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Original Research

The Impact of Load Mass and Distribution on Heart Rate, Perceived Exertion, and Accelerometer Measured Physical Activity During Running

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ABSTRACT

International Journal of Exercise Science 17(4): 929-940, 2024. Many tactical athletes (military and emergency personnel) have fixed load carriage occupational requirements. Understanding the effects of running with common military "fighting loads" (no load to approximately 18 kg) on heart rate (HR), perceived exertion (RPE), and measuring it with accelerometers has implications for training and ensuring physical readiness of recruits. Eleven (7 male and 4 female) civilians (21.5±2.3 years, 1.83±0.09 m, and 80.7±18.5 kg) completed four, 5-minute running (8.05 kph) conditions: no external load, rifle carriage (3.5 kg), pack carriage (13.6 kg), and rifle/pack carriage (17.1 kg) in random order, while HR, RPE, and hip worn ActiGraph accelerometer step cadence, and activity counts per minute (CPM) were collected. One way 4-level analysis of variance or Friedman test explored the condition main effect on HR, RPE, step cadence, and CPM. Pairwise comparisons with Bonferroni correction determined which conditions differed from each other. HR and RPE significantly differed ($p < 0.001$) by load condition. No external load had the lowest HR and RPE (HR=141.8 bpm, RPE=9.4), while rifle/pack carriage had the highest (HR=160 bpm, RPE=14.8). However, rifle carriage (HR=153.7 bpm, RPE=12.3) elicited similar physiological responses as pack carriage (HR=155.0 bpm, RPE=13.6). Step cadence was equal across conditions, but CPM decreased as loads increased. Because a lighter load carried in the hands caused similar HR and RPE response to wearing a heavier pack, recruits should practice both in preparation for military or tactical occupations. Accelerometers may be used to assess step cadence, but not the increased physiological demands of external load conditions.

KEY WORDS: Tactical athletes, weighted running, RPE, rucking, fixed load

INTRODUCTION

Load carriage is considered an essential and required task for military personnel (12,18,38), and many physically demanding occupations in the tactical community (first responders, firefighters, law enforcement, search and rescue)(39, 22, 35).

Typical military loads often consist of clothing, combat gear, equipment and sustainment stores, and can vary from 20 kg up to 70 kg (12, 18, 28), but the "fighting load" should not weigh more than 18 kg (23). Firefighters external loads can approach 30 kg (39). The dynamic nature of military and first responder tasks, including, but not limited to disaster response and humanitarian aid, medical evacuations, search and rescue, combat operations, and physical training, often require personnel to carry a fixed-load of mission-specific equipment (weaponry, tools, personal protective equipment, pack, sustainment), and move quickly on foot (16, 18). During locomotion, the load weight, load type, and amount of equipment needed for operational demands also impacts load placement.

Different job-related tasks vary across occupations, as does the composition and body region where the load is carried (13). In addition to torso-borne loads, many tactical athletes must perform manual material handling such as lifting and carrying equipment (i.e. tools, rifle) in their hands while on the move (8, 16). Depending on the operation, personnel may need to carry any combination of torso-borne, and hand-held loads. For example, during military training it is common to be given a prescribed load with no rifle, a rifle with no load, or both a load and rifle and be required to make movement to a specified location during a prescribed time frame. The performance, success and safety of many personnel serving in physically demanding occupations depends on their ability to move their body mass plus an external load (13, 19, 24). During U.S. Army Basic Combat Training, uniform wear (PT uniform only vs. additional items [e.g. protective vest, backpack]) and items carried (none vs weapon carry) vary during different 3-week training cycles (2). Trainees carried additional loads (e.g., uniform or equipment) between 3 and 9 kg, and ≥9 kg, for 60% and 10% of the day, respectively (2).

