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VALIDATION OF THE EQUIVITAL™ EQO2+ LIFEMONITOR FOR CONTINUOUS HEART RATE MONITORING DURING INTERMITTENT MILITARY-RELEVANT TESTS OF PHYSIOLOGICAL LIMITS

United States Army
Medical Research & Development Command

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VALIDATION OF THE EQUIVITAL™ EQO2+ LIFEMONITOR FOR CONTINUOUS HEART RATE MONITORING DURING INTERMITTENT MILITARY-RELEVANT TESTS OF PHYSIOLOGICAL LIMITS

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14. ABSTRACT

We evaluated the efficacy of the EQ02+ for measuring heart rate (HR) in military personnel during intermittent tests of physiological limits. Twenty-seven US Army personnel (age, 24 ± 6 years; height, 174 ± 7 cm; body mass, 77 ± 14 kg) were continuously monitored during two laboratory visits that included five activities: supine rest, incremental walk, incremental run, verification run, and load carriage. Heart rates recorded by the EQ02+ were compared against measurements from the chest-strap Polar H10 heart rate sensor. We examined the agreement between systems in the capability to measure continuous minute-by-minute, resting, and maximal HR. Heart rates continuously monitored by the EQ02+ and H10 systems over the laboratory visits were in close agreement (95% limits of agreement (LoA), [-7.5, 7.0 bpm]). The EQ02+ and H10 systems provided similar measurements of resting HR (95% LoA, [-2.7, 3.7 bpm]) and maximal HR (95% LoA, [-7.9, 5.3 bpm]). The EQ02+ is an accurate body sensor for continuous HR monitoring of work/rest cycles across the physiological limits of cardiovascular function.

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EXECUTIVE SUMMARY

Introduction: The Equivital EQ02+ LifeMonitor is a field-expedient body sensor system used for monitoring vital signs such as heart rate in warfighters, athletes, and manual laborers. However, the EQ02+ has only been validated for light-to-moderate and steady-state activities.

Purpose: We evaluated the efficacy of the EQ02+ for measuring HR in military personnel during intermittent tests of physiological limits.

Methods: Twenty-seven US Army personnel (2 women, 25 men; age, 24 ± 6 years; height, 174 ± 7 cm; body mass, 77 ± 14 kg) were continuously monitored during two laboratory visits that included five activities: supine rest, incremental walk, incremental run, verification run, and load carriage. Heart rates recorded by the EQ02+ were compared against measurements from the chest-strap Polar H10 heart rate sensor. We examined the agreement between systems in the capability to measure continuous minute-by-minute, resting, and maximal heart rates.

Results: Heart rates continuously monitored by the EQ02+ and H10 systems over the laboratory visits were in close agreement (Bias ± SD, -0.3 ± 3.7 bpm; 95% LoA, [-7.5, 7.0 bpm]; R^2, 0.991). The EQ02+ and H10 systems provided similar measurements of resting heart rate (Bias ± SD; -0.5 ± 1.6 bpm; 95% LoA, [-2.7, 3.7 bpm]; R^2, 0.954) and maximal heart rate (Bias ± SD; -1.3 ± 3.4 bpm; 95% LoA, [-7.9, 5.3 bpm]; R^2, 0.901).

Conclusion: The EQ02+ is an accurate body sensor for continuous HR monitoring of work/rest cycles across the physiological limits of cardiovascular function.

INTRODUCTION

Continuous monitoring of cardiorespiratory responses is critical for numerous military, ergonomic, occupational, research, and athletic applications [1]. Clinicians monitor heart rate (HR) responses to physical activity to ensure patients remain safely below pre-defined intensity limits [2]. Exercise physiologists commonly use HR as a criterion for verifying maximal effort during peak aerobic fitness testing [3]. In addition, HR is an essential input for real-time thermoregulatory models that estimate core body temperature during rest and strenuous physical activity for safety purposes [4, 5].

