

Task-Specific Effects of Modular Body Armor

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ABSTRACT Eleven recreationally active males performed 11 circuits of military work, wearing torso armor on one occasion, and full armor on another. Performance was measured by the time taken to complete individual tasks, and the overall time to completion (TTC) for each circuit. Heart rate, intestinal temperature, ratings of perceived exertion (RPE), and thermal sensation were recorded after each circuit. Participants' circuit TTC was no different between conditions; however, specific tasks were differentially impeded by the two armor configurations. Vaulting and crawling were significantly slower (0.28 ± 0.06 and 0.55 ± 0.26 seconds) in full armor; however, box lifting and shooting were significantly slower (0.36 ± 0.18 and 0.86 ± 0.23 seconds) when wearing torso armor. Heart rate and core temperature were significantly higher during the full armor trial (5 ± 1 beats·min⁻¹ and $0.22 \pm 0.03^{\circ}\text{C}$). Similarly, RPE and thermal sensation were significantly higher (1 ± 0 and 0.5 ± 0.0) during the full armor condition. Military tasks were differentially impaired by the armor configurations used, which suggests a need to explore role-specific armor for military personnel. Physiological and perceptual responses were elevated in full armor, which could be exacerbated during longer periods of work or in hot conditions.

INTRODUCTION

Modern warfare dictates that military personnel wear highly protective garments (i.e., body armor) to guard against increasingly sophisticated weaponry (e.g., improvised explosive devices^{1,2}). Since the advent of modern body armor, there have been significant decreases in the number of fatal thoracic and abdominal injuries sustained on the battlefield.³⁻⁵ However, extremity (arm and leg) injuries are continually prevalent, with musculoskeletal injury to the extremities accounting for 54% of the injuries sustained by soldiers deployed to Iraq or Afghanistan between 2001 and 2005.⁶ There is some qualitative evidence that suggests that extremity armor is often forfeited by military personnel in an operational environment because of the perceived additional burden it adds to an already cumbersome load.⁷ This worrying trend may reasonably contribute to the current injury rates.

Despite the relative absurdity of soldiers forfeiting all protective equipment in a hostile operational environment, the bulk of research to date has focused on the differences in performance between those wearing body armor and a "no armor" control condition.⁸⁻¹¹ Only one group has investigated the effect of torso protection (i.e., a Kevlar vest) compared to full body armor (i.e., a Kevlar vest with attached extremity armor) on military task performance.¹² This research observed decreases in sprint performance and box-lifting ability when participants were wearing full armor, compared to torso-only protection.¹²

Although the findings from this study support the idea that full armor impairs military task performance above and

beyond that of torso protection alone, it has limitations that prevent widespread application. Participants in this study performed just one maximal effort of the specified tasks (lasting <70 seconds in total¹²), which allows no insight into the relationship between armor and performance across longer periods of military work. Given the likelihood of armed forces personnel performing tasks repeatedly and urgently on the battlefield,^{13,14} research investigating intermittent and repeated high-intensity work is warranted. A further limitation is that no physiological or subjective responses were measured (or reported) during the performance of the military-style tasks. We have recently shown that, despite decrements in the overall performance time of a repeated, high-intensity military-style obstacle course, participants' core temperature and RPE were increased when wearing armor compared with a "no armor" control condition.⁹ If the same were true for full armor when compared to torso only protection, the increased heat stress and perception of exertion may explain the worrying trend of soldiers forfeiting their extremity armor in the field.⁷ Our previous work also highlighted the differential effect body armor had on some work tasks (i.e., shooting, vaulting, and crawling), although having no impact on others (i.e., box lifting⁹). Whether such findings persist if torso protection is compared with full armor remains unknown.

Therefore, the aim of this study is to assess the performance, and physiological and subjective responses to wearing full armor compared to a torso-only condition, during repeated circuits of intermittent, high-intensity military-style tasks.

METHODS

This study represents one arm of a larger study. Part of the data collected as part of the broader study has already been published.⁹

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Participants

Eleven recreationally active males volunteered for this study. The sample was limited to male participants as the vast majority of soldiers wearing body armor in combat are men.¹⁵ Following a short briefing, participants gave written informed consent and completed a modified medical questionnaire¹⁶ 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 and recorded (without shoes) using a stadiometer (Fitness Assist, England). Semi-nude body mass was measured on an electronic scale (A and D, Japan) pre- and posttrial for the calculation of whole body sweat rates, with allowances being made for ingested and expelled liquids.^{17,18} 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 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. During the trial, participants repeatedly performed a circuit comprising simulations of military-specific tasks while wearing torso armor on one occasion and full body armor on another. The armor condition order was randomized and counterbalanced to minimize learning effects. All trials were completed at the same time of the day to minimize the potential for performance and physiological diurnal variations¹⁹ to confound results.