While torso-borne loads increase absolute energy expenditure linearly as a function of the external load carried during tactical operations (13, 18, 29), carrying equipment in the hands may restrict the normal swing of the arms, and require continuous isometric contraction of the upper body skeletal muscles, increasing energy expenditure (1, 9, 31). The loads carried and their distribution increase cardiorespiratory, and metabolic demands (18, 35), and impact movement performance (19, 24).

Accelerometry can be used to estimate energy expenditure of physical activity in field-based settings (7, 15), but the technology has rarely been used to quantify physical activity during studies involving elements of basic combat training (2, 32). Results from two free-living studies used accelerometers to measure ambulatory physical activity intensity and showed trainees engaged in significantly high levels of moderate-to-vigorous physical activity (2, 32). Direct observation found trainees spent nearly half of the day doing weight-bearing load carriage (2). However, accelerometers cannot capture the additional energy expenditure of carrying loads or other upper body movements common of military personnel, and many physically demanding occupations in the tactical community (2, 32, 37).

There are limited studies involving both male and female participants that use accelerometry to measure basic combat training activity in a controlled lab setting that includes running with 3 different loads: torso-borne loads; carrying equipment in the hands; and the combination of torso-borne loads while carrying equipment in the hands.

Therefore, due to the high levels of moderate-to-vigorous physical activity and weight-bearing load carriage demand of military and tactical personnel, the aim of the present study was to investigate the impact of carrying 3 different loads, compared to no external load, on heart rate (HR) response, rating of perceived exertion (RPE), accelerometer-measured step cadence and activity counts per minute (CPM) during running. We hypothesized that both the external load and the load distribution would be related to significant increases in HR, and RPE, but step cadence and CPM would not differ across the multiple running conditions.

METHODS

Participants

A total of 11 healthy, recreationally active (participated in running activities at least 2 times per week, and capable of running 8.05 kph for at least 1.6 km) male (n=7) and female (n=4) (age range 18-27) civilians, with a history of running, representative of a fit recruit population, were recruited from the university and community. G*POWER 3.1 (Universitat Kiel, Germany) was used to do an a priori power analysis and established that a sample size of 7 participants were required to achieve a power of 0.8, with an effect size of 0.5 and an $\alpha = 0.05$. Participants were free of musculoskeletal injury, and acute illness, read and signed an informed consent form, which was approved by the college Institutional Review Board and completed the Physical Activity Readiness-Questionnaire (Canadian Society for Exercise Physiology, Health Canada) prior to starting the study. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (27).

Protocol

Using a crossover study design, all participants completed four 5-minute submaximal running conditions: no external load (control), rifle carriage (3.5 kg), pack carriage (13.6 kg), and rifle/pack carriage (17.1 kg). Specifically, 5-minute conditions were selected to allow steady-state HR values to be obtained (33), and to be reflective of temporal moderate-to-high intensity activities during military or tactical operations (14). The order of the conditions was randomized for each participant, to reduce the impact of fatigue during the 4th activity regardless of the condition and all conditions were completed within a single session.

Participants were instructed to arrive for the exercise protocol wearing comfortable running shoes, athletic shorts, and a t-shirt (army physical fitness uniform). Upon arrival, a verbal overview of the procedures was provided to familiarize participants with the equipment and protocol. Participants' height and weight were measured (in shorts and t-shirt, without shoes) using a wall mounted stadiometer (Health O Meter, McCook, IL, USA) and a standard floor scale (FS-0900, Befour, Inc. USA), respectively. Body mass index was calculated as: body mass (kg)/height (m)^2. Participants were fitted with a Polar HR monitor (Polar Electro Inc., Bethpage, NY, USA) and ActiGraph GT3X accelerometer (ActiGraph, Pensacola, FL, USA). The Polar HR monitor was worn at the chest and provided continuous HR measurement throughout data collection. During ActiGraph accelerometer initialization, the epoch period was set to 1 minute with a sampling rate of 100Hz. The monitor was attached to an elastic belt and worn around the waist fitted on each participant's right hip (2). The ActiGraph accelerometer provided step cadence (steps/minute) based on accelerometer data collected on the vertical axis using a proprietary step counting algorithm. Triaxial vector magnitude activity counts per minute (CPM) were used to determine physical activity intensity, using established triaxial thresholds for moderate (2690 – 6166 CPM), and vigorous (≥ 6167 CPM) intensity (10).