Laboratory tests of physiological limits are useful for designing and interpreting future training or field activities [6, 7]. For example, sport coaches can prescribe a common, individualized exercise intensity across a team of athletes by scaling HR training zones to the maximal heart rate (MHR) recorded during preliminary testing [6, 8]. Physical workloads may be further individualized by accounting for differences in resting heart rate (RHR): a useful indicator of cardiorespiratory fitness as well as autonomic stress level [9]. Longitudinal tracking of RHR is a prospective approach for identifying potentially severe performance decrements before they occur. Impairments in physical conditioning are often preceded persistent elevations in above baseline RHR or a reduced capacity to recover following acute stressors [10]. Key cardiorespiratory outcomes from laboratory exercise testing provide benchmarks for characterizing physiological demands of less structured activities such as casualty evacuation [11] and military load carriage over complex terrain [7]. Thus, identifying an ambulatory monitor that accurately measures both upper and lower cardiorespiratory limits is of great importance for many real-time and planning purposes.

The Equivital EQ02+ LifeMonitor (EQ02+; Equivital; Cambridge, UK) is a field-expedient body sensor [12, 13] that measures cardiorespiratory parameters such as HR. The EQ02+ has been shown to be a valid and reliable ambulatory monitor of vital signs during light-to-moderate laboratory exercise [14] and free living [15]. Researchers have utilized the EQ02+ for ambulatory monitoring of Warfighters [7], athletes [16], laborers [17], and other populations [18] that engage in exhausting physical work. However, the efficacy of the EQ02+ for monitoring HR during intermittent tests reaching physiological limits has yet to be determined.

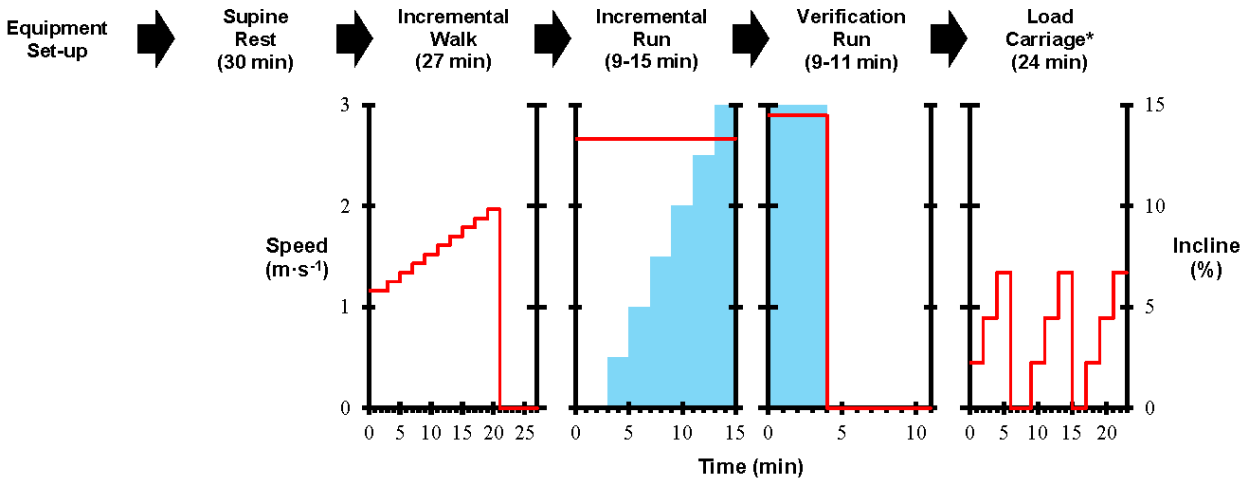
The purpose of this study was to evaluate the viability of the EQ02+ for continuous HR monitoring in military personnel during intermittent tests of physiological limits. In addition, we sought to compare measurements of upper and lower cardiovascular limits from the EQ02+ against a standard laboratory alternative. Proving the capabilities of the EQ02+ in these circumstances is an essential step towards identifying physiological body sensors with universal HR monitoring applications.

METHODS

Design

We compared HR measurements from the EQ02+ against concurrent measurements from the Polar H10 (H10; Polar Electro; Lake Success, NY); an established criterion HR monitor [19]. Heart rates were continuously monitored over five activity periods that collectively tested the systems from the lowest to highest physiological extremes with varying workrate increases and recovery dynamics (**Figure 1**). Participants were asked to perform each of the activities on two separate laboratory visits with the exception of the load carriage test (first visit only).

