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Body Armor, Performance, and Physiology During Repeated High-Intensity Work Tasks

Brianna Larsen, BEx & SportsSc (Hons); Kevin Netto, PhD*; Daniel Skovli, BA*;
Kim Vincs, PhD*; Sarah Vu†; Brad Aisbett, PhD**

ABSTRACT This study examined the effect of body armor during repeated, intermittent high-intensity simulated military work. Twelve males performed 11 repetitions of a military style circuit, wearing no armor on one occasion and full armor (~17 kg) on another. Performance was measured by the time to complete individual work tasks plus overall circuit time to completion. Heart rate, intestinal temperature, and rating of perceived exertion were recorded after each circuit. Participants' circuit time to completion was 7.3 ± 1.0 seconds slower ($p < 0.01$) when wearing armor. Shooting, vaulting, and crawling were also slower (0.8 ± 0.2, 0.4 ± 0.2, and 1.0 ± 0.4 seconds, respectively; all $p \leq 0.05$). No differences were observed for box lifting. Higher core temperatures were reported for the armor condition for circuit's 7 to 11 (p = 0.01–0.05). Rating of perceived exertion was higher (1 ± 0; p = 0.03) when wearing armor. No differences were observed for heart rate. Wearing armor impairs repeated high-intensity military task performance. In the relatively short work time utilized, this decrement did not accrue over time. The impairment may, then, be related to the armor load, rather than accumulating fatigue.

INTRODUCTION

Soldiers worldwide utilize specialized protective clothing, such as body armor, to protect themselves against hazards in an operational environment.[1] Body armor is commonly worn for prolonged periods of time and during varying types of physical activity.[2] Unfortunately, the bulk or the weight of the garment is often thought to have a negative impact, both physiologically and psychologically, on the wearer.[1–4]

Wearing body armor or personal protective clothing has been shown to increase heart rate,[1,5] oxygen consumption[6–9] ratings of perceived exertion (RPEs),[2,6,10] and thermal stress.[11,12] However, the majority of research investigating physiological and subjective responses to wearing body armor has utilized treadmill walking protocols. Although this may be an appropriate reproduction of marching and load carriage, it does not incorporate any of the other movements and actions identified in military task analysis literature.[13] Armed forces personnel commonly perform physically demanding upper body movements including lifting, carrying, and digging.[14–16] Other tasks, including running, crawling, and climbing, are also intrinsic to the successful performance of military duties.[14–16]

Other researchers have chosen to investigate how the performance of military tasks are affected by body armor and have found that it impedes sprint performance,[17–20] obstacle course runs,[8,9,19] army crawling,[8,19] upper body strength exercises,[2,8,18,19] grenade throwing,[8,9] and shooting ability.[9] Unfortunately, the single iteration, maximal-effort nature of the protocols used in the majority of body armor research does not afford insight into how these performance decrements accrue over time. This is an important consideration as the accrual of performance decrements could have serious implications for soldiers on the battlefield. Treloar and Billing[20] found that body armor impaired repeated sprint performance and the decrement accrued with each repetition. The total exercise duration for their protocol, however, was relatively short (five 30-m sprints at 44-second intervals), and thus may not reflect the performance decrements that would be incurred over a longer work period. Additionally, although sprinting is undoubtedly an important aspect of military work, their protocol does not reflect the other movements and actions that soldiers are likely to perform on the battlefield.[14–16] Finally, much of the existing research examining body armor and military task performance does not report the concurrent physiological or subjective responses, which prohibits understanding of the potential mechanisms behind any performance impairments observed.

The primary aim of the current study was to determine how military body armor impacts the performance of repeated, high-intensity military style tasks. Furthermore, the current study aimed to evaluate the physiological and subjective stress elicited from wearing military body armor during the performance of these tasks, focusing on thermal stress and physiological exertion.

METHODS

Participants

A flyer briefly detailing the study was distributed to sports science students studying at Deakin University. No incentive was provided for participation. Eleven recreationally active males volunteered for this study. Participants were considered recreationally active if they were involved in some type of exercise twice or more per week, at a subelite level. The

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*Deakin University, 221 Burwood Highway, Burwood, Victoria 3125, Australia.

†Australian Defence Apparel Pty Ltd, 14 Gaffney Street, Coburg, Victoria 3058, Australia.