Resting HR was obtained following 10-minutes of seated rest. Then, participants warmed-up with 5 minutes of walking (4.8 kph). Participants completed four, 5-minute submaximal running conditions (8.05 kph: no external load, running while carrying a 3.5 kg rubber M16 training rifle (Fort Knox Training Support Center Plastics Production Facility, Fort Knox, KY, USA) in both hands (rifle carriage), running while wearing an ALICE Mountain Ruck backpack (OV Innovations, Phoenix, AZ, USA) loaded with Meals Ready to Eat (MRE's), military field uniform items (socks, skivvies, fatigues, gloves), and military issued outdoor gear (sleeping bag, tarp, e-tool) so that the heavier items were placed closest to the individual and high in the pack allowing for an energy advantage (18) (13.6 kg) (pack carriage), and running while carrying the rubber training rifle in both arms, and wearing the ALICE Mountain Ruck backpack (17.1 kg total weighted load) (rifle/pack carriage)(Figure 1). For pack carriage conditions, participants tightened the packs straps and hip belt, so the load was carried near the center of mass, providing stability, and eliminating excess energy expenditure (17, 18). Similar to previous studies, the load was the same for all participants (24, 34, 36). Testing was conducted on a treadmill (L7, Landice, USA) set at 0% incline.

The Borg Rating of Perceived Exertion (RPE) Scale (6-20 scale) (6) was used to assess participant's perceived effort every 60 seconds during each 5-minute running condition. Despite the subjectivity of this scale, a person's exertion rating provides a good estimate of the overall body fatigue during physical activity (6).

Prior to each condition, participants straddled the belt of the treadmill for 1 minute, allowing the treadmill to achieve the desired speed, and the participant's HR to normalize. During each 5-minute condition, participants were asked to report their RPE every 60 seconds and HR was recorded. At the completion of each condition, the participants were relieved of their external load and sat quietly for at least 10 minutes to expedite the recovery process. Recovery was based on RPE returning to initial resting value, HR returning to within ±20 bpm of initial resting value, and verbal confirmation of feeling fully recovered and ready to start the next condition. The entire protocol was executed in a single visit that took approximately 60 minutes.

Average HR and RPE were calculated from steady state exercise for each condition utilizing the final three minutes (minutes 3 through 5). Following data collection accelerometer data files were downloaded and using time stamps of when each condition started, average step cadence and CPM were calculated from the middle three minutes after removing the first and last partial minutes of data (minutes 2 through 4). This was necessary because the accelerometer provided time stamped data in one-minute increments, however conditions did not always start or end exactly on the minute.