Figure 1. Testing sequence.



*, Visit 1 only; Blue fill, treadmill incline setting; Solid red line, treadmill speed setting.

Participants

Twenty-seven US Army soldiers and civilians (2 women, 25 men; age, 24 ± 6 years; height, 174 ± 7 cm; body mass, 77 ± 14 kg) volunteered for this study. Participants were briefed on the purpose of the study and potential risks before voluntarily giving their informed written consent. This study was approved by the Institutional Review Board (IRB) at the US Army Medical Research and Development Command (MRDC; Fort Detrick, MA). Investigators adhered to Department of Defense Instruction 3216.02 and 32 CFR 219 on the use of volunteers in research.

Procedures

On each of the two laboratory visits, participants arrived at a morning start time (0600-0900), wearing standard physical training attire (shorts, t-shirt, socks, and running

shoes). Precautions for testing included avoiding alcohol (> 24 h), vigorous exercise (> 48 h), high-intensity exercise (> 48 h), as well as caffeine, nicotine, and food intake (> 10 h). To avoid potentially deleterious effects of dehydration, bottled water (500 ml) was provided the night before and the morning of each visit and urine specific gravity was checked to be ≤ 1.030. Participants were queried upon arrival that they had adhered to study precautions.

After anthropometric measurements, participants were measured for lower chest circumference at the xiphisternum along the bottom of the pectoral muscles to choose a corresponding sensor belt size. The sensor belt clasp was positioned at the center of the chest below the pectorals, and fastened to one of three settings (tight, middle, loose); a correctly fitted belt was determined by placing two fingers between the belt and skin and finding a tight but comfortable fit. A Polar H10 HR monitor belt was also fitted for each participant, with the H10 system positioned directly below the EQ02+ sensor belt. Both belts were moistened with water on all electrodes to ensure a strong signal, and the EQ02+ sensor belt's serial number, size, and clasp settings were noted for use through all participant visits before refitting both systems.

An EQ02+ Sensor Electronic Module (SEM) was removed from the charging dock, activated, and placed in the SEM housing of the sensor belt underneath the left armpit; time of activation was also recorded. All SEMs were configured in ambulatory mode at a 15 sec reporting rate to optimize for highly vigorous activity, and measurements such as HR and ECG waveform were monitored for real-time accuracy via Bluetooth signal with the EqView Mobile Android Application live view. The EQ02+ ECG waveform signal and noise were also tested for robustness by asking participants to generate volatile upper body movement while observing waveform shape for excessive noise. Participants were then either deemed properly fitted, or had minor adjustments made to sensor belt positions before rechecking HR and ECG waveform validity.

Once properly fitted, participants completed the supine rest period by laying face-up on a cot for 30 min in a quiet, dimly lit room. Participants were instructed to remain as still as possible while remaining awake for the duration of the period. The minimum HR measured during each supine rest period was considered to be the individuals' RHR.

The incremental walk began with a 3 min stage at 1.16 $m \cdot s^{-1}$ on a level incline. The treadmill speed was increased by 0.09 $m \cdot s^{-1}$ increments each 2 min stage thereafter until the highest speed (1.97 $m \cdot s^{-1}$) was completed, or the participant was unable to continue without jogging, hopping, or running. Upon completion, the participant stood on the treadmill for a 6 min recovery period without supporting themselves on the handrails.

The incremental run involved participants running a modified Astrand incremental running test [20]. Each participant began by running for 3 min on a 0% incline at a speed based on their self-reported two-mile run pace. The treadmill incline was

increased by 2.5% for each 2 min stage thereafter until volitional exhaustion was reached. Following a 12 min rest interval, participants completed a verification run to exhaustion with the treadmill set to the average incline over the final 2 min of the incremental run with the speed increased by 10%. After volitional exhaustion was reached, the participant stood for another 6 min recovery period. Maximal heart rate was considered to be the highest HR measured during each run.

The load carriage test required participants to carry three rucksack loads (22, 44, and 66% of body mass) at three walking speeds (0.45, 0.89, and 1.34 $m \cdot s^{-1}$) on a 0% incline for 2 min each. Loads were carried in the Modular Lightweight Load-Carrying Equipment (MOLLE) 4000: the US Army's most recently developed military rucksack [21]. The MOLLE 4000 was loaded so that the heaviest mass was closest to the body. Rest periods of approximately 3 min were allotted between loads to unload, repack, and refit the MOLLE 4000.

