Quantification of energy expenditure of military loaded runs: what is the performance of laboratory-based equations when applied to the field environment?

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ABSTRACT

Introduction Performance during army loaded runs provides a synthetic indicator of a soldier's capacity to move while carrying loads and thereby remain able to execute a mission. The aim of this study was to estimate and compare the energy expenditure (EE) of army loaded runs, conducted in a field environment using laboratory-based equations and HR index (HR_{index}).

Methods 45 Ranger recruits had HR monitored during three loaded runs (10, 15 and 20 km) in full military equipment in the field environment. EE was calculated using reference equations (EE-Eq) and estimates of oxygen consumption based on HR_{index} (EE-HR_{index}). Correspondence between EE-Eq and EE-HR_{index} estimates was evaluated using a two-way analysis of variance, correlation test and Bland-Altman analysis.

Results EE-Eq relative to time and weight was significantly higher for the 10 km (0.175±0.016) compared with 15 and 20 km (0.163±0.016 and 0.160±0.013 kcal/kg/min, not different). The overall EE-Eq increased significantly with distance (1129±59, 1703±80 and 2250±115 kcal for 10, 15 and 20 km). EE-Eq was not different from and highly correlated with EE-HR_{index}, with a small and non-significant bias and good precision between methods.

Conclusions Our study provides the first comprehensive data on HR and EE during long-distance loaded army runs, in full combat equipment, in actual field conditions. Equation-based estimates of EE during these heavy-intensity activities were not significantly different from and highly correlated with HR-based estimates. This corroborates the general applicability of the predictive equations in the field environment. Furthermore, our study suggests that time-resolved HR-based estimates of EE during army runs can be used to evaluate for the effects of context specificity, individual variability and fatigue in movement economy.

Key messages

- The study determined the energy expenditure associated with three military loaded runs and evaluated the performance of the reference equation (ie, the Epstein's equation).
- HR index estimates are similar to those obtained from reference equations.
- Energy expenditure during loaded runs can be estimated using HR index.
- The results of our study corroborate the general validity of the equation-based approach when applied to the field environment.

INTRODUCTION

Performance during army loaded marches provides a synthetic indicator of a soldier's capacity to move while carrying loads and thereby remain able to execute a mission.[1] The absolute and relative effort associated with this demanding testing/selecting tool needs to be quantified to optimise recovery strategies, food intake and ultimately reduce injuries.[2–4] Specific equations that predict the mean energy expenditure of loaded marching and running have been developed[5–7] and are included in official North Atlantic Treaty Organisation technical reports as practical reference tools to support decision-making.[1] However, the mathematical models used in this approach present some potential limitations. Such models have been developed based on a limited number of individuals, for treadmill locomotion in a laboratory environment, and are referred to activities of short duration (around 30 min). This relatively 'artificial' approach is clearly far away from the reality of military operations, characterised by a high variability in exercise duration (typically longer than 30 min), terrain characteristics, soldiers' physical status and in environmental conditions. Moreover, the above equations, developed on USA Army soldiers, have not been validated in other contexts characterised by potential differences in soldiers' characteristics and equipment. Finally, this approach is unable to account for and to track possible changes of running economy associated with technique, exercise duration/fatigue/perceived effort, load amount, distribution[2] and the presence of the rifle (eg, arm swing restriction).[2] As a result, the application of these equations in non-standard conditions (eg, real mission in field, prolonged exercise duration, different nations, different specialisation of soldiers, variable fitness level, the presence of the rifle) entails potential inaccuracy and is unable to provide time-resolved data and to account for within-subject and between-subjects variability of energy expenditure at a given external or absolute work (ie, speed, load, slope and so on).