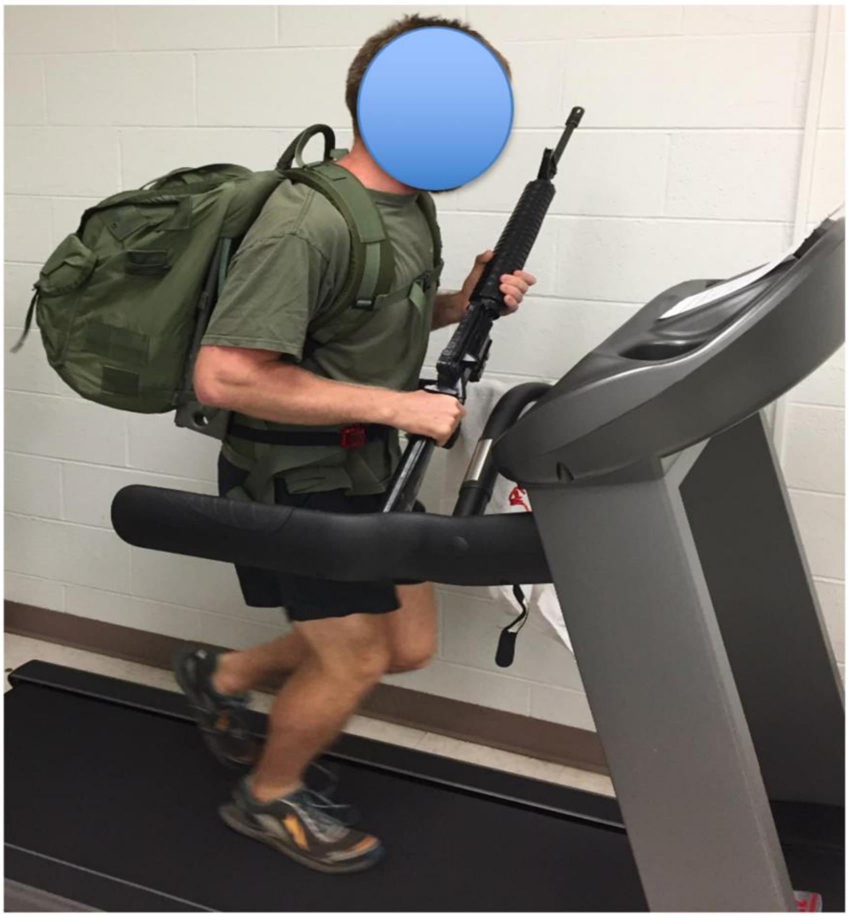

Figure 1. Placement of pack and carriage technique for rifle during rifle/pack carriage condition.

Statistical Analysis

IBM SPSS Statistics Version 28.0.1.0 (Armonk, NY) was used for data analysis. Shapiro-Wilk's test ($p > 0.05$) was used to assess the data distribution of each dependent variable (HR, RPE, step cadence, and CPM) during each condition, and check for assumptions required to run parametric tests. Despite the small sample, the dependent variables were found to be normally distributed in all conditions, with one exception: RPE during rifle/pack carriage. Subsequently, a one way 4-level analysis of variance (ANOVA) was conducted to explore the condition main effect for each of the normally distributed continuous variables (HR, step cadence, and CPM), and the Friedman test was used to explore the condition main effect for RPE (non-normally distributed continuous variable). The descriptive data are presented as mean ± standard deviation for each condition. In the case of significant interactions, pairwise comparisons with Bonferroni correction were used to determine which conditions differed from each other. Effect sizes for each ANOVA were reported as $\eta 2$, which define 0.02 as small, 0.13 as medium, and 0.26 as large (11). Kendall's W coefficient (w) was the effect size for the Friedman test and defines 0.1 - <0.3 as small, 0.3 - < 0.5 as moderate, and ≥ 0.5 as large. To determine the effect size of HR and accelerometer derived vector magnitude that differed by condition, Cohen's $d = (M_2 - M_1)/SD_{pooled}$ was calculated. Resulting effect size values were classified as trivial (0-0.19), small (0.2-0.49), medium (0.5-0.79), and large (≥ 0.8) (11). *PSdep* was reported for the effect size of RPE that differed by condition. Statistical significance was established as $p < 0.05$.

RESULTS

The participants baseline characteristics are reported in Table 1. Males were 12.9 cm taller than females (187.5 cm vs. 174.6 cm, respectively, $p = 0.014$), but there were no other differences between genders. Participants had normal BMI's (<25 kg/m^2), averaged more than 12 year's running experience, and relatively low resting HR values (62.5 ± 8.1 bpm) (indicative of a fit sample of young adults (21.5 ± 2.3 years)), who reported running at least 2 times per week.

Table 1. Sample and gender specific participant characteristics (mean ± standard deviation).