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.²⁰ Data were then continuously recorded on a core temperature data logger (Vitalsense, Minimitter, Oregon). On arrival for testing, participants were also fitted with a heart rate monitor (Polar, Finland). In both trials, participants wore supplied army fatigues (Australian Defence Apparel [ADA], Australia), their own sports shoes, an army helmet (500 gm; ADA), and carried a dummy rifle (2 kg; ADA). In the torso armor trial, participants also wore a protective chest plate (12.63 kg; ADA), whereas in the full body armor trial, participants wore the chest plate in conjunction with full arm, leg, and neck armor (17.46 kg in total; ADA). Nineteen reflective markers were affixed to the participants' joints to serve as locators⁹ with which the motion capture system used to capture the key movements performed during the work tasks. Participants were familiarized with the RPE²¹ and thermal sensation²² scales before testing. Ambient temperature was measured throughout testing using handheld weather monitors (Kestral Instruments, Australia).

Military Circuit

The military circuit was devised after both industry consultation with subject matter experts (SMEs) and thorough review of military task analysis literature.^{13,23–25} The SMEs 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 capture TTC data using the motion capture system, the circuit was not explicitly designed to replicate the size and different terrains that comprise a real-life military battleground. Rather, the circuit was designed to simulate actions and movements shown to be commonplace during military work.^{13,23–25}

The circuit began with participants dropping to a prone position and shouldering the rifle, pointing at a circular (10-cm diameter) target. 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. On completion of the army crawl, participants completed a repetitive box-lifting exercise, in which they lifted a 20-kg box (47 cm³) from the ground onto a 74-cm platform, five times. Participants then sprinted to the starting point (i.e., the shooting task) 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, and precisely measured, to ensure the same minimum distance was being covered during each circuit.

Participants were required to finish each circuit (i.e., 2 “laps”) within 2 minutes, or testing was terminated. 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. 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.^{13,26,27} Limiting the trial to 11 circuits (maximum 44-minute working period) was also developed in conjunction with the SME 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 precise task completion times (see Table I). Heart rate, core body temperature, RPE, and thermal sensation were also 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,

TABLE I. Task Time to Completion Start and Finish Points

Task	Marker	Initiation	Cessation
Shooting	Top Head	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	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	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	When the participants' hand first touched the box	When participants removed their hand from the box after the final lift

Champaign, Illinois). The distribution (normal or otherwise) of the data was evaluated using Shapiro–Wilk tests. All circuit performance measures and physiological and subjective responses were normally distributed, with the exception of box lift TTC. The normally distributed variables were then analyzed using repeated measures analyses of variance (ANOVA), with body armor condition and time as the two within-participant factors. When the ANOVA detected a significant interaction, simple effects analyses were used to isolate where the significant difference occurred. Box lift TTC data were not normally distributed, though these were corrected via reciprocal transformation. Two-way ANOVA of both the reciprocal and original box lift TTC data revealed identical results. Given the difficulty in interpreting back-transformed reciprocal data,²⁸ results from the ANOVA of the nontransformed box lift TTC data will be reported. 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 \pm standard deviations unless otherwise stated. Mean and peak RPE results were reported to the nearest whole number²¹ and thermal sensation values were reported to the nearest 0.5-increment,²² consistent with their respective scales.

RESULTS

The mean age of participants was 22 ± 2 years. The mean height of participants was 1.84 ± 0.73 m, and their mean body mass was 77 ± 14 kg. The torso armor configuration represented $17 \pm 3\%$ of participants' body mass, $6 \pm 1\%$ lower ($p < 0.001$) than the $23 \pm 4\%$ for the full armor configuration. Ambient temperature in the Motion Capture Laboratory was no different ($p = 0.622$) between the torso and full armor trials ($20.9 \pm 1.2^\circ\text{C}$ and $21.3 \pm 1.6^\circ\text{C}$, respectively).

There was no main effect for armor condition ($p = 0.989$), time ($p = 0.082$), and no interactions between condition and time ($p = 0.989$) for participants' mean whole-circuit TTC (torso only: 74.2 ± 17.4 seconds, full armor: 74.2 ± 16.2 seconds). It should be noted that participants were able to complete 9 ± 2 of the 11 bouts in the torso config-

uration, compared to 10 ± 1 in the full armor configuration. This difference did not reach statistical significance ($p = 0.059$).