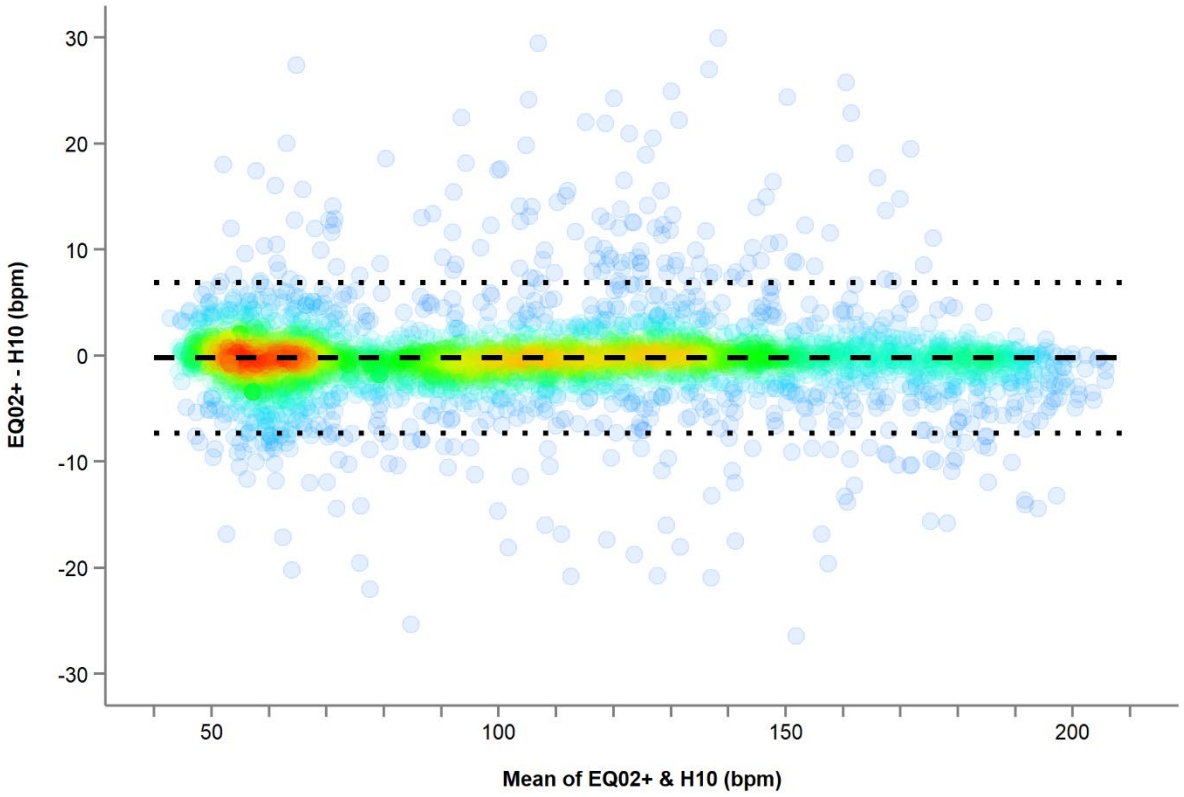
Statistical Analyses

Data were analyzed using R (Version 3.3.1; R Foundation for Statistical Computing; Vienna, Austria) [22] and are reported as mean ± standard deviation (SD) unless stated otherwise. Heart rates from both systems were averaged per minute. We employed a linear mixed effects modeling approach in order to quantify the agreement between HR monitoring systems while accounting for repeated measures. Random effects of activity within participants on intercepts were included for continuous monitoring comparisons while random effects of participants on intercepts were included for activity-specific, RHR, and MHR comparisons. Bland-Altman plots of agreement were generated for visual depiction of the agreement between the EQ02+ and H10 systems along with 95% limits of agreement (95% LoA) [23]. To limit overplotting effects, markers in the Bland-Altman plot for continuous monitoring were color-coded by two-dimensional binned kernel density estimation. Color-coding markers using two-dimensional kernel density estimation enables better visualization of the structure and density of the dataset [24]. Higher density regions are colored in progressively warmer colors from the least dense (light blue) to most dense (red). Disagreements between methods were also characterized by the bias and SD of paired differences, marginal coefficient of determination (R^2) [25], and concordance correlation coefficient (CCC) [26].