Based on the linear relationship that exists between HR and oxygen consumption (VO_2),[8] HR index (HR_{index}, equal to absolute HR divided by resting HR) has been used to obtain time-resolved

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estimates of energy expenditure (in metabolic equivalents (METs)) during a variety of activities. A robust relationship has been demonstrated between HR_{index}-based estimates (EE-HR_{index}) and VO_2-based measures of energy expenditure, independent of exercise mode, age, gender and body weight.[9]

By comparing equation-based estimates of EE with HR_{index}-based estimates, the study evaluated the performance of the reference equation (ie, the Epstein's equation) in estimating the energy expenditure of military loaded run in the field environment. We hypothesised that the mean values predicted from the reference equation would not differ from HR_{index}-based estimates, confirming the general validity of the equation-based approach when applied to the field environment.

METHODS

From the total of 97 trainees enrolled in three consecutive Army Rangers Training courses between 2013 and 2015, we randomly recruited a sample of 15 individuals for each course for a total of 45 soldiers. Good current health at the moment of the measures was the only inclusion criterion. No exclusion criteria were applied. All procedures performed were in accordance with the 1964 Helsinki declaration and informed consent was obtained from all individual participants included in the study.[10]

All tests were conducted at the national Rangers Training Company and were part of the standard evaluation/selection protocol of Ranger trainees in the first 6 months of the programme. During the first week of training, before breakfast, body mass (digital scale, Seca 877, Seca, Leicester, UK) and stature (vertical stadiometer, Seca, Leicester, UK) were measured. Percentage of body fat was determined by skin fold thickness. Skin fold thickness was measured, in triplicate, by a single skilled investigator (pectoral, scapular, triceps, iliac, abdominal, thigh) using a pincer type calliper (Holtain T/W, Holtain, UK). Percentage of body fat was estimated based on the sum of the six skinfold thickness with the formula described by Golding *et al*.[11] On a different day of the same week, in the morning, 2 hours after breakfast and after a standardised 15 min warm up, subjects performed the functional test battery designed by the regiment in the barracks' gym. Three loaded runs (10, 15 and 20 km) took place between the third and fourth months of training.

Resting HR

In the morning, before breakfast, after a 5 min rest in a seated position, resting HR was measured over a 3 min period, using a heart monitor (Memory belt, Suunto, Finland, acquisition frequency: 10 s).

Loaded runs

Three loaded runs (10, 15 and 20 km) took place in the morning (08:00) after a standardised breakfast that included 500 mL of water and a standardised 15 min warm up. The ambient temperature was 15°C–20°C, relative humidity of 40%–70% and there was no wind, corresponding to 10.6°C–17.6°C wet-bulb globe temperature (WBGT). As per Army Rangers Training programme schedule: (1) the 10 km trial was performed first, followed by the 15 km and the 20 km trials; (2) a minimum of 1 week of recovery separated the trials and (3) activities that may entail physical tiredness were avoided in the 24 hours preceding the tests. The runs took place in the countryside of Verona, on an unpaved, flat road, with the soldiers in full military equipment comprising standard combat uniform and boots (2.4 kg), standard replica rifle (2.4 kg) and backpack (15–20 kg). The mass of the backpack corresponded to the mean load used in practice during marches and was equivalent to the minimum deemed essential for a mission.[1] Participants were asked to maintain the same backpack weight for the three trials and the individual weight was monitored before and after the trial with a dynamometer scale (PCE-HS 50N, range 0.2–50 kg, PCE instruments, Italy). Prior to the tests, participants were informed that completion of the loaded runs within a predetermined time limit, which was not disclosed to the soldiers (1 hour 12 min, 1 hour 55 min and 2 hour 52 min for 10, 15 and 20 km, respectively), was required to pass selections and that lower times would result in proportionally better evaluations. The task was not paced by an instructor and participants had no notion of either time, distance or their HR. Soldiers were required to drink a minimum of 1, 1.5 and 2 L of water during the 10, 15 and 20 km trials, respectively. Water consumption during the runs was individually recorded as the loss of backpack weight from start to end of each loaded run.

