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Larsen, Brianna, Netto, Kevin and Aisbett, Brad 2011, The effect of body armor on performance, thermal stress, and exertion : a critical review, *Military medicine : international journal of A M S U S*, vol. 176, no. 11, pp. 1265-1273.

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The Effect of Body Armor on Performance, Thermal Stress, and Exertion: A Critical Review

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ABSTRACT Armed forces worldwide utilize some form of body armor as part of their personal protective system. This is particularly essential in recent times because of the increased sophistication of weapons employed during modern warfare and the advent of unconventional combat methods (such as the increased use of improvised explosive devices). There is some evidence to show, however, that the usage of military body armor impairs physical performance. This review of the literature will focus on the effect of body armor on the performance of, and physiological and subjective responses during, military-style physical tasks. Because of the paucity of research investigating body armor, this review will also draw upon more generalized personal protective clothing and equipment literature from a range of physically demanding occupations (i.e., firefighting and other emergency services). The review will conclude with suggested directions for future research in this area.

HISTORY OF BODY ARMOR

Throughout recorded history, military personnel have used various types of materials to protect themselves from injury during combat.¹ This protective clothing (or body armor) has progressed from rudimentary leather protection to mail and full-plated suits of armor, and more recently, ballistic cloth (i.e., Kevlar).^{1,2} Although creating stab- and bulletproof material was once the primary objective of body armor developers, the increasingly sophisticated weaponry employed in modern warfare promotes the need for even greater levels of protection for military personnel.^{1,2}

Since the advent of modern protective body armor, a number of epidemiological studies have shown a substantial reduction in the number of fatal thoracic and abdominal injuries incurred during conflict situations.³⁻⁵ During Operation Iraqi Freedom and Operation Enduring Freedom, only 5 to 7% of reported injuries were thoracic; the lowest for American military personnel in modern warfare.⁵ The use of body armor has also significantly reduced the lethality of gunshot wounds.⁵ There is, however, a considerable proportion (34.7%) of military personnel reporting noncombat injuries, the majority of which are musculoskeletal.⁶⁻⁸ Musculoskeletal health significantly affects individual readiness and performance, and is a primary source of disability among deployed military service members.⁷ Moreover, such injuries have the potential to cause long-term health consequences even after soldiers have retired from active duty.⁸ Among the veterans returning from Iraq and Afghanistan who sought Veterans Administration health care between 2002 and 2006, 42% were related to musculoskeletal issues such as joint and back disorders.⁹ It has been hypothesized that the wearing of modern body armor can alter soldier's movement patterns, increase joint stress and potentially increase their risk of suffering musculoskeletal injuries.⁸ Without the availability of time-course data, however, it is

impossible to determine a causal relationship between body armor and musculoskeletal injury.

Dedicated research exploring the impact of modern body armor on the long-term incidence rates of musculoskeletal injury is warranted; however, such information is not yet available and thus will not be the focus of this review. The purpose of this review is to summarize the existing controlled, scientifically valid research that investigates the impact of military body armor on the performance of military tasks and further, the impact of such protective gear on an individual's thermal stress and exertion. The review will commence by outlining the tasks and duties required of personnel, as reported through various job task analyses, to give context to the subsequent performance discussions. The research selected for inclusion in the review was sourced from Medline, PubMed, Google Scholar, and various military technical reports. Because of the limited availability of research investigating military body armor, the review will supplement the existing research with studies exploring the effect of general personal protective clothing on tasks that resemble the material-handling profile of military work. All salient articles will be presented throughout the review and in a summary table at the end of this review (Table I). It should be noted that many of the studies reviewed focus solely on body armor or on personal protective clothing without taking into consideration the additional equipment soldiers are required to carry in their combat load, i.e., weapons, ammunition, communication devices, first aid kits, goggles, and gloves.^{8,18} As such equipment is often heavy and cumbersome, it is possible that the findings of studies researching only body armor may not report the degree of functional limitation and thermal stress and exertion decrements incurred during a military deployment.