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sample was limited to male participants as the vast majority of soldiers wearing body armor in combat are men.[21] Following a short briefing, participants gave written informed consent and completed a modified medical questionnaire[22] to ensure they were able to complete vigorous exercise without medical supervision. Ethical approval was obtained from the Deakin University Human Research Ethics Committee before the commencement of the study.

Participant height was measured using a stadiometer (Fitness Assist, Wrexham, England) and recorded without shoes. Seminude body mass was measured on an electronic scale (A and D, Tokyo, Japan) pre-and post-trial for the calculation of whole body sweat rates, with allowances made for ingested and expelled liquids.[23,24] There were no significant differences in whole body sweat rates between conditions; so, for brevity, this data will not be reported.

Experimental Protocol

All testing for this study was completed in a 24-camera infrared motion capture facility (Motion Analysis Corporation, Santa Rosa, California) to allow for precise (frame capture rate 120 Hz) calculation of the time to completion (TTC) for each task. Participants attended two sessions, each lasting 1 hour, with 1 week allowed between sessions for adequate recovery and rehydration. During the trial, participants repeatedly performed a circuit comprising simulations of military-specific tasks while wearing no body armor on one occasion and full body armor on another. The armor condition order was randomized to minimize learning effects. All trials were completed at the same time of day to minimize diurnal variation.[25]

Participants ingested a core temperature tablet 6 hours before testing to allow adequate time for the tablet to pass through the stomach into the small intestine.[26] Upon arrival, participants were fitted with a heart rate monitor (Polar, Kempele, Finland) and core temperature data logger (Vitalsense, Minimitter, Oregon). In both trials, participants wore army fatigues (Australian Defence Apparel [ADA], Coburg, Australia), their own sports shoes, an army helmet (500 g; ADA), and carried a dummy rifle (2 kg; ADA). In the body armor trial, participants also wore a protective chest plate in conjunction with full arm, leg and neck protection (16.98 kg in total [medium size, ~1 kg fluctuation between small and large sizes]; ADA). Nineteen reflective markers were affixed to the participants' joints to serve as locators from which the motion capture system used to capture the key movements performed during the work simulation (Table I). Participants were familiarized with the RPE[27] scale before testing. Ambient temperature was measured throughout testing using handheld weather monitors (Kestral Instruments, Brooklyn, New York).

TABLE I. Marker Placement

Marker Location	Marker Number	Description
Head	1	Apex of the Helmet
	2	Left Section of the Helmet Above Rim
	3	Right Section of the Helmet Above Rim
Back	4	C7; Cervical Vertebrae 7 (or First Join on the Armor During the Armor Trial)
	5	L3; Lumbar Vertebrae 3 (or Second Join on the Armor During the Armor Trial)
Shoulder	6	Left Medial Acromion
	7	Right Medial Acromion
Elbow	8	Left Epicondyle
	9	Right Epicondyle
Wrist	10	Middle of Left Wrist
	11	Middle of Right Wrist
Hip	12	Left Greater Trochanter
	13	Right Greater Trochanter
Knee	14	Left Epicondyle
	15	Right Epicondyle
Ankle	16	Left Malleolus
	17	Right Malleolus
Foot	18	Left Fifth Toe (Over Shoe)
	19	Right Fifth Toe (Over Shoe)

Military Circuit

The military circuit was devised after industry consultation with subject matter experts (SME) and thorough review of military task analysis literature.[13–16] The SME were current or retired soldiers of the Australian Defence Force. Given the size of the testing area (6 m × 7 m work space) and the need to test multiple participants per day because of time constraints, the circuit was not explicitly designed to replicate the size and different terrains that comprise a real-life military battleground. Rather, the circuit aimed to simulate actions and movements shown to be commonplace during military work.[13–16]

The circuit began with participant's dropping to a prone position and shouldering the rifle, pointing at a circular target (10-cm diameter). The rifle was fitted with a laser, which participants held within the center of the target for 2 seconds. Participants then stood from the prone position, turned, and performed a vault over a 74-cm platform. Participants were then required to again drop to a prone position and complete a 6-m army crawl while still cradling their rifle. Upon completion of the army crawl, participants completed a repetitive box-lifting exercise, in which they lifted a 20-kg box (47 cm^3) from the ground onto a 74-cm platform, five times. Participants then sprinted to the starting point and performed all tasks in sequence again without rest. Participants were encouraged to complete the circuit as fast as possible; therefore, participants sprinted from one station to the next. Participants had to maneuver their way around cones that were strategically placed between tasks, and precisely measured, to ensure the same minimum distance was being covered during each circuit and between trials (Fig. 1).

