VALIDATION OF HEART RATE MONITOR–BASED PREDICTIONS OF OXYGEN UPTAKE AND ENERGY EXPENDITURE

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ABSTRACT
Montgomery, PG, Green, DJ, Etxebarria, N, Pyne, DB, Saunders, PU, and Minahan, CL. Validation of heart rate monitor-based predictions of oxygen uptake and energy expenditure. J Strength Cond Res 23(5): 1489–1495, 2009—To validate VO2 and energy expenditure predictions by the Suunto heart rate (HR) system against a first principle gas analysis system, well-trained male (n = 10, age 29.8 ± 4.3 years, VO2 65.9 ± 9.7 ml·kg−1·min−1) and female (n = 7, 25.6 ± 3.6 years, 57.0 ± 4.2 ml·kg−1·min−1) runners completed a 2-stage incremental running test to establish submaximal and maximal oxygen uptake values. Metabolic cart values were used as the criterion measure of VO2 and energy expenditure (kJ) and compared with the predicted values from the Suunto software. The 3 levels of software analysis for the Suunto system were basic personal information (BI), BI + measured maximal HR (BIhr), and BIhr + measured VO2 (BIhr + v). Comparisons were analyzed using linear regression to determine the standard error of the estimate (SEE). Eight subjects repeated the trial within 7 days to determine reliability (typical error [TE]). The SEEs for oxygen consumption via BI, BIhr, and BIhr + v were 2.6, 2.8, and 2.6 ml·kg−1·min−1, respectively, with corresponding percent coefficient of variation (%CV) of 6.0, 6.5, and 6.0. The bias compared with the criterion VO2 decreased from −6.3 for BI, −2.5 for BIhr, to −0.9% for BIhr + v. The SEE of energy expenditure improved from BI (6.74 kJ) to BIhr (6.56) and BIhr + v (6.14) with corresponding %CV of 13.6, 12.2, and 12.7. The TE values for VO2 were −0.60 ml·kg−1·min−1 and −2 kJ for energy expenditure. The %CV for VO2 and energy expenditure was −1 to 4%. Although reliable, basic HR-based estimations of VO2 and energy expenditure from the Suunto system underestimated VO2 and energy expenditure by −6 and 13%, respectively. However, estimation can be improved when maximal HR and VO2 values are added to the software analysis.

KEY WORDS aerobic capacity, intermittent exercise, team sport

INTRODUCTION
The measurement of oxygen consumption (VO2) and energy expenditure in the laboratory is well established for individual endurance-type sports such as running, cycling, and rowing. In contrast, the ability to measure or monitor changes in VO2 specific to a team-based field or a court-based sport is technically difficult. Information on the changes in VO2 and energy expenditure during play would provide insight for coaches and scientists about the metabolic demands of the sport and the adaptations that occur with training. Moreover, the determination of VO2 in a laboratory is time consuming in the context of a busy training schedule and financially challenging to test an entire team.

The accuracy (typical error [TE]) of laboratory-based VO2 systems should be <3% (26). A comprehensive review of the relevant literature shows that many of these systems, if not calibrated correctly, show error values up to 12% (18). However, the growing awareness of test reliability, along with the guidelines of acceptable tolerances (26), highlights the need for scientists to quantify the level of accuracy in laboratory equipment. Portable metabolic measurement systems have been developed and validated (4,6,17,18); however, these have their limitations and are generally impractical for team-based sports. Several studies have showed a high degree of error from 2 to 22% across low- and high-intensity workloads (18,11). Errors in these systems arise from both mechanical and sampling issues and the inherent biological variability in subjects from test to test.

Heart rate (HR) is a reasonable surrogate measure of VO2 and energy expenditure, given its linear relationship with these parameters at submaximal exercise intensities (5). A
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correlation coefficient of 0.91 showed that after adjusting for age, gender, body mass, and fitness, it is possible to estimate the energy expenditure during physical activity from HR values (15). However, the estimation of \( \dot{V}O_2 \) and energy expenditure from HR values is limited in the team sport setting, where steady state conditions are infrequent. The recent development of HR monitoring systems, which incorporate algorithm-based predictive software to assess \( \dot{V}O_2 \) and energy expenditure, is appealing to many sport practitioners. Heart rate–based monitoring of these variables could be useful in quantifying physiological responses to the training and competitive environment. However, the reliability and validity of these systems with highly trained athletes need independent evaluation before widespread use.