MILITARY TASKS AND DUTIES

Armed forces personnel are required to combat enemy forces, keep the peace, and assist in post-disaster situations.¹ Over the past 45 years, researchers have consistently reported a range

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TABLE I. Summary of Key Findings

Variable	Author(s)	Participants	Body Armor /Personal Protective Clothing	Tasks	Major Findings	Comments
Performance	Ricciardi et al ¹⁰	34 Military personnel (17 males and 17 females)	Body armor (~10 kg)	Hand grip strength, stair step test, pull-ups (males), hang time (females)	Number of pull-ups ↓ 61%, hang time ↓ 63%, stair stepping ↓ 16%, no difference in hand grip strength	
	Pandorf et al ¹¹	12 Female soldiers	Body armor (~14 kg) plus additional equipment loads of 27 and 41 kg	3.2-km Run, obstacle course (comprising straight sprints, hurdles, zigzag runs, low crawling, wall climbing)	19 and 44% Slower when completing the 3.2-km run with the 27- and 41-kg loads, respectively; 12-26% slower to perform the obstacle course with the 27-kg load compared to the 14-kg load	
	Hasselquist et al ¹²	11 Male soldiers	Tactical vest (8.7 kg) plus 3 versions of extremity armor (ranging from 5.6 to 6.4 kg)	10-Minute walk, 10-minute run, repetitive box lift and carry, 30-m rushes, obstacle course runs	↑ Sprint and obstacle course run time; altered walk/run biomechanics (wider strides, increased stance time, and decreased swing time); ↓ number of box lifts performed	For all activities, the vest elicited poorer performance than no armor, further exacerbated by the presence of extremity armor
	DeMaio et al ¹³	21 Soldiers (19 males, 2 females)	Kevlar vest (9.8 ± 0.9 kg)	Maximal uphill walking, balance activity, shuttle runs, box agility, rope pull, dummy drag	Participants withdrew from the maximal walking test earlier (14.4 ± 1.5 vs. 16.4 ± 1.6 minutes) when wearing the vest; ↑ shuttle run time; balance impairments; no differences in upper body strength exercises	
Thermal Stress	Cadarette et al ¹⁴	6 Male volunteers (nonmilitary)	6 Body armor configurations (ranging from 8.3 to 10.1 kg)	100-Minute continuous treadmill walking	No differences between any of the armor configurations for rectal temperature or sweat losses	No control group, small participant number (n = 6)
	Montain et al ¹⁵	7 Males volunteers (nonmilitary)	Full (pants, coat, boots, gloves, face mask with hood) or partial (pants, coat) personal protective clothing	180 Minutes (or until exhaustion) of continuous walking in either a "tropical" (35°C, 50% relative humidity) or "desert" (43°C, 20% relative humidity)	Rectal temperatures actually higher for partial than full trial	Results are misleading as participants withdrew earlier in the "full" trial thereby not allowing rectal temperatures to rise
	Payne et al ¹⁶	10 Male volunteers (nonmilitary)	3 Different personal protective clothing ensembles over a T-shirt, underwear, shorts, and socks	Simulated firefighting work including: walking with a charged hose, moving 200-L chemical drums, moving 20-L car buoys and stacks	No differences between any of the personal protective clothing configurations for rectal temperature or sweat losses	Relatively low-intensity work may not reflect the often high-intensity of military work; small sample size (n = 10); garment weight not specified, possible it did not reflect the burden of military body armor

(Continued)

TABLE I. Continued

Variable	Author(s)	Participants	Body Armor /Personal Protective Clothing	Tasks	Major Findings	Comments
Physical Exertion	Hasselquist et al ¹²	11 Male soldiers	Tactical vest (8.7 kg) plus 3 versions of extremity armor (ranging from 5.6 to 6.4 kg)	10-Minute walk, 10-minute run	VO ₂ ↑17 and 7% during the walking and running activities, respectively, for the 3 extremity armor conditions when compared to the control and "vest only" conditions	
	DeMaio et al ¹³	21 Soldiers (19 Males, 2 females)	Kevlar vest (9.8 ± 0.9 kg)	Maximal uphill walking	DeMaio actually observed ↓ VO ₂ during the vest trial compared to the control	Results are misleading; participants withdrew earlier in the "vest" trial thereby not allowing VO ₂ to rise
	Ricciardi et al ¹⁰	34 Military personnel (17 males and 17 females)	Body armor (~10 kg)	30-Minute continuous treadmill walking at slow and moderate paces	Significantly ↑ heart rate for both the slow (118 ± 16 vs. 107 ± 14) and moderate (180 ± 13 vs. 164 ± 16) treadmill walking during the body armor trials compared to the control	
	Cheuvront et al ¹⁷	11 Male volunteers (nonmilitary)	Tactical vest (7.5 kg)	4-hour intermittent treadmill walking	Heart rate ↑7 and 19 bpm for the vest condition compared to the control after 1 and 4 hours, respectively	