RESULTS

The full range of HR measurements across all participants was similar between the EQ02+ (43 to 205 bpm) and H10 (41 to 207 bpm). **Figure 2** shows the agreement between measurements from the EQ02+ and H10 monitoring systems from the complete dataset. Heart rates continuously monitored over the laboratory visits by the EQ02+ and H10 were in close agreement (Bias ± SD, -0.3 ± 3.7 bpm; 95% LoA, [-7.5, 7.0 bpm]; R^2, 0.991; CCC, 0.996).

Figure 2. Bland-Altman plot of agreement between heart rate (HR) measured by the Equivital EQ02+ and Polar H10 monitoring systems.



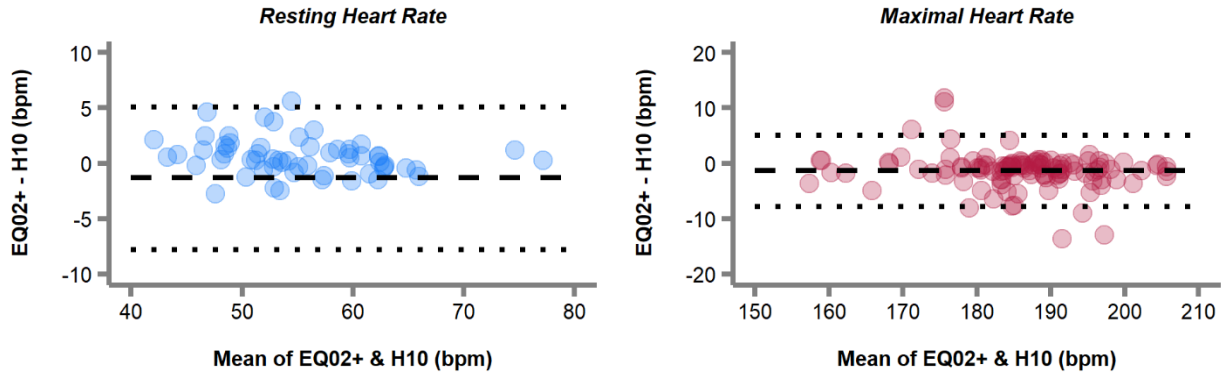
Markers are color-coded by two-dimensional kernel density estimation to distinguish the lowest (light blue) to highest (red) density regions of the overall dataset. Dashed line, bias; dotted lines, 95% limits of agreement.

When examining individual activities, the EQ02+ demonstrated similar accuracy and precision for the supine rest (Bias ± SD, -0.3 ± 3.4 bpm; 95% LoA, [-6.6, 5.5 bpm]; R^2, 0.775; CCC, 0.878) as during the incremental walk (Bias ± SD, -0.4 ± 2.8 bpm; 95% LoA, [-5.8, 5.0 bpm]; R^2, 0.977; CCC, 0.988). The EQ02+ and H10 systems had slightly lower precision but higher correlations during the incremental run (Bias ± SD, -1.1 ± 4.0

bpm; 95% LoA, [-8.9, 6.8 bpm]; R^2, 0.982; CCC, 0.990) and verification run (Bias ± SD, -0.3 ± 3.8 bpm; 95% LoA, [-7.6, 7.1 bpm]; R^2, 0.981; CCC, 0.990). Out of the five activities, the limits of agreement were widest during the load carriage test (Bias ± SD, 1.1 ± 5.4 bpm; 95% LoA, [-9.5, 11.6 bpm]; R^2, 0.875; CCC, 0.932).

Figure 3 displays the agreement between systems when measuring RHR and MHR. The EQ02+ and H10 systems recorded similar measurements of RHR (Bias ± SD; -0.5 ± 1.6 bpm; 95% LoA, [-2.7, 3.7 bpm]; R^2, 0.954; CCC, 0.973). Relative to RHR values, MHR measurements were slightly less consistent between the EQ02+ and H10 systems (Bias ± SD; -1.3 ± 3.4 bpm; 95% LoA, [-7.9, 5.3 bpm]; R^2, 0.901; CCC, 0.940).