Participants were required to finish each circuit (i.e., two "laps") within 2 minutes or testing was terminated. In this event, the data of the completed bouts were still utilized for

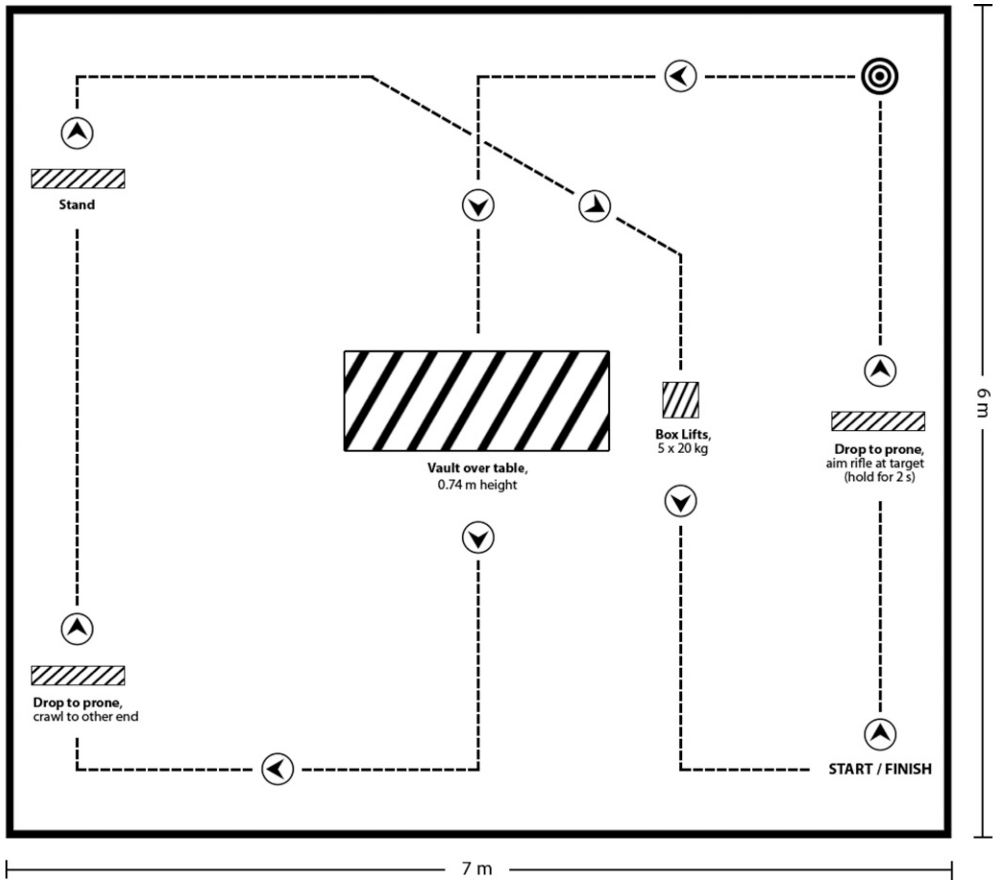

FIGURE 1. Work simulation.

analysis. Participants were not given a second opportunity to complete all bouts. If the circuit was finished within the 2-minute period, participants were allowed to rest for the remainder of those 2 minutes, in addition to the designated 2-minute rest period between circuits. Participants were instructed to perform the circuit 11 times or until they reached volitional exhaustion (44-minute maximum exercise period). The 2-minute completion time restriction and resting periods were devised alongside SME to serve as a proxy for the high-intensity, intermittent nature of military work.[1,13,19] Limiting the trial to 11 circuits was also developed as a practical compromise between the real-life durations of military work and timely completion of the study.

Analytical Procedures

To determine the effect of body armor on performance, TTC for each individual task and each circuit were recorded. Specific markers were used to determine the exact start and end points of each task, allowing for extremely precise task completion times (Table II). Heart rate, intestinal temperature, and RPE were recorded at the end of each circuit.