of material-handling and movement tasks performed by military personnel to carry out these duties.¹⁹⁻²¹ Material-handling tasks included "rifle-firing and loading," "grenade throwing," and "digging foxholes," whereas "maneuverability" and "marching and moving" were also identified.²² Both material-handling and movement tasks were identified as prevalent and relevant for success in military combat.²² In more recent military task analyses, material-handling tasks were again identified as fundamental to military work.¹⁹⁻²¹ Furthermore, tasks such as marching, walking and running, low and high crawling and climbing (which reasonably correspond with "maneuverability" and "marching and moving") were identified as important despite the increased mechanization of army operations in modern times.¹⁹⁻²¹

MODERN WARFARE

In recent times, there has been a palpable shift toward the use of improvised explosive devices (IEDs, commonly known as roadside bombs) as weapons.^{2,5} IEDs range from simplistic devices to sophisticated detonators.^{2,5} These devices are commonly planted on roads, in vehicles, or in heavily populated civilian areas and may be used to distract, disrupt, or delay an opposing force.^{2,5} In the 2003–2010 Iraq War, IEDs have been used extensively against coalition forces, and by the end of 2007, they were responsible for at least 60% of coalition fatalities in Iraq.²³ In the current Afghanistan conflict, IED-related

fatalities have increased by 400% since 2007, while the incidence of reported woundings by these devices has increased seven-fold during the same period, rendering IEDs the number one cause of death among troops in Afghanistan.²⁴ The steep rise of IED use increases the need for the development of highly protective, yet comfortable and nonrestrictive, protective clothing and equipment for armed forces.^{2,5}

BODY ARMOR AND PHYSICAL TASK PERFORMANCE

Military body armor is worn to protect soldiers from injury during conflict situations; however, the level of protection given must be contrasted against the performance decrements elicited from the body armor itself. Many researchers who have investigated military body armor have focused on the physiological changes elicited from the body armor usage without further exploring the corresponding performance decrements.^{14,25} Those that do incorporate a performance aspect often fail to adequately simulate the range of tasks performed by military personnel, thereby decreasing the validity of results.²⁶ Prolonged treadmill walking is the most common form of exercise examined in reference to military performance. Walking at a set pace, though effective for comparing the physiological responses between two protective ensembles, does not permit analysis of the speed in which soldiers can perform military tasks in simulated military scenarios. Movement speed

is thought to be an important component of both individual survival and the effectiveness of fighting units.^{11,26} Indeed, a soldier must be able to not only carry loads to a battlefield but also to traverse the battlefield quickly while under fire.^{11,26,27} As such, although treadmill-walking protocols may provide insight into how the performance of marching and load carriage is altered by body armor, they do not provide insight into the speed of soldiers' movement while wearing various armor ensembles or the performance of other military tasks relevant for combat success.^{21,22,26}

Ricciardi et al¹⁰ incorporated a "physical performance battery" into their study examining the effect of body armor on performance, energy cost, and physiological fatigue. The physical performance measures included were "hand grip strength," "stair step test," and "pull-ups (for men) and hang time (for women)" to represent the high level of upper and lower body strength required by those in military occupations.¹⁰ When wearing body armor, the men completed 61% fewer pull-ups and women's hang time was reduced by 63%, whereas stair stepping was reduced by 16% for both men and women.¹⁰ No significant differences in hand grip strength were noted between conditions.¹⁰ The decrements in these upper body strength and lower body speed tests when wearing body armor may potentially serve as proxies for how certain military tasks could be adversely affected.¹⁹⁻²¹ The performance decrements observed during the upper body exercises may reflect how military tasks such as "lift" and "carry loads" (which also comprise contractions of the biceps brachii and upper back musculature)²⁸ could be impaired by body armor.¹⁹⁻²¹ Similarly, the lower body exercise (stair step test) may indicate the negative impact of body armor on marching, running, or climbing task performance.¹⁹⁻²¹