During the three runs, HR was monitored (Memory belt, Suunto, acquisition frequency: 10 s). Data points were time aligned for the test start (time 0), and overall session mean was calculated between time 0 and the end of the run. Furthermore, 1 min means were calculated every 10 min during the runs for each individual. HR data were expressed in b/min units and as % of maximal HR (as estimated based on age).[12]

Mean speed was measured based on individual time (chronometer) over the established path distance (measured and marked by the instructors using a GPS (GPS Foretrex 701 Ballistic edition, Garmin, USA)).

Energy expenditure estimation

The energy expenditure of loaded marches was calculated as follows: first the energy expenditure of walking was calculated based on mean speed, subject's nude weight, clothing and equipment weight, terrain gradient and characteristics (terrain factor; we used 1.1 corresponding to 'dirt road' on a weighting scale that goes from 1.0 for the black topping road to 4.1 for soft snow of 35 cm)[7] based on the Pandolf's equation:

Pandolf's equation

$$M_w = 1.5 \bullet W + 2.0 \bullet (W + L) \bullet (L/W)^2 + T \bullet (W + L) \bullet (1.5 \bullet V^2 + 0.35 \bullet V \bullet G)$$

where M_w = metabolic cost of walking (watts), W = body mass (kg), L = load mass (kg), T = terrain factor, V = velocity or walk rate (m/s) and G = grade (%)

Thereafter, the calculated energy expenditure of walking was corrected using the Epstein's equation to obtain the energy expenditure of loaded running.

Epstein's equation

$$M_r = M_w - 0.5 \bullet (1 - 0.01 \bullet L) \bullet (M_w - 15 \bullet L - 850)$$

where M_r = metabolic cost of running (watts), M_w = metabolic cost of walking (watts) and L = load mass (kg).

The values in watts were then converted to kcal/kg/min or total kcal by using the 0.01433 conversion factor and the appropriate time calculation.[5,13]

Based on 10 s means, individual HR_{index} was calculated as actual HR/resting HR and the following equation was applied to estimate a 10 s mean VO_2[9]:

$$VO_2(L/min) = \{[(HR_{index} \bullet 6) - 5] \bullet (3.5\ \text{body weight})\}$$

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Table 1 Anthropometric and functional characteristics of the 45 Ranger recruits who performed the three loaded runs

	Age (years)	Stature (cm)	Weight (kg)	Body fat (%)	2 km run (s)	Pull-ups (#)	Dips (#)	Push-ups (#)	Sit-ups (#)
X	26	179	78	11	428	16	23	49	49
SD	3	7	9	4	40	6	4	8	3

Data are presented as mean (X) and SD. Pull-ups and Dips refere to the maximal number performed. Push-ups and Sit-ups refere to the maximal number performed in 60 seconds.

Finally, energy expenditure (EE-HR_{index}), relative to time and weight (kcal/kg/min) and total (total kcal) was calculated based on an energy equivalent for VO_2 equal to 5 kcal/L.[13]

Statistics

Mean, SD and 95% CIs were calculated for all parameters. After preliminary assumption verification, the differences among mean values of speed and HR for the three distance runs were tested by one-way repeated measures analysis of variance (ANOVA). Differences among values of energy expenditure as calculated based on either Epstein's equation (EE-Eq) or HR (EE-HR_{index}) were tested by two-way repeated measures ANOVA (method of estimate and distance), followed by Holm-Sidak. α was set at 0.05. Statistical significance was declared when $p<\alpha$. In addition, after testing for homoscedasticity, the linear relationship between EE-Eq and EE-HR_{index} was modelled and Pearson's product moment correlation coefficient was calculated. A Bland-Altman analysis, followed by one-sample z test, was used to determine accuracy and between-subjects precision of EE-Eq compared with EE-HR_{index}. Potential differences between mean values of HR as a function of time (1 min means every 10 min of test) were tested by two-way repeated measures ANOVA (time and distance).

