mixtures.

Accelerometry

The HRA device, a triaxial MEMS accelerometer model ADXL210 (G-link Wireless Accelerometer Node ± 10g Microstrain, Inc., Williston, VT) was placed anatomically at the intersection of the sagittal and axial planes on the posterior side of the body in line with the top of the iliac crest in order to approximate the center of mass (28). The accelerometer was mounted to a semi-rigid strap and additionally secured with elastic tape in order to any extraneous movement not associated with locomotion. Acceleration in g's was streamed in real time using telemetry to a base station at a frequency of 625 Hz.

Data Analysis

Raw accelerometry signal (in g's) was saved in Agilelink software (Microstrain, VT) and exported to Signal Express software (Labview, TX) in ASCII format. Full length files were parsed into 1 min segments, and the last one minute of each treadmill stage was used to calculate Root Mean Square (RMS) value using Signal Express for each axis, vertical (VERT), lateral (LAT), anterior/posterior (A/P), and Resultant (RES). The RES value was calculated according to the equation

$$RES_{xyz}^2 = (ix)^2 + (jy)^2 + (kz)^2 \qquad \text{(Equation 1)}$$

Where x, y and z equal the Vertical, Lateral and Anterior/Posterior axes, respectively.

The 1 minute RMS of acceleration were generated using Signal Express and compared to the 1 minute average of VO_2 for the last minute of each corresponding stage. Comparisons were made using Pearson's product correlation, RMS of raw signal were also compared to VO_2 using a linear regression curve fit. Validity and reliability of the HRA were determined by calculation of coefficient of variation (CV), test-retest reliability (R) and Interclass Correlations (ICC) (SPSS, IL; α=0.05).

$$x_{\mathrm{rms}} = \sqrt{\langle x_1^2 + x_2^2 + x_3^2 + ... + x_N^2 \rangle / N} \qquad \text{(Equation 2)}$$

Results

Correlations

Significant correlations were observed between RMS of raw acceleration of each of the axes, as well as VO_2 (Table 2). Although all correlations were highly significant, the strength of the correlations varied with A/P and RES most highly correlated to VO_2, and to a similar extent (Table 2).

Regressions

Results of regression curve fits of accelerometry vs. VO_2 can be seen in Table 3 and Figure 1 (a-d). Linear, quadratic and cubic regressions were attempted for VO_2 against each axis, and in all cases, quadratic and cubic regressions were not more significant than linear. It is readily apparent that the prediction of VO_2 when regressed to the VERT axis exhibited the weakest relationship across the entire range of speeds tested. When VO_2 was regressed against A/P and RES, similarly strong R values were observed, although the RES was much more significant as evidenced by the F values (Table 3). The strong linear relationship between VO_2 and RES can be seen when comparing the plot of RES vs speed in Figure 2 d and VO_2 vs speed in Figure 3. Both plots show a clear change in VO_2 and RES at the walk to run transition occurring between 6 and 8 km/h. Above and below this transition, both variables exhibit a similar relationship to speed. This bimodal response to speed has been well established with regard to VO_2 (24), and confirms the observation in the current study.

Reliability

The reliability of the HRA and VO_2 instruments used for this study are presented in Table 4. It can be seen that the test-retest reliability was quite high for all axes, but highest for RES, which was comparable to VO_2. Further evidence of the reliability of using RES is demonstrated by the CV which was also on par with VO_2. On the other hand, CVs were quite high in the LAT and A/P axes. This may be due to the well known sensitivity of CV as mean values approach zero. In the case of both Lat and A/P, means were much closer to zero than in VERT and RES, yet, the variance was quite high for both axes. Therefore, the high CVs in this case may be an artifact associated with the nature of the data.

Discussion

The present investigation is the first to report the relationship of HRA to VO_2 at a range of walking and running speeds, including maximal aerobic speed, in highly trained runners. It was determined that the RMS of the RES acceleration value calculated from the three individual axes exhibited a strong correlation with VO_2 (Table 2), strong internal validity (Table 3) and strong test-retest reliability (Table 3). These data indicate that HRA may prove of value for monitoring training load in trained runners in similar fashion to portable HR monitors, while providing additional information on gait characteristics, and changes in speed with high accuracy.