Several researchers²⁹⁻³³ have purportedly studied the effect of body armor on military performance using the tasks identified earlier in this review (see Military Tasks and Duties),²² or similar, as the basis for a test battery. These researchers calculated an "average performance decrement" to provide an overall impression of how body armor affects the performance of military tasks. This value is expressed as a percentage decrement per kilogram of armor. Decrement values have ranged from 2.4 to 3.5% per kilogram.²⁹⁻³³ Goldmann and Kampmann³⁴ observed that the functional obstruction by an average shell fragmentation protective vest (4.5 kg, 30% body coverage) resulted in a 30% loss of performance. Treadmill walking or "marching" has been shown to elicit smaller performance decrements (1.5% per kg) than agility or obstacle courses.³² This further indicates that prolonged treadmill walking may not be a true representation of the overall physical requirements of military work, and therefore should not be the only way of measuring the effects of body armor on military performance. The average performance decrements per kilogram of body armor were, however, only broadly covered in a military report³⁵ and, as such, the primary sources are not readily accessible to the public (in either electronic or paper versions). Consequently, it is impossible to determine whether

the methodologies used and the consequent results obtained are valid measures of the effect of body armor on military performance.

In contrast, Pandorf et al¹¹ examined the speed in which female soldiers took to complete a 3.2-km run while carrying loads of 14, 27, and 41 kg. These researchers also investigated the time to completion of an obstacle course, with the same cohort of participants carrying the 14- and 27-kg loads. The obstacle course consisted of activities such as straight sprints, hurdles, zigzag runs, low crawling, and wall climbing.¹¹ Participants were instructed to complete both the 3.2-km run and obstacle course as fast as possible, after adequate time had been allowed for technique instruction and practice.¹¹ It was observed that soldiers took 19% more time to complete the 3.2-km run with the 27-kg load than with the 14-kg load, and 44% more time to cover the distance with the 41-kg load than with the 14-kg load.¹¹ In addition, it also took participants 12 to 26% longer with the 27-kg load to traverse the hurdle, zigzag, and straight sprint obstacle-course tasks, respectively, compared to their performance in these tasks with the 14-kg load.¹¹ The biggest difference was noted with the low-crawl obstacle, which took more than twice as long to negotiate with the 27-kg load when compared to the 14-kg load.¹¹ When wearing the heavier armor load, a number of participants were unable to complete certain obstacles, such as the "climbing" aspect of the course.¹¹ This study, although only utilizing a relatively small sample size ($n = 12$) of all female participants, gives valuable insight into the effects of carrying various loads on the performance speed of military tasks.

Hasselquist et al¹² and DeMaio et al¹³ also conducted research that incorporated military-style tasks into a test battery to determine what performance decrements, if any, were incurred by wearing military body armor. Hasselquist et al¹² had 11 army-enlisted men performing walking, running, sprinting, repetitive lifting, and obstacle course exercises in five armor conditions; no armor, a tactical vest, and the tactical vest with three different configurations of extremity armor. The extremity armor designs were similar in weight (ranging from 5.6 to 6.4 kg in addition to the 8.7-kg vest load) but differed in body surface area coverage.¹² DeMaio et al¹³ utilized 21 active U.S. military personnel in their study, in which participants completed uphill walking, climbing strength, balance, shuttle runs, box agility, rope pull, and dummy drag activities in either a Kevlar protective vest (9.8 ± 0.9 kg) or a "no armor" control condition. DeMaio et al¹³ observed that participants withdrew from their maximal uphill walking test significantly earlier when wearing the Kevlar vest than during the control trial (14.4 ± 1.5 minutes compared to 16.4 ± 1.6 minutes, for the armored and control trials, respectively). Similarly, both studies witnessed sprint performance decrements; participants performed sprint activities slower during the armored trials than the control trials,^{12,13} an effect that was further exacerbated by the presence of extremity armor.¹² Hasselquist et al¹² also observed significant changes in walking and running biomechanics in the armored conditions when