There was no main effect for time ($p = 0.309$, 0.387 , and 0.591), and no interaction between armor and time ($p = 0.579$, 0.938 , and 0.805), observed for the vaulting, crawling, or shooting tasks. However, there was a main effect for condition observed for both vaulting and crawling TTC, such that these tasks were 0.28 ± 0.06 seconds ($p < 0.001$) and 0.55 ± 0.26 seconds ($p = 0.036$) slower when participants were wearing the full armor. Conversely, the shooting task was found to be 0.36 ± 0.18 seconds ($p = 0.046$) slower during the torso armor condition compared with the full armor trial. There was a main effect observed for time during the box-lifting task ($p = 0.020$); however, no interaction between armor condition and time was observed ($p = 0.990$). Participants did, however, perform this task 0.86 ± 0.23 seconds slower (<0.001) when wearing the torso-only armor.

There was no difference ($p = 0.449$) in resting heart rate values measured before the torso (85 ± 14 beats·min⁻¹) and full (90 ± 13 beats·min⁻¹) armor trials. Similarly, no interaction between armor and time was observed ($p = 0.814$) throughout the trials. There was, however, a main effect for condition observed, with participants' heart rates reaching an average of 5 ± 1 beats·min⁻¹ higher ($p = 0.001$) during the full armor condition (180 ± 1 beats·min⁻¹) than the torso-only trial (175 ± 1 beats·min⁻¹). There was also a main effect observed for time ($p < 0.001$), illustrating that participants' heart rates increased over the duration of the testing period, regardless of condition. There was no difference ($p = 0.174$) in peak heart rate between the torso and full armor conditions (182 ± 9 and 187 ± 11 beats·min⁻¹, respectively).

There was no difference between conditions ($p = 0.438$) in resting intestinal temperature before completing the work simulations (torso only: $37.21 \pm 0.22^\circ\text{C}$, full armor: $37.30 \pm 0.19^\circ\text{C}$). There was also no armor \times time interaction ($p = 0.928$) observed for intestinal temperature across the trial. Main effects were, however, observed for both armor condition ($p < 0.001$) and time ($p < 0.001$). Participants' core temperature was, on average, $0.22 \pm 0.03^\circ\text{C}$ hotter ($p < 0.001$) when wearing the full armor ($38.29 \pm 0.03^\circ\text{C}$) than when wearing the partial armor ($38.07 \pm 0.02^\circ\text{C}$). Further, participants' core temperature rose steadily across the course

of the simulation, regardless of experimental condition. The peak core temperatures reached throughout the simulation were not different ($p = 0.122$) between the torso-only ($38.35 \pm 0.40^\circ\text{C}$) and full armor conditions ($38.71 \pm 0.50^\circ\text{C}$).

There was no interaction observed between armor condition and time ($p = 0.972$) for participants' RPE. However, RPE across all time points were 1 ± 0 units higher ($p = 0.003$) for the full armor condition (17 ± 1) than for the torso armor trial (16 ± 1). There was also a significant main effect observed for time ($p < 0.001$), with participants consistently reporting higher RPE values as the trials progressed. As with heart rate and core temperature, peak RPE values were not different ($p = 0.184$) between conditions (torso only: 18 ± 1 , full armor: 19 ± 1).

No armor \times time interaction was observed for participants' thermal sensation values ($p = 0.999$). Thermal sensation ratings did, however, show a small but significant main effect for armor condition, with participants reporting values 0.5 ± 0.0 higher ($p < 0.001$) over the course of the trial when wearing extremity armor. A main effect for time was also observed ($p < 0.001$), with participants reporting higher thermal sensation values as the trial progressed during both conditions. There was no difference ($p = 0.621$) in peak thermal sensation between torso-only (7.0 ± 0.5) and full armor (7.0 ± 0.5) conditions.