Statistical Analyses

All statistical analyses were carried out using the program Statistical Package for the Social Sciences (SPSS V.17.0; Champaign, Illinois). The distribution of the data was evaluated

TABLE II. Task Time to Completion Start and Finish Points

Task	Marker	Initiation	Cessation
Shooting	Top Head (1)	When the marker began to drop vertically as the participant descended to prone	When the marker had reached its peak vertical position as the participant returned to a stand
Vaulting	Ankle (16 or 17)	When the ankle marker of the first foot had left the ground during the action	When the first foot made contact with the ground after clearing the platform
Crawling	Top Head (1)	When the marker began to drop vertically as the participant descended to prone	When the marker began to ascend vertically at the completion of the crawl
Box Lifting	Left Wrist (11)	When the participants' hand first touched the box	When participants removed their hand from the box after the final lift

using Shapiro–Wilk tests. Peak heart rate data were not normally distributed; therefore, Wilcoxin signed-rank tests were used in order to detect significance between armor conditions. As the other circuit performance measures and physiological responses were normally distributed, they were analyzed using repeated measures analysis of variance, with body armor condition and circuit completion time as the two within-participant factors. Bout number was treated as a continuous variable. When the analysis of variance detected a significant interaction, simple effects analyses were used to isolate where the significant difference occurred. Analyses of individual task TTC were based on the second rotation through the task sequence within each circuit as tasks were preceded by a stable quantity of work rather than a variable rest period (i.e., between circuits) which could confound the results. Statistical significance was set at $p \leq 0.05$, and all data were presented as means ± SDs unless otherwise stated. Results will be explained in terms of main effects, i.e., the effect of the change in level of one factor (e.g., armor type) measured independently of other variables (e.g., circuit completion time), and interactions, i.e., the extent to which the effect of one factor depends on the level of another factor. Mean and peak RPE results were reported to the nearest whole number, consistent with the scale.

RESULTS

The mean age of participants was 22 ± 2 years. The mean height of participants was 1.85 ± 0.10 m and the mean body mass was 77 ± 14 kg. The body armor and equipment (fatigues, helmet, and imitation rifle) was 17 ± 1 kg heavier ($p < 0.01$) than the equipment alone (utilized in the control trial). Body armor represented an additional 26 ± 5% of the participants' body mass compared to 3 ± 1% for the control condition. Ambient temperature in the Motion Capture Laboratory was 21.3 ± 1.9°C.

There was a significant main effect observed for armor ($p < 0.01$) as participants were 7.3 ± 1.0 seconds slower ($p < 0.01$) per circuit when wearing the armor, irrespective of the time point in the trial (Fig. 2, Table III). There was also a main effect observed time ($p = 0.01$) for participants' TTC for each circuit (Fig. 2). There were no interactions observed between armor and time ($p = 0.96$); in that, any observed difference in circuit TTC between conditions did not significantly vary over the course of the trial. It should also be noted that two participants were unable to complete all 11 circuits during the armored trial, both withdrawing after completing circuit 8.

There was a main effect for shooting TTC such that this task was 0.8 ± 0.2 seconds slower ($p = 0.01$) when wearing the armor (Table III). No main effect for time was observed ($p = 0.90$), however, indicating that shooting did not improve or worsen over the course of the trial, irrespective of armor condition. There was also no interaction observed between armor and time ($p = 0.31$). A main effect for armor was also observed for the vaulting task, which participants performed 0.4 ± 0.2 seconds slower ($p = 0.05$) than during the control trial (Table III). However, no main effect for time was observed ($p = 0.50$) and there were no interactions observed between armor and time ($p = 0.93$). A main effect for armor was observed for the crawling phase of the circuit, which was performed 1.0 ± 0.4 seconds slower ($p = 0.05$) than when participating in the control trial (Table III). There was no