Correlations

Previous work by Fudge et al. (14) examining the utility of accelerometers for the assessment of running workload relative to VO_2 in trained runners at high running speeds (8-18 km/h) showed some promise. They reported reasonably strong predictions of VO_2 in walking and running with a triaxial activity monitor accelerometers, but these strong relationships required correction using HR. In the current study, no correction for HR was examined, and yet, stronger relationships were observed than in the Fudge et al. study when VO_2 was regressed to RMS of accelerometer signal, in particular, when regressed to RMS of RES (Figure 1d). The stronger relationships between VO_2 and RES observed in the present investigation are presumably because of the higher resolution of the HRA devices used. In the case of activity monitor accelerometers such as those used for the Fudge et al. study, considerations such as the thresholds for determining activity counts, as well as filtering bands applied are important (9, 25, 41). In the case of HRA, the continuous signal “captures” all movement, and more complete information regarding the movement is collected. Additionally, it should be noted that in the current study, no filtering was applied to the signal as to avoid losing sensitivity at lower exertion levels (e.g. 2 kph). Therefore, if used in athletes where sensitivity to low level activity is of little interest, it is plausible that stronger relationships between HRA and VO_2 could be obtained by the use of different filtering strategies. On the other hand, if this technology were employed for activity monitoring in other situations, the strong relationship observed in the present study demonstrates the sensitivity that can be achieved with HRA at low activity levels with little or no filtering. Therefore, the use of HRAs may be more broadly applicable for estimation of VO_2 and/or energy expenditure than simply in trained runners, but this will require further investigation.

Recently, Halsey et al. (17) used a similar approach to the current investigation by mounting HRA on the lower back (as well as other sites) of humans and reported strong relationships with VO_2 (l/min) during walking and running. In contrast to the current study, they used absolute VO_2 (l/min) as the criterion measure, and as such, relationships were improved by adding subject weight as a covariate in regression analysis. In the current investigation, the use of relative VO_2 (ml/kg/min) as the criterion inherently corrects for bodyweight, and therefore strong correlations were observed and VO_2 was strongly predicted by acceleration when regressions were performed using only relative VO_2 and RMS of RES. Another interesting contrast between the Halsey et al. and the present study is the fact that Halsey reported two separate regressions equations for walking and running, whereas in the current study, it can be seen in Figure 1d that the same regression of VO_2 to RMS of RES showed a strong relationship ($r = 0.95$). This is of interest because the use of a single regression equation simplifies data analysis and interpretation by negating the requirement of distinguishing walking and running activities.

Neither of the aforementioned studies investigated reliability of the devices used, and the reproducibility of their measures within subjects. Importantly, we show in the present investigation that HRA is not only valid relative to VO_2, but also reliable on re-test. This is in comparison with a report from Henriksen et al. (18) in which HRA mounted to the lower back and RMS of vector sum derived values exhibited ICCs of 0.81-0.85. In the current study, the ICCs for the analogous RES were higher (0.99; Table 4). Although CVs of individual axes A/P and Lat were higher in the present study (Table 4) than in the Henriksen et al. (18), they were within generally acceptable range for the VERT, and importantly, the RES. This is a serious consideration if HRA is to be used as a device to monitor training load across multiple workout sessions, or over extended periods. Also, from a practical perspective, it seems that if the HRA are not mounted in the exact same orientation on different occasions, the RES should not be dependent upon orientation, and therefore, the RES should be robust for determination of workload over the span of multiple workout sessions.

Potential applications of this work are significant on several levels. First, the use of HRA in the same sense as a traditional, downloadable HR monitors for the quantification of global training load becomes readily apparent, while HRA would not be susceptible to some of the limitations to HR (e.g. dehydration, psychological motivation etc) (1). This could be of particular value for the application of performance modeling approaches such as the training impulse (TRIMPS), with the use of a work output based metric as opposed to HR. The TRIMPS system have been used extensively in various sports (2, 12, 31, 34), including running (31). HR has been quite convenient with the advent of downloadable monitors, but poses some limitations with regard to its dependence on environmental conditions (e.g. cardiac drift), lag with efforts, and the fact that it cannot account for supramaximal efforts (1). Therefore, a metric that is more responsive to efforts, particularly at high intensities, and is not influenced by environmental factors is of interest.

A second, potentially quite valuable application is that, aside from simple estimation of training workload, HRA can provide post-hoc information in great detail with regard to the mechanics of the runner which, in turn, can be informative with regard to overall performance. For example, in Figure 4, we see a comparison of two different runners who compete at similarly high levels, and yet have quite different characteristics. In particular, Athlete A (Green/White) possesses a lower $VO_{2\ max}$ (65 ml/kg/min) than Athlete B (Red; 78 ml/kg/min), and yet is on par competitively, and in fact won a conference championship in front of Athlete B. As can be seen from the figures, on test day one, the week prior to a conference championship, Athlete A exhibits a strikingly unique pattern of acceleration spikes in the anterior plane. Athlete B who exhibits a greater aerobic capacity and maximal running speed in the incremental trial doesn't display these spikes. The difference in aerobic characteristics between these two runners is evidenced by the fact that Runner A reached $VO_{2\ max}$ at 22 km/h, but was able to start the 24 km/h stage. Runner B reached $VO_{2\ max}$ during the 24 km/h stage and also reached exhaustion. Despite the differences in aerobic capacity, Runner A won the conference 5 km championship in front of Athlete B four days after the Trial 1. In contrast the week after the conference championship where Athlete A expressed comments about fatigue, the athlete did not exhibit the striking acceleration spikes, and also became exhausted upon reaching $VO_{2\ max}$ at 22 km/h (Figure 4 a) White plot). It is not entirely clear why some runners can outperform others with equal or higher aerobic capacity, some have proposed anthropomorphic differences (13, 23), while others have argued for neuromuscular characteristics (32), and HRA may provide insight into this question. The value in using HRA as opposed to other biomechanical measures to determine such differences is that in traditional gait mechanics analysis, only a few gait cycles can be measured, whereas if HRA are worn over the course of entire workout, or multiple workouts, a more complete picture of running mechanics/dynamics may be obtained and some characteristics identified that might not be observed in a limited lab testing scenario.