DISCUSSION

The primary aim of this study was to assess whether extremity armor would have an effect on the performance of repeated,

high-intensity military-style tasks beyond that of a protective vest alone. The major finding was that there was no difference in participants' whole-circuit TTC between trials. This finding illustrates that wearing extremity armor in addition to a protective vest does not negatively affect the global performance time of a repeated military task simulation, at least across the work to rest ratios examined in this study. This finding is in opposition to previous research that has used obstacle course TTC as a performance measure, in which performance decrements of 30 to 36% were reported for the "heavier" armor conditions.^{26,29} Two possible reasons exist that may explain the novel findings observed in this study. First, the loads imposed in this study (12.63 and 17.46 kg, respectively) were considerably lighter than the loads used in past research (ranging from 27 to 31 kg).^{26,29} Although the loads used in this study were significantly different between conditions, it is possible that the small weight difference between conditions (4.83 kg) relative to past research (~ 13 kg)^{26,29} was not enough to elicit a global performance decrement. Second, this study examined the performance of repeated military tasks, whereas previous researchers have focused on the performance decrements incurred during just 1 repetition of a military-style circuit.^{26,29} It is possible that the performance decrement incurred during a maximal effort could be greater than during a repetitious circuit of self-paced, albeit high intensity, work tasks.

The whole-circuit TTC results observed during this study can be further explained through analysis of individual task TTC (Fig. 1). In support of past research, the vaulting and crawling tasks in this study were significantly slower with the

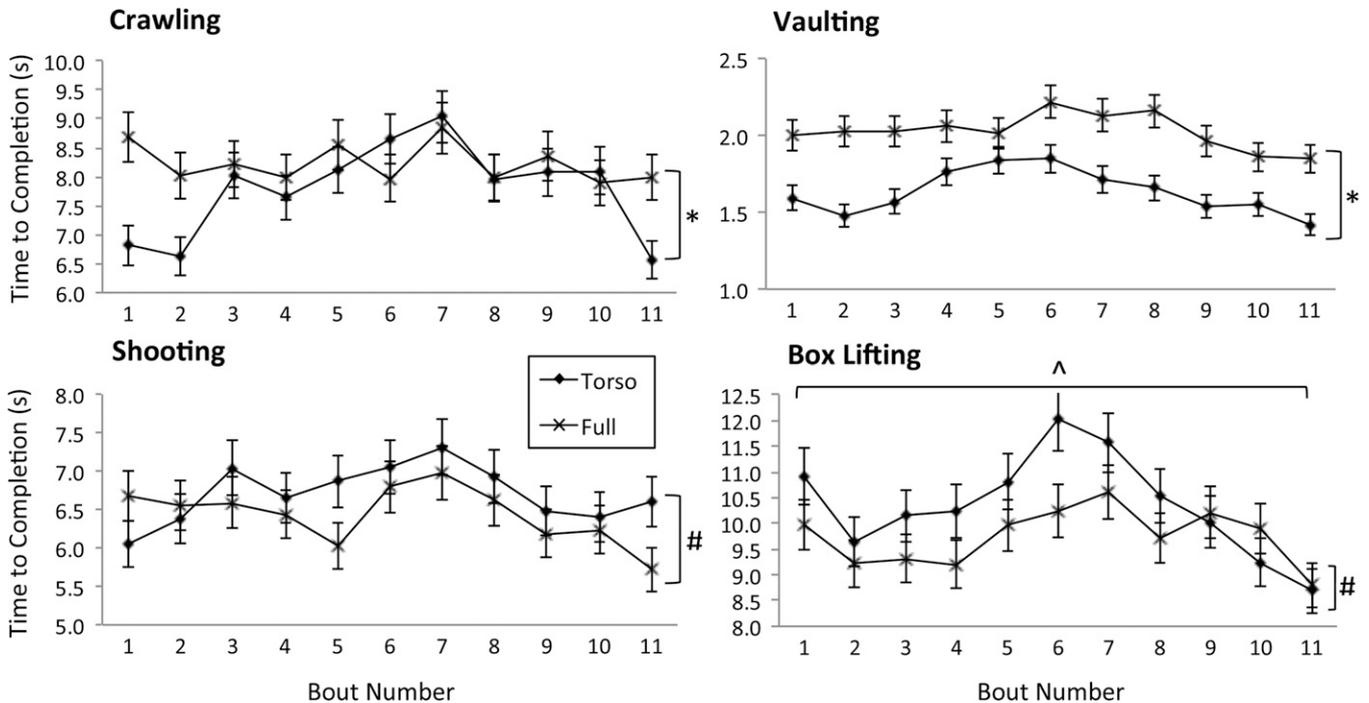


FIGURE 1. Individual task completion times. *, extremity armor higher (main effect; $p < 0.05$); #, torso armor higher (main effect; $p < 0.05$); ^, main effect for time ($p = 0.020$).