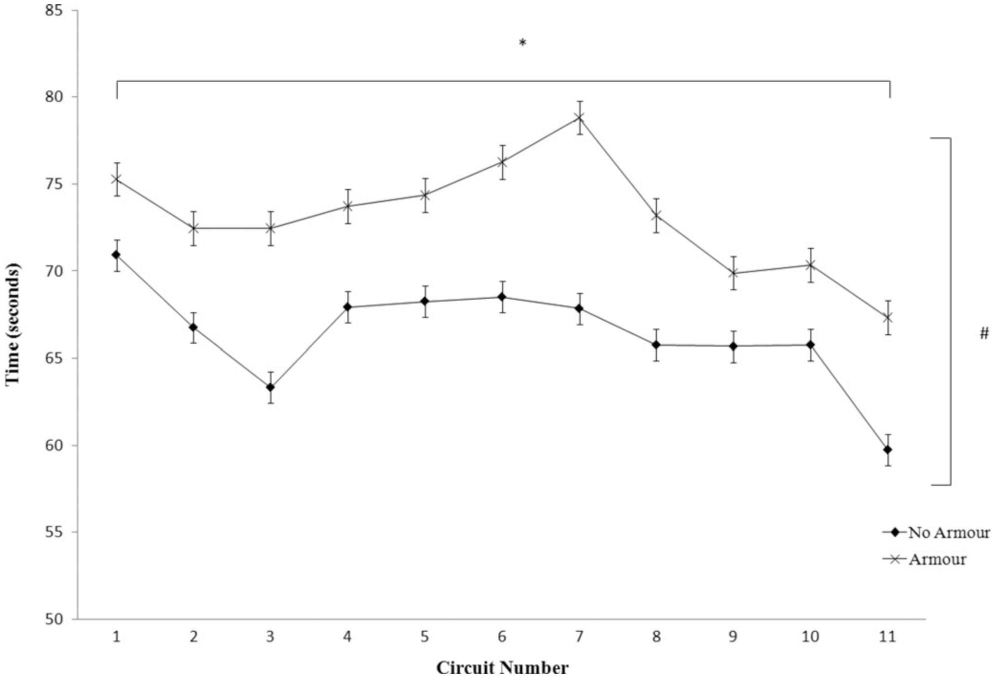

FIGURE 2. TTC for each work circuit. *, armor higher (main effect; $p < 0.01$) than control; #, main effect for time ($p = 0.01$). $n = 11$ for circuits 1 to 8, $n = 9$ for circuits 9 to 11.

TABLE III. Individual Task Time to Completion and Total Circuit Time to Completion

Task	Without Body Armor	With Body Armor
Shooting	5.4 ± 0.2	6.3 ± 0.3*
Vaulting	1.6 ± 0.1	2.0 ± 0.2*
Crawling	7.4 ± 0.8	8.4 ± 1.0*
Box Lifting	9.6 ± 1.2	10.0 ± 1.4
Total	66.8 ± 3.5	74.1 ± 5.6*

*$p \leq 0.05$.

main effect for time ($p = 0.44$), and no interactions between armor and time ($p = 0.34$). There was also no main effect for armor ($p = 0.40$), time ($p = 0.06$), and no interactions between armor and time ($p = 0.57$) for participants' box lift TTC (Table III).

Participants' resting intestinal temperature before completing the work simulations was 37.23 ± 0.32 and 37.30 ± 0.19°C for the no armor and with armor conditions, respectively ($p = 0.52$). Their peak intestinal temperature during the work simulation was 0.50 ± 0.41°C hotter ($p = 0.02$) for the armored condition (38.62 ± 0.43°C) when compared to the control (38.13 ± 0.27°C). There was a significant armor × time interaction for intestinal temperature during the work ($p < 0.01$; Fig. 3). There were no differences in intestinal temperature between the armor and control conditions for circuits 1 ($p = 0.16$) and 2 ($p = 0.11$). For circuit's 3 to 6, there was a trend ($0.5 < p < 0.1$) for differences in intestinal temperature between the armor and control conditions. Intestinal temperature measured after each circuit from 7 to 11 were between 0.39 ± 0.35 and 0.81 ± 0.81°C higher ($p = 0.01$–0.05) in the armor trial compared to the control trial.

There was no difference ($p = 0.42$) in resting heart rate values between the control (93 ± 8 beats·min^{-1}) and armor (90 ± 13 beats·min^{-1}) conditions. There was also no difference ($p = 0.33$) in peak heart rate values between the control and armor conditions (184 ± 8 and 187 ± 11 beats·min^{-1}, respectively). The interaction observed between armor and time fell short of reaching statistical significance ($p = 0.06$). There was also no main effect for observed for armor ($p = 0.16$), indicating that both armor conditions elicited comparable heart rate responses. There was, however, a significant main effect observed for time ($p < 0.01$), with participants' heart rates increasing over the duration of the testing period, regardless of condition.

The peak RPE reached was 1 ± 0 higher ($p < 0.01$) during the armored condition (19 ± 1) when compared to the control (18 ± 1). There were no interactions observed between armor and time ($p = 0.35$) for participants' RPE at the end of every circuit bout. However, RPE across all time points were significantly higher ($p = 0.03$) for the armored condition (17 ± 0) than for the control (16 ± 0; Fig. 4). There was also a significant main effect observed for time ($p < 0.01$), with participants reporting higher RPE values as the trial progressed.