RESULTS

Anthropometric and functional data of the recruits included in the study are presented in table 1. All participants successfully completed the three loaded runs. Mean running speed, HR and energy consumption estimations (EE-Eq and EE-HR_{index}) are presented in table 2. Subjects ran the 10 km distance at a significantly higher speed and higher mean HR and %HR_{max} compared with 15 km and 20 km runs (not different from each other). Accordingly, the relative energy expenditures (kcal/kg/min) was higher for the 10 km runs compared with 15 km and the 20 km trials, but no statistical difference was found between the 15 km and the 20 km runs. Increasingly and significantly higher total energy expenditures were recorded for the three trials.

HR values, calculated every 10 min of running, are presented in figure 1 as mean and SD. A significant increase in HR values was found between the first 10 min of the 10 km loaded run and the successive time windows and between 30 min and the 40 and 50 min time windows (not different from each other). At all time windows, the HR of the 10 km trial were significantly higher compared with both the 15 km and 20 km trials (not different from each other). However, no significant difference in mean HR was found in the 15 km and 20 km runs between the first 10 min and the subsequent time windows.

No statistical difference was found between the mean values (total amount and kcal/kg/min) of EE-Eq and EE-HR_{index}. Furthermore, a consistent correspondence was found between measures of energy expenditure (Eq-EE vs HRindex-EE) across the range of the measures. The EE-Eq (kcal/kg/min) was significantly correlated with the EE-HR_{index} ($r=0.79$, $p=0.00$). Furthermore, as it can be appreciated from the Bland-Altman plot, where the difference between measures is plotted as a function of the mean of the two measures (figure 2), there is a non-significant mean difference (bias) between measures (0.0004 kcal/kg/min) and a good between-subjects precision (0.01 kcal/kg/min, equal to 5.9% of the mean value) between EE-Eq and EE-HR_{index}.

DISCUSSION

Loaded runs are a typical evaluation and selection tool within the Italian Ranger Regiment. Our study is the first to estimate the energy expenditure during this form of locomotion, performed in the field environment on different distances, on a flat terrain and in full combat uniform. The study evaluated the performance of the Epstein's equation, developed in a laboratory environment and used as a practical reference by the military forces, in estimating the energy expenditure of military loaded run performed in the field environment. To this aim, we compared equation-based estimates of EE with HR_{index}-based estimates relative to three distances. The main finding of the study is that the mean EE values predicted from the reference equation are not different from and highly correlated

Table 2 Running speed, HR values and energy expenditure during the three loaded runs

Run distance	10 km	15 km	20 km
Average speed (km/hour)	9.3±0.7*° (9.2 to 9.4)	8.7±0.7 (8.6 to 8.8)	8.6±0.6 (8.52 to 8.66)
Average speed (min/km)	6′30″±30″*° (6′30″; 6′25″)	6′54″±36″ (7′00″; 6′48″)	7′00″±24″ (7′05″ to 6′57″)
Average HR (b/min)	175±8.0*° (174 to 176)	170±8.0 (168 to 170)	170±9.1 (169 to 172)
Average HR (%max)	92±4.1*° (91.7 to 92.7)	89±4.2 (88.6 to 89.6)	89±4.7 (88.7 to 89.9)
EE-Eq (kcal/kg/min)	0.175±0.016*° (0.173 to 0.177)	0.163±0.016 (0.161 to 0.165)	0.160±0.013 (0.158 to 0.161)
EE-Eq (total kcal)	1129±59*° (1121 to 1136)	1703±80° (1693 to 1712)	2250±115 (2236 to 2264)
EE-HR_{index} (kcal/kg/min)	0.174±0.011*° (0.172 to 0.175)	0.163±0.012 (0.162 to 0.165)	0.162±0.011 (0.160 to 0.163)
EE-HR_{index} (total kcal)	1125±96*° (1113 to 1137)	1714±158° (1694 to 1733)	2289±232 (2260 to 2317)

Data are presented as mean (X), SD and 95 % CIs (reported in parenthesis). Differences among mean values of speed and HR for the three distances runs were tested by one-way repeated measures analysis of variance (ANOVA). Asterisks and the degree symbol indicate a significant difference from 15 km and 20 km run, respectively. Differences among the mean values of energy expenditure (EE) for the three distances runs, as calculated based on either Epstein equation (EE-Eq) or HR based calculations (EE-HR_{index}) were tested by two-way ANOVA (method of estimate and distance), followed by Holm-Sidak.