	Total (n=11)	Males (n=7)	Females (n=4)
Age (yrs)	21.5 ± 2.3	21.7 ± 2.9	21.0 ± 0.8
Height (cm)*	182.5 ± 8.8	187.1 ± 7.0	174.6 ± 5.6
Weight (kg)	80.3 ± 17.6	86.9 ± 18.8	68.9 ± 7.3
BMI (kg/m^2)	23.9 ± 3.4	24.6 ± 4.1	22.6 ± 1.4
Resting heart rate (bpm)	62.5 ± 8.1	61.9 ± 8.2	63.8 ± 9.0
Resting RPE	6.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0
Years as a runner	12.9 ± 5.2	11.9 ± 6.4	14.8 ± 1.0

*Denotes significant difference ($p < 0.05$).

HR was found to differ significantly by load condition ($p < 0.001$; $\eta 2 = 0.83$). Specifically, the HR with no external load (141.8 bpm) was significantly lower than all other conditions [rifle carriage: 153.7 bpm ($p = 0.021$; $D = 1.07$), pack carriage: 155.0 bpm ($p < 0.001$; $D = 1.28$), and rifle/pack carriage: 161.0 bpm ($p = 0.001$; $D = 2.03$)]. Additionally, rifle carriage HR were significantly lower than rifle/pack carriage HR ($p = 0.038$; $D = 0.75$) (Figure 2).

There was a significant difference in mean RPE across submaximal running conditions ($p < 0.001$; $w = 0.90$). No external load RPE (9.4) was significantly lower than all other conditions RPE [rifle carriage: 12.3 ($p = 0.003$; *PSdep* = 1.00), pack carriage: 13.6 ($p = 0.003$; *PSdep* = 1.00), rifle/pack carriage: 14.8 ($p = 0.003$; *PSdep* = 1.00)]. Both rifle carriage and pack carriage RPE were also significantly lower than rifle/pack carriage RPE ($p = 0.005$; *PSdep* = 0.91 and $p = 0.005$; *PSdep* = 0.91, respectively) (Figure 2).

Participants took an average of 159±9 steps/min (796±45 total steps) during all submaximal running conditions independent of load mass or distribution and there was no significant difference in step cadence between conditions ($p = 0.059$; $\eta 2 = 0.22$) (Figure 2).

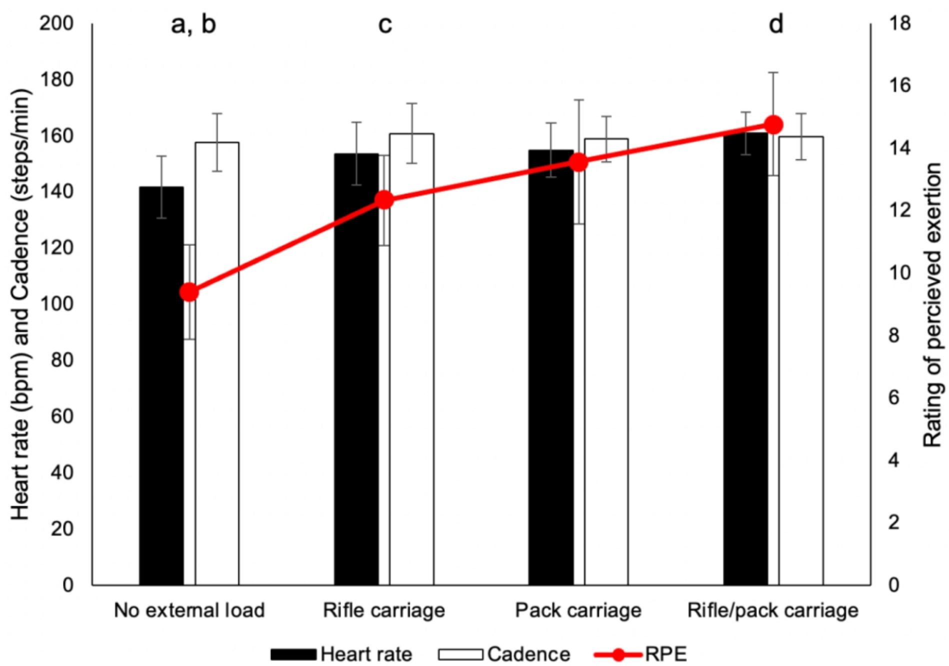

Figure 2. Mean heart rate, step cadence and rating of perceived exertion (RPE) at each load condition. [a] Denotes no external load heart rate was significantly different from all other load conditions. [b] Denotes no external load RPE was significantly different from all other load conditions. [c] Denotes rifle carriage heart rate was significantly different from rifle/pack carriage. [d] Denotes rifle carriage and pack carriage RPE were both significantly different from rifle/pack carriage.