DISCUSSION

The first aim of this research was to investigate the effect of body armor on the performance of repeated, intermittent high-intensity military work. The major finding was that participants' circuit TTC was 10% slower during the armored trial; yet, the observed performance decrements did not accrue as the trial progressed. This finding illustrates that although the body armor had a negative impact on performance from

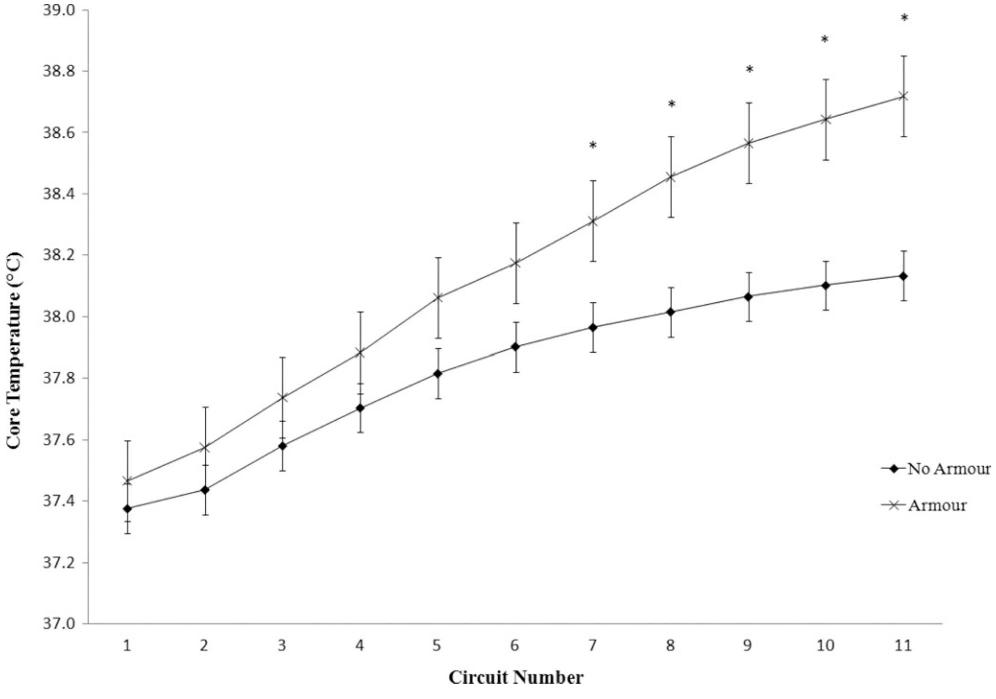

FIGURE 3. Core temperature measured after each work circuit. *, armor trial higher ($p \leq 0.05$). $n = 11$ for circuits 1 to 8, $n = 9$ for circuits 9 to 11.