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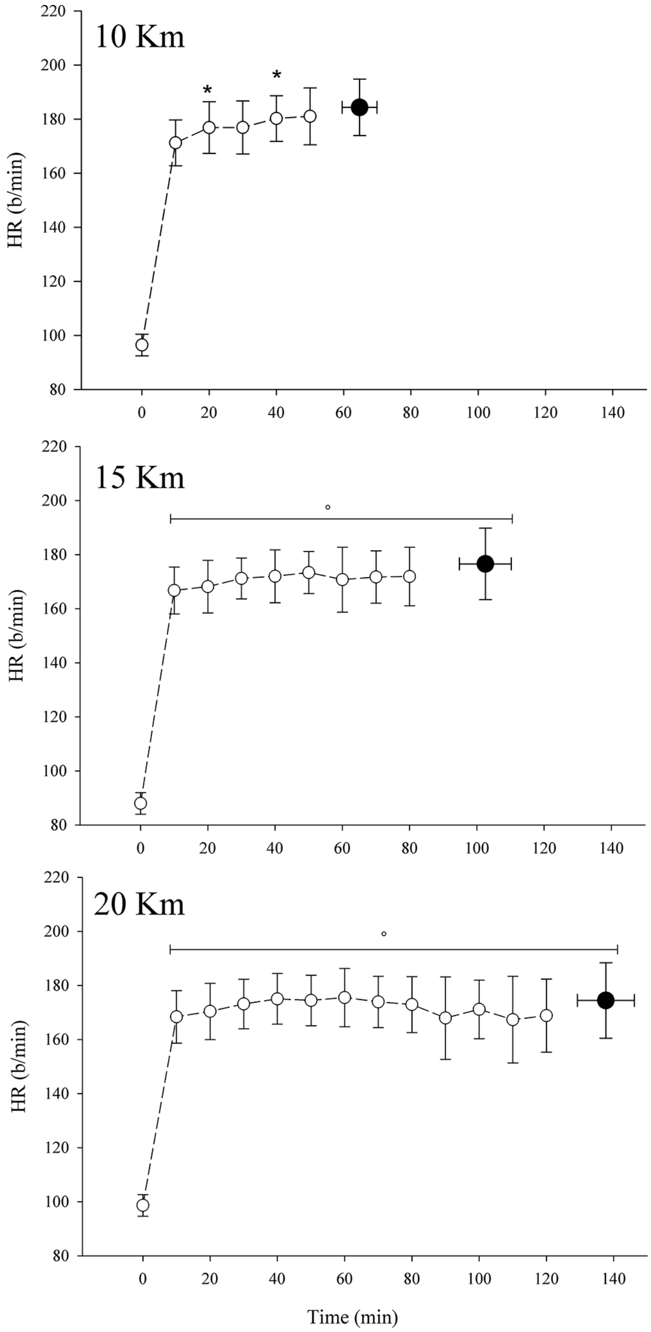

Figure 1 Mean HR values (calculated as 1 min means, every 10 min during the runs for each individual) and SD are plotted as a function of time for the 10, 15 and 20 km loaded runs, respectively, in the upper, middle and lower graphic, as empty circles. In the three graphics, the filled circles represent the mean of the final values of HR (measured as the mean of the last minute before finishing the run) plotted as a function of mean final time. Asterisk indicates a significant difference from the immediately preceding time window. Degree symbol indicates a significant difference from the 10 km trial.