The Suunto personal HR monitoring system includes software for estimation of \( \dot{V}O_2 \) and energy expenditure based on methods developed by Firstbeat Technologies, Ltd (Jyväskylä, Finland). Basically, neural networks were constructed for estimation of \( \dot{V}O_2 \) and energy expenditure from R-R heart beat intervals, R-R–derived respiration rate, and the on-and-off \( \dot{V}O_2 \) dynamics during various exercise conditions (8,21–24). Although the investigators acknowledge the limitations in the accuracy of the predictions when individual values for maximal HR and \( \dot{V}O_2 \) are included, they give little information on the validity against pulmonary gas exchange values or correction factors to account for variation in these estimates. Recently, evaluation of the Firstbeat software in predicting \( \dot{V}O_2 \) and energy expenditure across 25 low- to high-intensity daily tasks revealed a mean under-prediction of 1.5 ml·kg\(^{-1}\)·min\(^{-1}\) and 27 kcal (113 kJ) (25). No substantial difference was observed in the low-intensity tasks, with the variation increasing to 3.5 and 2.2 ml·kg\(^{-1}\)·min\(^{-1}\) for the moderate- and high-intensity tasks, respectively. Although informative, whether these magnitudes of variation in predictive capacity are maintained for higher level intensities of exercise commonly undertaken by elite athletes is unclear. The use of the Suunto software was restricted to the determination of the validity and variation of the Suunto HR system compared with pulmonary gas exchange values for the estimation of \( \dot{V}O_2 \) and energy expenditure during submaximal- and maximal-intensity treadmill running in well-trained runners.

**METHODS**

**Experimental Approach to the Problem**

Each participant completed a 2-component (submaximal and maximal) treadmill running test where pulmonary gas exchange was measured and recorded over 30-second intervals throughout the testing period. We used an open-circuit, computerized, metabolic cart comprising Ametek \( O_2 \) and CO\(_2\) analyzers as described previously by Pierce et al. (20). The analyzers were calibrated with 3 \( \alpha \) gases of known concentration (BOC Gases Australia) before each test. Calibration was accepted at \( \pm 0.03\% \) of the target value. The accuracy of the analysis system was compared with an automated \( \dot{V}O_2 \) calibrator for open-circuit indirect calorimetric systems (11). Estimated \( \dot{V}O_2 \) values were within \( \pm 5\% \) as specified by guidelines of the National Sport Science Quality Assurance Program (Australian Sports Commission, Canberra, Australia). During the test, each participant wore a commercially available HR monitoring device (Suunto; Vantaa, Finland), and HR was recorded continuously during the entire testing period. The peak HR was recorded every 30 seconds during each component. Validity of the Suunto software to estimate \( \dot{V}O_2 \) and energy expenditure was compared against the criterion values of the metabolic cart. Three levels of the Suunto software analysis were evaluated. The first level of analysis required the input of the participant’s basic personal information (BI) of age, body mass, height, gender, and level of activity. The software then predicted maximal HR and \( \dot{V}O_2 \). The second level of analysis used the same basic personal information with the addition of the maximal HR (BIhr) as determined from the treadmill test. The third level of analysis added the laboratory-measured \( \dot{V}O_2 \)peak to the maximal HR and basic personal information (BIhr + v). In total, the HR recordings for each participant’s test were analyzed 5 times to determine any improvement in the accuracy for the software estimations. Estimations of energy expenditure were calculated from equations and tables of energy equivalents for the oxidation of fat-carbohydrate mixtures as described previously (7).

**Subjects**

Ten male (age 29.8 ± 4.3 (mean ± SD) years, body mass 70.0 ± 7.7 kg, height 1.79 ± 0.51 m, \( \dot{V}O_2\)peak 65.9 ± 9.7 ml·kg\(^{-1}\)·min\(^{-1}\), and maximum HR 189 ± 8 b·min\(^{-1}\)) and 7 female (25.6 ± 3.6 years, 59.6 ± 2.9 kg, 1.69 ± 0.39 m, 570 ± 4.2 ml·kg\(^{-1}\)·min\(^{-1}\), and 189 ± 11 b·min\(^{-1}\)) well-trained runners, who had been training continuously for the previous 6 months, volunteered to participate in the study. The study was approved by the Ethics Committee of the Australian Institute of Sport, and all subjects were verbally informed of the study requirements and signed an informed consent document before commencement.