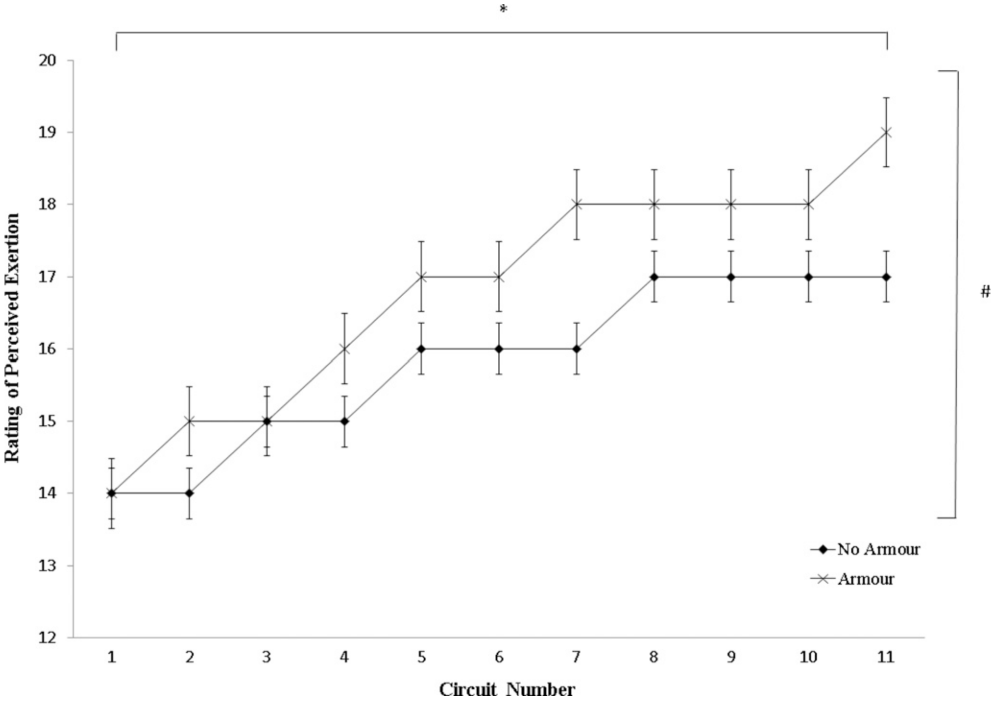

FIGURE 4. RPEs measured after each work circuit. *, armor higher (main effect; $p = 0.03$) than control; #, main effect for time ($p < 0.01$). $n = 11$ for circuits 1 to 8, $n = 9$ for circuits 9 to 11.

the moment it is put on, it did not appear to cause an accumulation of fatigue over time. It is possible, however, that the length of the present study (maximum "work" time of 44 minutes) was not long enough to allow significant accumulation of fatigue. This finding is in opposition to that of Treloar and Billing,[20] who found that sprint performance impairments were exacerbated over multiple efforts. It is possible that the slightly larger rest periods employed during the present study allowed for greater recovery between work bouts. The observed increase in performance time is in agreement with previous research utilizing single iteration obstacle course TTC as a measure of performance.[8,19] The 10% increase in whole circuit TTC observed in the present study, although significant, was much smaller than the 30 to 36% time increase reported in previous studies.[8,19] However, previous researchers used circuits that were designed as one-off, best effort exercises, and as such it is presumed that they were extremely difficult to complete. The circuit used in the current study was designed to be repeated a number of times, in line with the primary aim of the research. As such, the difference in the magnitude to which whole circuit TTC was impaired could be attributed to the differences between maximal and repeated, self-paced work protocols.

The fact that the performance decrements were relatively stable over the course of the trial suggests that impairment of specific tasks, rather than accumulating fatigue, could be responsible for the increases in whole circuit TTC. In the present study, the shooting task included participants dropping to a prone position, aiming and shooting, and returning to a standing position. As this entire movement sequence TTC, rather than individual components, was analyzed, it is not clear as to which aspect of shooting performance was most heavily impacted by the armor. Previous research conducted by Harman et al[8] observed that participants wearing an "approach load" (28.8–30.8 kg) were 30% slower at performing stand to prone and prone to stand actions than when wearing a "fighting" load (16.9–17.5 kg). Although these former loads are far heavier than that employed in the present research, their analysis of these movements could represent evidence that the slower performance times observed during the shooting exercise in the current study were also the result of impaired stand to prone and prone to stand actions. As in the present study, Pandorf et al[19] and Harman et al[8] found vaulting activities to be largely impaired by armor; over half of participants tested were unable to traverse a 1.37-m wall in the heavier armor conditions. Although the body armor configurations tested in these studies were appreciably heavier than that used currently (ranging from 27 to 30.8 kg), these findings, together with the observed decrements (~60%) in chin ups,[2] hang time,[2] and climbing activities,[8,19] infer that performing tasks against gravity are likely to be particularly impaired by an additional load. Both shooting and crawling performance were significantly impaired in the present study, both of which required participants to exert force against gravity in the prone to stand component of each task. The magnitude of the decrement in crawl TTC is far smaller than that reported by previous researchers,[8,19] who observed that participants crawling TTC was greater than 50% slower during the heavy armor conditions. The discrepancy in performance impairments could again be due to the heavier armor loads imposed by these researchers.

Box lift TTC was not significantly different between armor conditions. Conversely, Hasselquist et al[18] observed that participants completed fewer box lifts in a 5-minute repetitive lifting exercise when wearing an 8.7-kg tactical vest compared to the control condition and fewer again with the addition of extremity armor (ranging from 14.3 to 15.1 kg). Anecdotal evidence from researchers and participants in the current study suggests that although participants seemed to struggle more with the lifting stage of the movement when wearing armor, they actually used the armor to their advantage in the lowering phase of the movement. The armor configuration contained protective leg armor, which may have cushioned the thighs against the weight of the box, therefore allowing participants to bring the box to ground level at a quicker pace. This suggests changes in lifting technique may, at least in part, explain similar box lift TTC between the armor and control trials.