Based on CPM, the accelerometer classified all conditions as vigorous intensity (≥ 6167 CPM); however, the values were significantly different across conditions ($p < 0.001$; $\eta 2 = 0.61$) (Figure 3). No external load (9153.3 CPM) was significantly higher than pack carriage (7777.8 CPM, $p = 0.008$; $d = 0.85$) and rifle/pack carriage (7496.0 CPM, $p < 0.001$; $d = 1.06$). Rifle carriage (8520.2 CPM) was significantly higher than rifle/pack carriage ($p = 0.01$; $d = 0.69$). However, no external load and rifle carriage; and pack carriage and rifle/pack carriage were not different from each other.

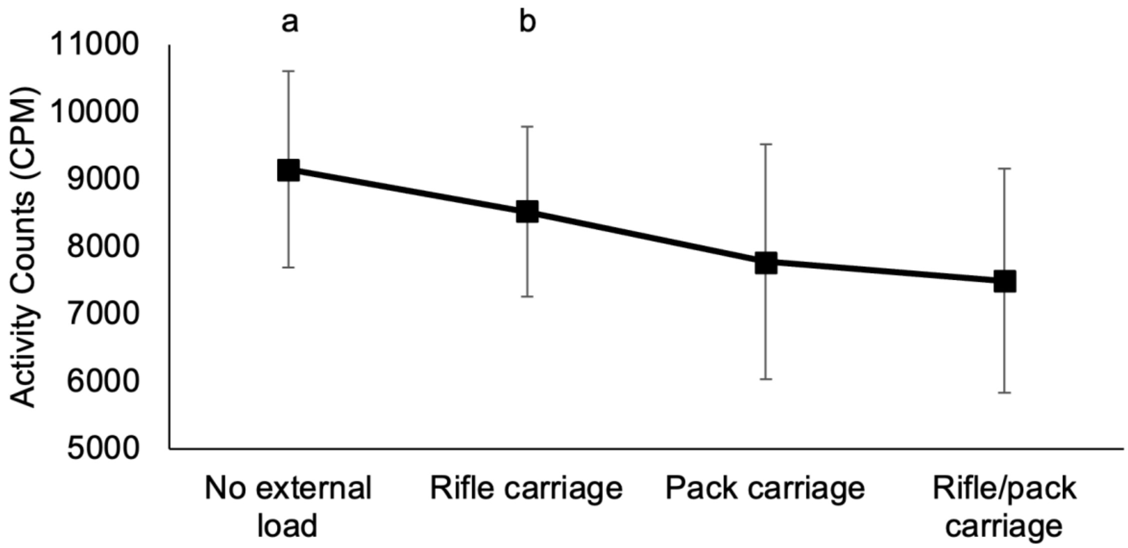

Figure 3. Mean and standard deviation of activity counts (CPM) at each running condition. [a] Denotes a significant difference between no external load and pack carriage and rifle/ pack carriage CPM. [b] Denotes a significant difference between rifle carriage and rifle/pack carriage CPM.

DISCUSSION

Carrying loads of different mass and distributions during steady state running were examined to determine their impact on physiological responses and accelerometer assessed physical activity. This study demonstrated that HR and RPE values increased with increased load, but that the distribution of the load also uniquely impacted the HR and RPE responses. HR and RPE values significantly increased when running while carrying a rifle and running while wearing a pack compared to running with no external load, but there was no difference between these two loaded conditions. Considering the difference in mass between the two loaded conditions (rifle carriage =3.5 kg and pack carriage =13.6 kg), it was expected that the heavier mass of the pack would elicit a greater HR and RPE response (26).