**Procedures**

Subjects were required to fast overnight before performing submaximal and maximal treadmill testing (0600-0800 hours). At the beginning of the test, all subjects were seated passively (semisupine) on the treadmill for a 5-minute period while resting expired gases and HR were recorded. The treadmill protocol included 2 exercise components: (a) submaximal, a series of at least five 4-minute exercise intervals (stages) performed below the individual’s gas exchange threshold, and (b) maximal, a short incremental run to exhaustion. Depending on the participant’s running ability, the first stage of the submaximal component commenced at a predetermined running speed (range 9-15 km·h\(^{-1}\)), at a set gradient of 1%. The predetermined running speed was set at an intensity that would allow the subject to complete at least five 4-minute submaximal stages of increasing intensity and reach...
a blood lactate concentration of 4 mmol L\(^{-1}\). A 1-minute rest period was taken between stages for collection of a capillary blood sample. Running speed for each subsequent stage increased by 1 km h\(^{-1}\). At the completion of the submaximal component, subjects kept the mouthpiece in place and remained seated on the treadmill while expired gases were collected for a further 10 minutes. After the 10-minute period, subjects were allowed 1 minute to prepare for the maximal component of the test, which consisted of 1-minute stages commencing at the same initial running speed as the submaximal component. Running speed was increased by 1 km h\(^{-1}\) every minute until volitional fatigue, with the treadmill gradient held constant at 1% for the duration of the test.

**TABLE 1.** SEE and CV in \(\dot{V}O_2\) measures across 3 levels of analysis within the Suunto software compared with the criterion measures from the metabolic cart.*†

<table>
<thead>
<tr>
<th></th>
<th>SEE (ml kg(^{-1})·min(^{-1}))</th>
<th>%CV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower CL Upper CL Pearson (r)</td>
<td>Lower CL Upper CL Pearson (r)</td>
</tr>
<tr>
<td>BI Estimate</td>
<td>2.6 2.1 3.4 0.98</td>
<td>6.0 4.9 8.1 0.98</td>
</tr>
<tr>
<td>Mean bias</td>
<td>-6.4 -7.8 -4.9</td>
<td>-10.9 -13.1 -8.7</td>
</tr>
<tr>
<td>TE SWC</td>
<td>2.2</td>
<td>1.4 1.1 1.9</td>
</tr>
<tr>
<td>BI(_{hr}) Estimate</td>
<td>2.8 2.3 3.7 0.98</td>
<td>6.0 4.8 8.0 0.98</td>
</tr>
<tr>
<td>Mean bias</td>
<td>-2.5 -3.6 -1.4</td>
<td>-3.9 -6.0 -1.7</td>
</tr>
<tr>
<td>TE SWC</td>
<td>2.4</td>
<td>1.8 1.4 2.5</td>
</tr>
<tr>
<td>BI(_{hr} + v) Estimate</td>
<td>2.6 2.1 3.5 0.98</td>
<td>6.5 5.2 8.7 0.98</td>
</tr>
<tr>
<td>Mean bias</td>
<td>-0.9 -2.1 0.3</td>
<td>-0.4 -3.1 2.3</td>
</tr>
<tr>
<td>TE SWC</td>
<td>2.2</td>
<td>1.3 1.0 1.8</td>
</tr>
</tbody>
</table>

*CL = 90% confidence limits; SWC = smallest worthwhile change (calculated as 0.2 \times between participant SD); CV = coefficient of variation; HR = heart rate; TE = typical error; SEE = standard error of estimate.
†BI represents estimations based on the use of basic personal information only; BI\(_{hr}\) measures are based on the inclusion of correct (measured) individual maximal HR to BI; BI\(_{hr} + v\) measures are based on the addition of the correct (measured) \(\dot{V}O_2\) values to BI\(_{hr}\).