heavier load.^{9,26,29} Conversely, the shooting and box-lifting tasks were observed to be significantly slower during the torso armor condition. These results refute findings by previous researchers that have reported impaired stand to prone and prone to stand movements (as seen in the shooting task²⁹) and box-lifting performance³⁰ with increased loads. It is hypothesized that participants in this study used the extremity armor to their advantage when performing these two tasks. Anecdotal evidence from participants and researchers alike suggests that, during the box-lifting task, participants were able to lower the box to the ground more quickly by using the protective leg armor on their thighs. During the shooting task, participants appeared to be able to move from stand to prone more quickly during the full armor condition, as the joints that first made contact with the ground (knees and elbows) were cushioned by the extremity armor. It is likely that the stand to prone movement in the crawling task would have been similarly affected; however, any advantages granted by the extremity armor at the beginning of this task seemed to be eclipsed by the additional resistance of the extremity armor during the crawling phase of the task. Although healthy norms formed the participant group in this study, no learning effects (e.g., no meaningful main effects for time) were observed. Thus, the results obtained may be the first step in contextualizing the effects of body armor use on performance for military personnel.

Another aim of this research was to assess the physiological and subjective responses to wearing full body armor when performing military-style tasks. Heart rate increased at a quicker rate during the full armor condition, and this elevation in heart rate was consistent over the course of the trial. This finding reflects the additional physiological exertion placed on the wearer when using extremity armor. This is in contrast to our previous work,⁹ where participants wearing full armor slowed their performance time of a military circuit and, thus, elicited comparable heart rates to the “no armor” control condition. In this study, overall performance time remained the same; however, physiological exertion (i.e., heart rate) increased, as is commonly observed during set-paced treadmill walking and running protocols.^{12,30–32} This trade-off between work output and physiology is intrinsic to self-paced work; if performance is to be maintained under “stressful” conditions (e.g., hot environments, wearing body armor), it will require an increased level of exertion.³³

Participants’ intestinal temperature was also consistently higher over the course of the extremity armor trial. This is in support of work by Caldwell et al³² who found that core body temperature increased at a quicker rate when wearing extremity armor compared to a vest alone during extended bouts of treadmill walking. It is possible that the combination of additional load and body surface coverage in the full armor trial resulted in the observed increases in intestinal temperature. The relationship between increased surface area coverage and thermal stress when wearing protective clothing has been well established.³⁴

In conjunction with the physiological responses, participants also reported higher RPE and thermal sensation throughout the full armor condition. Our previous research also showed higher RPE values for participants performing military-style tasks when wearing full body armor compared with a control.⁹ We are unaware of any other researchers that have used RPE or thermal sensation when examining the effect of body armor during a range of military-specific tasks. Caldwell et al³² observed no differences in RPE between “vest-only” and “vest plus extremity armor” conditions during prolonged treadmill walking. The differences in the exercise protocols used may explain, at least in part, the differing results. It is plausible that participants were more aware of, and impeded by, the extremity armor when performing the military circuit used in this study than during a treadmill walking exercise, because of the complex movement patterns involved. Such subjective responses should be further explored in future research, as increases in perceived exertion and thermal stress could potentially act as a driver for behavior (e.g., the removal of extremity armor in an operational setting³⁵).

Implications for Armor Design and Armed Forces

The results obtained in this study, together with the concerning statistics surrounding military personnel extremity injury, highlight the need for the continued redevelopment of protective extremity armor. In this study, full body armor was shown to negatively impact the performance of specific military-style tasks. This finding highlights a potential need for the development of role-specific armor, tailored to the tasks commonly performed by personnel in each position. The full body armor also caused greater thermal stress and exertion than the torso protection alone. Although the negative effects observed for both performance and physiological stress in this study were relatively small, it is possible that these effects could be exacerbated over longer working periods or during hot/humid environmental conditions. Future research should attempt to quantify the differential effects of modular body armor under such conditions using military personnel, to more precisely predict the impact of body armor use on the battleground. Further, body armor manufacturers should continue to strive for cooler, less cumbersome, and more comfortable protection for armed forces personnel.

CONCLUSION

The performance of certain military tasks, specifically crawling and vaulting, were impeded by full military body armor. However, full armor appears to assist with the performance of certain tasks (i.e., box lifting and shooting), potentially because of the cushioning granted by the extremity protection. All physiological and subjective measures were elevated during the full body armor trial. This finding was not unexpected, given participants were able to maintain their global performance time. It is likely that additional

load and surface area coverage played a role in the increased physiological and subjective responses observed.

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