Previously, HR increases during isometric exercises exceeded those during dynamic muscular contractions of similar oxygen consumption (4), and adding an isometric activity to a dynamic exercise task increased the cardiovascular response compared to the dynamic exercise alone (40). This suggests that even though the pack was substantially heavier than the rifle, the amount of oxygen needed to maintain an almost continuous isometric contraction of the forearms and biceps to carry the rifle while running (a variable not measured in this study) was similar in terms of its impact on HR response. The explanation for a lighter load carried in the arms further away from the center of mass (rifle) appearing to increase RPE values similar to a substantially heavier load (pack) carried on the back, but closer to the center of mass, may be that the perceived local arm fatigue could have been a more dominating factor in shaping the overall perception of exertion for that condition (30). Future studies with arm carrying tasks should ask participants for differentiated local and overall RPE. Measured oxygen consumption would also be valuable to assess the potential energy expenditure differences during different load conditions.

Accelerometers, typically worn on the hip, are used to measure ambulatory steps and estimate the energy expenditure of ambulation caused by the large muscles of the lower extremity (5). In this study, accelerometer step cadences were the same across all conditions (159±9 steps/min), which classified participants running as vigorous physical activity (≥135 steps/minute) (25). During running at a pace of 8.05 kph, our participants cadence matched that of an average runner (150-170 steps/minute), which allowed them to accumulate about 800 steps in 5 minutes. Step cadence (pace) and step counts (volume) can provide valuable information about the activity level of military personal. Our step cadence data support accelerometers ability to measure moderate-to-vigorous ambulatory physical activity, common among military trainees (2, 32). Objective devices have been used to classify the ambulatory activity of military trainees as "highly active" (>12,500 steps/day) (2, 20). Therefore, a lack of difference in step cadence data between conditions may be explained by the pace remaining constant across all trials (8.0 kph) and indicates no significant change in stride length despite the increased load mass or distribution.

One of the known limitations of step data (both cadence and total step counts) is its inability to account for added intensity carrying external loads/upper body energy expenditure, which are common in many physically demanding occupations in the tactical community (2, 32, 37). Our results showed the CPM for no external load and running while carrying a rifle were the same, while running with the pack resulted in significantly lower CPM, showing the limited ability of the accelerometer CPM to differentiate between the increased intensity of the conditions. Interestingly, the condition with the greatest HR and RPE, produced the lowest CPM. This well-known limitation of accelerometers results in an underestimation of energy expenditure for activities involving the upper extremities and increases in additional mass (5, 37).

While external loads increase the energy demand of running, they also create different movement patterns that are subsequently being measured by the accelerometer, which appear to have caused the reduction in CPM measured at the hip during loaded conditions (3).

The data collected in this study may be applicable to recruits entering the military. Our rifle carriage (3.5 kg), pack carriage (13.6 kg), and rifle/pack carriage (17.1 kg) loads fall within the ranges typically carried by trainees during U.S. Army Basic Combat Training (2, 21) and could represent initial training load and rescue related skills such as running, rucking, and equipment carry which are common in the fields of military, police/law enforcement and firefighting occupations. This information could be used by aspiring recruits to improve tactical fitness and prepare for intense tactical selection testing (35, 38).

In conclusion, due to the increased RPE and HR responses to load mass and distribution, physical training programs should be designed and implemented to reflect the physical requirements of specific occupational tasks to maintain physical readiness for recruits and tactical trainees. Accelerometers can be used to quantify volume of steps but need to be combined with other data sources to capture the increased physiological demands of carrying increased external loads. Research on the physiological demands of running under load is necessary for officers to understand how much load their soldiers can handle before fatigue sets in and compromises the effectiveness of the mission, as well as their health and safety.

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