**TABLE 2.** SEE and CV in energy expenditure measures across 3 levels of analysis within the Suunto software compared with the criterion measures of the metabolic cart.*†

<table>
<thead>
<tr>
<th></th>
<th>SEE (kJ)</th>
<th>%CV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower CL Upper CL Pearson (r)</td>
<td>Lower CL Upper CL Pearson (r)</td>
</tr>
<tr>
<td>BI Estimate</td>
<td>6.7 5.5 8.9 0.96</td>
<td>13.6 10.8 18.4 0.93</td>
</tr>
<tr>
<td>Mean bias</td>
<td>-7.5 -10.4 -4.6</td>
<td>-8.1 -12.5 -3.4</td>
</tr>
<tr>
<td>TE SWC</td>
<td>1.5 1.2 2.0</td>
<td>2.3 1.8 3.2</td>
</tr>
<tr>
<td>BI(_{hr}) Estimate</td>
<td>6.6 5.3 8.7 0.96</td>
<td>12.2 9.8 16.5 0.94</td>
</tr>
<tr>
<td>Mean bias</td>
<td>-2.7 -5.2 -0.2</td>
<td>-1.6 -6.0 3.0</td>
</tr>
<tr>
<td>TE SWC</td>
<td>2.7 2.2 3.6</td>
<td>4.3 3.4 5.9</td>
</tr>
<tr>
<td>BI(_{hr} + v) Estimate</td>
<td>6.1 4.9 8.1 0.96</td>
<td>12.7 10.1 17.1 0.94</td>
</tr>
<tr>
<td>Mean bias</td>
<td>-0.2 -2.8 2.3</td>
<td>-2.1 -2.4 6.9</td>
</tr>
<tr>
<td>TE SWC</td>
<td>1.4 1.1 1.9</td>
<td>2.3 1.8 3.2</td>
</tr>
</tbody>
</table>

*CL = 90% confidence limits; SWC = smallest worthwhile change (calculated as 0.2 \times between measurement SD); CV = coefficient of variation; HR = heart rate; TE = typical error.
†BI represents estimations based on the use of basic personal information only; BI\(_{hr}\) measures are based on the inclusion of correct (measured) individual maximal HR to BI; BI\(_{hr} + v\) measures are based on the addition of the correct (measured) \(\dot{V}O_2\) values to BI\(_{hr}\).
remained seated with the mouthpiece in place for another 10 minutes. Data from the last 60 seconds of each of the 4-minute submaximal stages were used to determine the associated steady state O₂ consumption, and \( \text{VO}_2\text{peak} \) was calculated from the highest value recorded during any 60 seconds of the maximal running component.

**Statistical Analyses**

Simple descriptive statistics are reported as mean and SD. Raw values for \( \text{VO}_2 \) and energy expenditure from the metabolic cart and Suunto were log transformed to account for any nonuniformity of effects and errors. Validity was expressed as the standard error of the estimate (SEE) and the coefficient of variation (CV). Reliability was determined from 8 subjects who completed a retest within 7 days of their initial test; the results were expressed as TE and CV. Precision of estimation was indicated with 90% confidence limits where applicable. Bias between the practical and criterion measures was assessed by linear regression. The correlations between the criterion and predicted measurements were calculated with a Pearson correlation coefficient and expressed as an
established with a small effect size (0.2 - 0.5, moderate; and \( r > 0.5 \), large). The smallest worthwhile change in an outcome measurement was established with a small effect size (\( 0.2 \times \) between-subject SD) as described previously (14).

**RESULTS**

The validity of the predicted \( \dot{V}O_2 \) measurements from the Suunto system expressed with 90% confidence limits is shown in Table 1. The validity of the \( \dot{V}O_2 \) and energy expenditure values predicted by the Suunto system improved across the 3 levels of analysis with the sequential addition of the measured physiological information. There was little difference between the \( \dot{V}O_2 \) estimates for BI, BIhr, and BIhr + v, and the corresponding percent coefficient of variation (%CV). The degree of bias compared with the criterion \( \dot{V}O_2 \) showed an underestimation of 0.64, 0.72, and 0.57 ml \( \cdot \) kg\(^{-1} \cdot \) min\(^{-1}\) for BI, BIhr, and BIhr + v, respectively. The reliability of the Suunto system for \( \dot{V}O_2 \) expressed with 90% confidence limits is shown in Table 2. Values of energy expenditure generated by the software were also underestimated in comparison with criterion gas analysis. The mean error of the estimated energy expenditure, compared with the criterion gas measure, showed small improvements from -10.9% for BI, -3.9% for BIhr, to -0.4% for BIhr + v.