The second aim of this research was to assess the physiological and subjective consequences of wearing body armor. Intestinal temperatures were comparable across the first two circuits but then increased at a faster rate during the armored condition, an effect that was particularly noticeable during the last five circuits. These findings support work by Caldwell et al,[11] who found that during 2.5 hours of treadmill walking, core temperature increased 38% faster when wearing full armor and 11% faster when wearing a combat vest in comparison to the control trial. It is interesting in the current study that despite this accumulation of heat stress, the performance decrements remained stable across the testing period. It seems, therefore, that participants were able to find a way to negate the increasing thermal strain and produce a stable work output, at least in the mild ambient temperatures and 44-minute work periods encountered in the present study. However, it is possible that the thermal strain induced during longer work periods or in hot or humid weather conditions could amplify the level of performance impairment incurred, which could have severe implications for soldiers in an operational setting.

There were no significant differences observed in peak or mean heart rate between conditions in the present study. Increased physiological exertion (heart rate and oxygen consumption) has been observed between body armor conditions using slow,[2] moderate,[2,6,18] fast,[18] and intermittent[5] treadmill exercise protocols. Inherent differences in the interaction between physiology and performance in self-paced and fixed-paced work protocols may explain the different findings between the current study and earlier work. In the present study, participants may have anticipated that the work period would be harder when wearing the body armor, and so deliberately slowed the pace in which they completed the work simulation.[24] All bouts, including bout 1, were performed more slowly in the armored trial, which suggests that participants were employing pacing techniques in anticipation of the load. The observed results may also reflect participants being able to move faster (in the control condition) without the burden of the additional load, which may also increase heart rate.

The significant differences observed in peak and mean RPE indicate that participants consistently felt as though they were working slightly harder (1 ± 0 units) during the armored trial. Although it is possible that such a small difference would have little impact on soldiers in an operational setting, it is also plausible that this increase in RPE when wearing full armor would be magnified over longer working periods or in extreme environmental conditions. The small but significant difference in RPE observed in the current study supports that of previous research, which has found personal protective clothing to elicit higher RPE values during treadmill walking[2] and gross arm movement activities.[10] Interestingly, this finding occurred without concurrent elevations in heart rate. It is possible that a psychological element was involved; participants may have assumed that the armor would cause greater levels of exertion, regardless of afferent physiological signals. It is also possible that RPE is sensitive to musculoskeletal as well as cardiovascular and thermoregulatory load.[28] Goslin and Rorke[28] observed that backpack loads can increase subjective ratings of exertion by twice the amount of the physiological measures of exertion, inferring that RPE may be able to detect changes in load where heart rate cannot during self-paced tasks.

Implications for Armed Forces

The results from this study underline the trade-off between body armor weight and maneuverability or speed during the performance of military tasks. Theoretically, increased armor weight results in increased protection against hazards for military personnel. However, we have observed that increased weight leads to decreased performance, which indicates that the weight of modern body armor may have increased to a point where it has exceeded the optimum point for battlefield survivability. Thus, the impaired performance observed in the current study has profound implications for armor design. As soldiers in an operational environment are required to traverse the battleground quickly and efficiently, armor design should be continually moving towards lightweight, highly protective garments with minimal performance and physiological consequences. The performance, physiological and subjective impairments observed in the present study may be particularly significant given the relatively short (44 minutes) working period and "light" loads utilized. It is likely that armed forces personnel performing physical military work over a full shift and carrying heavier loads would experience greater levels of impairment and accumulating fatigue, which has the potential to threaten combat survivability in a hostile environment.

CONCLUSIONS

The performance of military tasks is adversely affected by the presence of body armor. In the present study, this impairment did not accrue over the 44-minute working period utilized. This suggests that load factors, rather than accumulating fatigue, could be primarily responsible for the observed short-term performance decrement. Such findings highlight the need for the development of lightweight protective clothing for armed forces personnel. Core temperature was significantly higher during the armor trial in the final five circuits. Although this elevated core temperature did not induce parallel performance decrements in the present study, it is possible that performance would further decline over a longer working period or in hotter environmental conditions.

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