Finally, a potential implementation of these devices is for the application of complex frequency or non-linear dynamical analysis of such data to gain further insight into the nature of fatigue or the constraints of running. There has been some interest in the field of biomechanics with regard to high level mathematical (e.g. non-linear dynamical analysis, spectral analysis etc.) of walking/running gait patterns (7, 16, 20, 21, 27, 30). There have been a few attempts to extend some of these techniques to theories of fatigue in competitive running and this area potentially holds promise (5, 22, 33). The use of HRA signal for these types of analysis may provide additional insight due to the high accuracy and high frequency sampling of these devices.

In conclusion, we report here that RMS of unfiltered HRA signals, particularly RES, provide valid, reliable estimates of VO_2 during walking and running in highly trained runners. Further work is necessary to determine if these results, obtained in highly trained runners, are generalizable to a broader population by looking at untrained individuals. It should also be determined if the same relationship between HRA and VO_2 hold on inclined surface, and in open terrain.

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Table 1: Physical Characteristics of Subjects (N=7)

	Mean	**SD**	**Range**
Body Mass (kg)	65.5	5.7	58.2-75
Height (cm)	181.8	4.1	175.3-188.0
Age (yr)	21.4	1.7	19-24
VO_{2max} (mL/kg/min)	70.1	6.2	60-79

Values are mean ± SD and range. BM, body mass. VO_{2max}, peak oxygen uptake.

Table 2. Correlations between RMS of acceleration in individual axes and VO_2.

Correlations

		Vert	Lat	AntPos	Result	VO2
Vert	Pearson Correlation	1.000	.787**	.779**	.953**	.868**
	Sig. (2-tailed)	.000	.000	.000	.000	.000
	N		148	148	148	148
Lat	Pearson Correlation		1.000	.931**	.929**	.879**
	Sig. (2-tailed)			.000	.000	.000
	N			148	148	148
AntPos	Pearson Correlation			1.000	.919**	.946**
	Sig. (2-tailed)				.000	.000
	N				148	148
Result	Pearson Correlation				1.000	.945**
	Sig. (2-tailed)					.000
	N					148
VO2	Pearson Correlation					1.000
	Sig. (2-tailed)					
	N					

**. Correlation is significant at the 0.01 level (2-tailed).

Table 3. Regression parameters of VO_2 vs individual axes.

Axis	**Equation**	**F**	***R***	**Adjusted *R^2***
Vertical	Linear	444.7	.868	.751
	Quadratic	221.0	.868	.750
	Cubic	221.2	.868	.750
Lateral	Linear	496.3	.879	.771
	Quadratic	420.3	.924	.851
	Cubic	280.1	.924	.851
Ant/Pos	Linear	1242.3	.946	.894
	Quadratic	668.3	.950	.900
	Cubic	445.1	.950	.900
Resultant	Linear	1213.5	.945	.892
	Quadratic	602.9	.945	.891
	Cubic	603.4	.945	.891

Table 4. Reliability parameters for test-retest conditions and VO_2.

Axis	**ICC**	**CV**	**Pearson's R**
Vertical	.980	5.7	.964
Lateral	.972	23.7	.945
Ant/Pos	.968	23.7	.939
Resultant	.990	5.1	.982
VO2	.992	5.2	.984

Figure 1. Regressions of VO_2 vs RMS of acceleration of individual axes during walking and running in highly trained distance runners. Linear regressions are significant in all cases (*p*<.001). a) Vertical b) Lateral c) Ant/Pos d) Resultant. = linear, = quadratic, = cubic.

Figure 2. RMS of accelerations (g) for individual axes vs. speed in highly trained runners during walking and running in trials 1 and 2. A) Vertical b) Lateral c) Ant/Pos d) Resultant. Green = Trial 1 and Blue = Trial 2.

Figure 3. VO_2 vs speed in highly trained runners during walking and running for trials 1 and 2. Green = Trial 1, Blue = Trial 2.

Figure 4. Raw acceleration in Ant/Pos axis for two different athletes. Green = athlete A trial 1, White = Athlete A trial 2, Red = Athlete B , trial 1. A) Acceleration plots for the entire run portion of the incremental test. B) highlighted segment at 18 km/h which shows acceleration "spikes" in anterior plane. C) a four stride segment showing successive acceleration spikes. D-F) three spikes from c) shown individually to demonstrate they are not aberrant artifacts and appear to be characteristic of the athletes running mechanics on this test day.