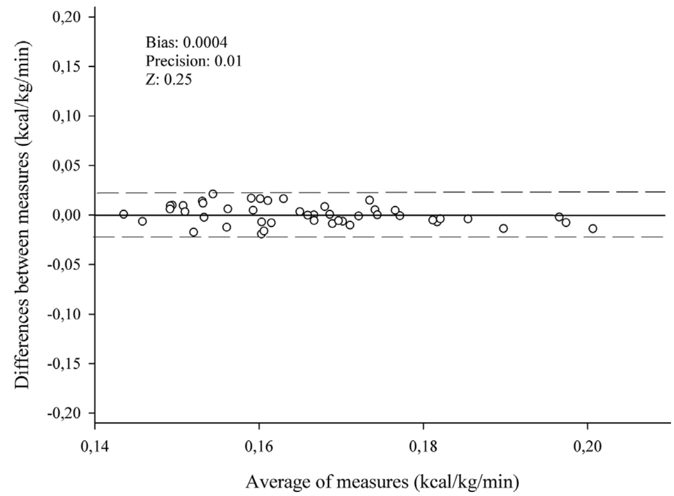

Figure 2 Individual differences between the estimated energy expenditure from the Epstein's equation (EE-Eq) and the HR_{index}-based estimates of energy expenditure (EE-HR_{index}) are plotted as a function of the mean of the two measures. Bias (ie, mean difference between measures; solid line) and precision (ie, limits of agreement; dashed line) are displayed along with numerical values and the results of the one-sample z test on the bias.

with HR_{index}-based estimates, with a non-significant bias and a good precision between methods; these findings corroborate the general validity of the equation-based approach when applied to the field environment.

The anthropometric and functional characteristics and the mean speed of the three run trials [1]in our sample of Italian Ranger Trainees were similar to those reported in the literature for special forces in Europe.[14–16] This likely reflects a similar reference population, selection process and comparable training practices.[15 16]

As expected, based on the well-known inverse relationship between relative exercise intensity and exercise duration,[17] the shorter distances were associated with both a higher speed of locomotion, higher HRs and $\%HR_{max}$ compared with the 15 and the 20 km runs. This may reflect a pacing strategy by experienced soldiers,[18] as a disproportionately wider time allowance was permitted for the 15 and the 20 km than the 10 km trial.

The mean absolute and relative HRs ($\%HR_{max}$) recorded during the 10, 15 and the 20 km loaded runs (table 2) suggest a physical effort between 'vigorous' and 'near to maximal' intensity.[10] These values appear ~10 b/min higher compared with previous reports.[18–20] This difference may be ascribed to the different type of exercise (continuous vs intermittent),[19] terrain characteristics (unpaved road vs treadmill), exercise duration (over 1 hour vs few minutes)[18 20] and load amount and distribution (the presence/absence of the rifle).[18 20] In agreement with previous studies on a different form of loaded locomotion (ie, loaded walking/marching),[21 22] a significant increase in HR over time was observed during the 10 km trial (in particular between 20 and 30 min and between 30 and 40 min). While our data does not allow us to determine if this is due to an increase in speed or an increase of the energy cost of locomotion, this finding corroborates the importance of time-resolved monitoring during shorter-duration trials. On the contrary, the mean HR remained stable during the longer trials (figure 1), possibly reflecting a more effective pacing strategy in the longer-duration trials.

This is the first study to use HR_{index} [9] for the determination of the energy expenditure of army loaded runs. One previous study focused on the performance (ie, speed) and on the ability to complete soldiering tasks following runs with variable loads and load distributions.[19] The study concluded that load amount and distribution affect the HR response to loaded running, yet a quantification of individual EE was not attempted. A more recent study on British soldiers demonstrated that internal load (ie, $\%VO_{2max}$) can be accurately predicted based on subjective

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perception of effort (ie, rate of perceived exertion) during an incremental loaded run on the treadmill.[20] A successive study by the same group directly measured the VO_2 elicited by loaded army run in a small group of British soldiers during a treadmill incremental test (3 min duration steps) with backpack and no rifle.[18] It is noteworthy that, when translated into EE units, also accounting for the difference in weight caused by the presence of the rifle, Simpson's data provide an estimate of total energy expenditure (for comparable speeds) that is ~90, 115 and 120 kcal lower (8, 7 and 5% of the trial total EE, respectively) than our HR_{index}–based estimates for the 10, 15 and 20 km trials, respectively. The near correspondence between our 'field' estimates and the direct laboratory measures corroborates the validity of our simple and low-cost approach.