The reliability of the Suunto system for \( \dot{V}O_2 \) expressed as the TE is shown in Table 1. Small improvements in TE were seen across the 3 levels of analysis of BI, BIhr, and BIhr + v, with TE values of 0.64, 0.72, and 0.57 ml \( \cdot \) kg\(^{-1} \cdot \) min\(^{-1}\), respectively, and corresponding %CV of 1.4, 1.8, and 1.3. For energy expenditure, there were small improvements in the TE values of 1.49, 2.70, and 1.38 kJ for BI, BIhr, and BIhr + v, with little difference in the corresponding %CV values of 2.3, 4.3, and 2.3.

**DISCUSSION**

Providing key physiological information on \( \dot{V}O_2 \) and energy expenditure has great appeal for practitioners monitoring long-term changes in athletes. This study has shown that during submaximal- and maximal-intensity treadmill running, the estimates of \( \dot{V}O_2 \) from the Suunto HR system typically vary by \( \sim 6\% \) in comparison with criterion measures of a calibrated expired gas analysis system. This relative inaccuracy can be improved when known (measured) maximal values of HR and \( \dot{V}O_2 \) are included into the software analysis. However, even with the addition of measured HR and \( \dot{V}O_2 \) values, the level of error is inferior to laboratory-based methods. Estimates derived via the Suunto system are therefore not directly interchangeable with those from laboratory-based analysis systems. Nevertheless, the Suunto system should be useful for identifying moderate or large changes in oxygen demand and energy expenditure in field settings.

The smallest worthwhile change concept is useful for assessing the practical or clinical significance of effects in a sports setting (14). Quantifying the test-retest reliability of a performance test or measurement tool generates the TE. The TE permits the utility of a test to be interpreted via the signal to noise ratio. Where the TE (noise) is less than the smallest worthwhile change (signal), then the ability of the tool to detect worthwhile change is good. Conversely, if the TE is substantially greater than the smallest worthwhile change, a researcher or practitioner is less confident in detecting worthwhile changes in the laboratory or field. On this basis, given a TE of \( \sim 0.6 \) ml \( \cdot \) kg\(^{-1} \cdot \) min\(^{-1}\) and a smallest worthwhile change of \( \sim 2.3 \) ml \( \cdot \) kg\(^{-1} \cdot \) min\(^{-1}\), it follows that the Suunto system is useful for identifying moderate or large changes in estimated \( \dot{V}O_2 \). However, the margin of error is too large for a practitioner to be confident of detecting subtle (but worthwhile) changes observed in a highly trained athlete during serial monitoring. Similarly, the TE of \( \sim 2.1 \) kJ and smallest worthwhile change of \( \sim 1.7 \) kJ for energy expenditure indicate that the system is not as useful in predicing energy expenditure.

In a team-based situation, the Suunto system may be adequate for assessing the moderate to large changes in within-player fitness measures taken at preseason through competition and off-season periods. Substantial changes in \( \dot{V}O_2 \) have been observed during these training phases in various team sports (2,9,12,13,16). The system should also have utility in assessing the physiological responses and categorizing the energy demands of various field (or court) training sessions. Distinguishing low-, moderate-, and high-intensity training drills is useful information for conditioning coaches in team-based settings, as it allows training to be modified according to the accumulated load and intensity experienced during a series of drills. The Suunto system has acceptable reliability, which allows practitioners to compare drills or sessions that have the same temporal and training characteristics, for differences in intensity and physiological demand. The system may also have utility in monitoring the long-term development of the aerobic capacity of junior athletes as they progress to senior levels and for injured players undertaking rehabilitation programs. Given the limited amount of technology available for use in the field for team sports, the Suunto system seems to be an advanced method of quantifying activity compared with current practices.