Figure 3. Bland-Altman plot of agreement between the Equivital EQ02+ and Polar H10 systems for resting heart rate (left panel) and maximal heart rate (right panel).



Dashed line, bias; dotted lines, 95% limits of agreement.

DISCUSSION

Our study demonstrates that the Equivital EQ02+ LifeMonitor is accurate for ambulatory HR monitoring in several previously untested conditions. Most notably, we found that minute-by-minute measurements from the EQ02+ were in close agreement with recordings from a standard research HR monitor over a series of variable intensity exercises and intermittent rest periods. The EQ02+ provided similar measurements of RHR and MHR compared to this standard during common laboratory assessments. These findings emphasize the utility of the EQ02+ and encourage future evaluation of the system in other austere conditions endured by Warfighters, firefighters, and manual laborers.

The accuracy of the EQ02+ demonstrated in the current study is similar to that shown by earlier validation research involving less strenuous exercise. Liu et al. [14] found similar agreement (Bias, 1.2 bpm; 95% LoA, ± 6.6 bpm) comparing the EQ02+ against another Polar sensor (S810i HR Monitor, Polar Electro Oy, Kempele, Finland) in six male participants at rest and during low-to-moderate intensity laboratory exercise. Akintola et al. [15] compared raw ECG data from the EQ02+ against the gold standard

Holter monitoring system (SEER MC Holter monitor; GE Healthcare, USA) in eighteen adults over a 24 h data collection period. Predictably, the bias (-0.8 bpm) and Pearson correlation coefficient (0.997) were highest in the analyzed datasets with the lowest ECG artifact content.

Other HR monitoring systems have demonstrated comparable or lesser functionality for monitoring high-intensity exercise. Flanagan et al. [27] reported a R^2 of 0.99 and 95% LoA [-2.84, 2.42 bpm] comparing the Armour39 monitoring system (Under Armour; Baltimore, MD, USA) versus a laboratory ECG (IXBIO4; iWorx Systems, Inc, Dover, NH, USA) in seventy-five men during graded cycle ergometer exercise. Kim et al. [1] compared HR measured by the Zephyr BioHarness™ against a 12-lead ECG (Vmax Spectra System, VIASYS, Yorba Linda, CA) during a graded exercise test in thermal-neutral conditions as well as a sustained exercise in a hot environment (30 °C, 50% relative humidity). They also found low bias but with less precision for both the graded exercise test (Bias, 0.5 bpm; 95% LoA, [-15.3, 16.3 bpm]) and exercise in the heat (Bias, 0.5 bpm; 95% LoA, [-17.2, 17.8 bpm]).

Although our current study demonstrates the accuracy of the EQ02+ for continuous HR monitoring at physiological extremes, there are many conditions that haven't been examined to universally validate the system across the spectrum of military tasks. Extreme environmental conditions, such as heat [28], cold [29], or water immersion [30] present challenges to both the human and monitoring device. The US Army also has a wide diversity of body sizes and shapes that require proper equipment fitting for accurate HR measurements [31, 32]. Additionally, Warfighters often conduct dynamic and complex activities while wearing cumbersome protective clothing [33-38], which may complicate proper physiological monitoring. However, this study shows that the EQ02+ is accurate over a large range of HR including the on-set of the rest-to-work transition and during recovery following hard physical work.

CONCLUSION

The Equivital EQ02+ LifeMonitor is an acceptable body sensor for continuous heart rate monitoring of work/rest cycles across the physiological limits of cardiovascular function. Users can be confident in the accuracy of resting and maximal heart rates measured by the EQ02+ during standardized laboratory testing. These advantages combined provide military users with enhanced programming and evaluation of relative physical workloads in individual Warfighters.

Conflicts of Interest and Source of Funding

The authors have no conflicts of interest to declare. Funding for this work has been provided by U.S. Army Medical Research and Development Command (USAMRDC), Military Operational Medicine Research Program (MOMRP).

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