Our study compared estimates of energy expenditure derived from the HR_{index} approach with those derived from the armed forces reference method (Epstein's equation).[1] The estimates of EE based on HR_{index} were not significantly different from and significantly correlated with Epstein's estimates (r=0.79). Furthermore, the Bland-Altman analysis showed a non-significant bias (0.0004 kcal/kg/min) between estimates, a small imprecision (0.01 kcal/kg/min, equal to 5.9% of the signal). It is well known that the HR–VO_2 relationship during dynamic, aerobic exercise in a given individual is acutely affected by a number of factors such as exercise mode,[23] priming,[24] hypoxia,[25] hydration,[25] training,[23] fatigue[26] and increases in core temperature.[27] Estimates of VO_2 that rely on HR measurements will be affected accordingly. The long interval between trials (ie, 1 week), the relative rest before each test as well as hydration and aerobic training, possibly via a better control of core temperature over time,[28 29] would tend to minimise a longitudinal cumulative loading/training effect and the possible effect of fatigue and core temperature rise on the HR-VO_2 measured in our study. Based on data of untrained subjects, in a condition that was similar to that of our study in terms of exercise intensity/duration, hydration strategies and heat risk category (<18°C WBGT, equivalent to low risk), HR increased of roughly 11% (10–15 b/min) between 10 and 60 min into exercise, while core temperature increased of about 1°C. About 50% of the increase in HR was explained by the increase in core temperature and the other 50% by a concurrent increase in VO_2 as a function of time (ie, the so called VO_2 slow component).[26] Furthermore, in well trained, hydrated athletes who exercised for 120 min at ~70% of VO_{2max} in extreme heat stress conditions (WBGT 29°C), HR increased of ~6% over time while core temperature was unaffected by exercise duration.[28] In our study, HR significantly increased between the 10th and the final minute of exercise by 9±6, 7±5 and 6±9 b/min, respectively, for the 10, 15 and 20 km trials (change significant for the 10 km trial only). We are unable to determine if the observed increase in HR is due to raised core temperature (and as such not reflective of an increased metabolic rate). However, it appears plausible that in our well hydrated, trained individuals, in the low heat risk conditions of our study (10.6°C–17.6°C WBGT), at least 50% of the observed increase in HR is reflective of an increased metabolic rate over time (associated with a VO_2 slow component). Based on the above considerations, we speculate that our HR-based method, in the present experimental conditions, could be associated with an overestimation of the total EE of roughly 4%–6%. Future studies intended to validate the use of HR-based approach proposed in our study should perform direct measures of core temperature and explore the effect of different ambient conditions on the estimates of internal and external load associated with loaded military run.

In summary, our study is the first to test the feasibility of a 'sport sciences' approach to estimate internal and external load during army loaded runs, on different distances in the field environment. Furthermore, this is the first study to use HR-based estimates of EE as a reference method to validate equation-based estimates developed in the laboratory environment. The HR-based method proposed in our study is feasible and provides estimates of EE that coincide with equation-based estimates. The results of our study corroborate the general validity of the equation-based approach when applied to the actual field environment. Our study suggests that, within the limitation of all HR-based methods (ie, provided that exercise is dynamic in nature, conducted with large muscle masses, in hydrated, unfatigued state, in low heat risk conditions and at sea level), time-resolved HR-based estimates of EE can account for the effects of context specificity, individual variability and fatigue in movement economy, overcoming some of the limitations of the equation-based estimates. This simple, low cost yet valid approach can be useful to monitor the individual as well as the mean physiological responses of soldiers when performing different activities during short or medium time-duration operative periods in actual field conditions and inform decision-making.

Contributors Both authors developed the study methodology and contributed to the analysis of the results; drafted the manuscript and reviewed and revised the work and reviewed the final manuscript and approved it for submission. ALC collected the data.

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