The utility of the Suunto system can be improved by providing additional individual athlete inputs to the software before estimation of \( \dot{V}O_2 \) and energy expenditure values. However, practitioners need to account for the amount of bias in the estimates. At the basic personal information level, there is substantial uncertainty (up to 10%) in the precision of the estimates of \( \dot{V}O_2 \) and energy expenditure. The large
amount of bias associated with the basic level decreases the confidence in the results, but as the bias improves across the additional levels, the results have a higher degree of utility. Presumably, the error associated with the basic level relates to the quality and quantity of the subjects in the original studies of which the algorithms are based on (23,24). The use of a more homogenous subject group, who were highly trained, may decrease the amount of error. The outcomes from the subsequent levels of analysis highlight the close relationship between HR and \( \dot{V}O_2 \) (3): The prediction becomes more agreeable with the criterion measure when the measured values of these variables are included. There is only minimal improvement with the addition of the measured \( \dot{V}O_2 \) values (Figure 1). Given that the software only requires a single figure for maximal values of HR and \( \dot{V}O_2 \), determined at the conclusion of the maximal test, it is of interest that the software is able to make relatively accurate predictions of submaximal \( \dot{V}O_2 \) values across several running speeds.

Our estimates for \( \dot{V}O_2 \) at higher intensity running are in agreement with previous reports of \( \dot{V}O_2 \) for “high-intensity” daily tasks (25). We observed that the values for higher intensity running are underestimated by \(-2 \text{ ml kg}^{-1} \text{ min}^{-1}\). In general settings, this margin of error would be acceptable as the broad categorization of the energy cost for daily tasks may not require the precision of laboratory-based measures and would allow practitioners involved with energy balance to make suitable dietary or activity-related decisions. A moderate degree of accuracy may be acceptable for those practitioners and researchers who are interested in the demands of lower level activities or daily living activities. However, given that the Suunto system is marketed as a sports training tool, the benefit for higher level recreational and elite athletes is somewhat limited for assessing small serial changes in physiological measures during a training season.

Energy expenditure in the current study was underestimated during the submaximal component of the treadmill test across all levels of analysis. Although the SEEs of energy expenditure showed large improvements over the 3 levels of analysis, the degree of bias did not improve, showing an underestimation against the criterion measure. Similarly, the CV did not change substantially with the inclusion of all measured variables (Figure 2). This finding demonstrates the (in)effectiveness of the algorithms when all measured information is included; the large variation at the basic level of assessment has implications for those using the system in the absence of measured maximal values.

During the maximal stage of the test, estimations of energy expenditure were overestimated at the initial running speeds. One possible explanation for this finding may be that the HR was slightly elevated as a response to the previous submaximal component. We observed an elevated HR of \(-5 \text{ b min}^{-1}\) (3%) between the first 4 stages of the maximal component compared with the corresponding stages (i.e., same speeds) of the submaximal component. Although we stipulated a 10-minute rest period between the submaximal and maximal components of the test, this was insufficient to reestablish a resting HR. Even though subjects were permitted to drink ad libitum between stages, elevated HR may reflect cardiac drift associated with dehydration (19) or an altered autonomic tone (10) carried over from the previous submaximal component. These ancillary elevations in HR are a limitation to the Suunto system, as misleading estimations of energy expenditure could be made from results obtained from HR not essentially associated with the underlying exercise demand.

**Practical Applications**

The Suunto HR monitoring system is useful for field-based estimations of \( \dot{V}O_2 \) and, to a lesser extent, energy expenditure. However, the Suunto HR monitoring system lacks the precision needed to be a viable alternative to a calibrated metabolic cart in the laboratory setting. Although the system shows a high degree of reliability in a test-retest situation with a TE of \(-1.5\%\), the magnitude of error shown in this study of \(-6\%\) compared with an accurate metabolic cart is outside the acceptable limits of \(<3\%\) for quantifying small changes or differences in energy demand. The estimation of energy expenditure seems more problematic with error values of \(-13\%\). The system may have some utility in field-based assessments of gross changes in aerobic capacity or assessing the energy demands of a training/competition session, as a practitioner can be assured of the accuracy between sessions. Although the measures provided by the Suunto software are underestimated in comparison with criterion measures of HR and energy expenditure, these predictions are certainly no worse than information reported for portable \( \dot{V}O_2 \) systems. The Suunto system appears suitable for assessing energy balance estimations in daily tasks: However, practitioners should be aware of the bias associated with the software and account for this in their reporting and exercise programming. The ease of use of the system, with telemetry functionality, facilitates immediate feedback of changes in both \( \dot{V}O_2 \) and energy expenditure, which should provide new insight into field-based assessments.

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