compared to the control, including wider strides, increased stance time, and decreased swing time. Additionally, DeMaio et al¹³ reported balance impairments when their participants were wearing the Kevlar vest in comparison to the control trial. Interestingly, Hasselquist et al¹² found the box lifting exercise to be significantly impaired by all armor configurations, whereas DeMaio et al¹³ observed no difference in the upper body strength exercises employed in their study (box agility, rope pull, dummy drag) between armor conditions. It is likely, then, that extremity armor imposed by Hasselquist et al¹² is the main contributor to upper body performance decrements witnessed during the performance of military-style tasks. The studies by Pandorf et al¹¹, Hasselquist et al¹², and DeMaio et al¹³ provide important information regarding the impact of various armor configurations on walking and running activities, as well as strength and speed tasks. However, as participants in all studies completed just 1 maximal effort of the specified strength and speed tasks, the impact of body armor across several repetitions of military-style tasks, such as happens in real military operations,^{11,26,27} remains unknown.

It is clear that the performance of strength-related,^{10,12} speed-related,¹¹⁻¹³ and balance-related¹³ tasks is adversely affected by wearing body armor, and the impairment appears to increase proportionally with the load carried¹¹ or the area of body surface covered.¹² The performance of prolonged treadmill walking has also been shown to be impaired by wearing personal protective clothing.¹⁵ What remains unanswered, however, is how the performance of repeated and intermittent high-intensity military-specific tasks is affected by the addition of body armor or load. Given the importance of high-intensity tasks and the need to do them repeatedly and urgently on the battlefield,^{11,26,27} quantifying the effect that external load has on the performance of repeated, high-intensity tasks is critical for armed forces personnel and the design of the personal protective clothing and equipment they wear and carry.

THERMAL STRESS

Although military body armor is designed to enhance personnel safety, these garments can often negatively impact an individual's ability to tolerate heat.^{36,37} In military operations and training in the United Kingdom, for instance, approximately 80 service personnel are hospitalized each year with symptoms of heat stress,³⁸ often in ambient temperatures of well below 20°C, such is the thermal insulation of the armor.³⁷ Research into the effects of body armor or similar personal protective clothing or equipment on thermal stress is paramount for the ongoing safety of workers in hazardous occupations, such as military personnel and civilian emergency service workers.^{36,37} Because of the lack of available literature investigating the effect of body armor on thermal stress during military tasks other than prolonged marching,^{14,15} this review will supplement the existing findings with research regarding the thermal strain elicited from fire-retardant personal protective clothing during simulated firefighting tasks,^{16,39} as these

tasks share the repeated, intermittent material-handling profile of military work.^{19-21,40}

Cadarette et al¹⁴ and Montain et al¹⁵ investigated the physiological consequences of different configurations of modular body armor and protective clothing during continuous treadmill walking (100 and 180 minutes, respectively). The authors measured both rectal temperature and total body sweat losses as indicators of thermal strain, as sweating and subsequent evaporation is used by the body to dissipate heat and keep core temperature stable.⁴¹ Cadarette et al¹⁴ tested six configurations of body armor, ranging in weight from 8.3 to 10.1 kg, whereas Montain et al¹⁵ compared the physiological consequences of wearing either a full (pants, coat, over-boots, gloves, and face mask with hood) or partial (pants and coat) protective clothing outfit. Cadarette et al¹⁴ found no significant differences in rectal temperature or the pre-post change in body mass between any of the body armor configurations tested. With only six participants, it is possible that the study by Cadarette et al¹⁴ did not have sufficient statistical power to detect subtle differences in thermal stress between body armor configurations. Further, Montain et al¹⁵ actually observed higher rectal temperature and sweat loss values for the partial compared to the full protective clothing ensemble. These latter results can be misleading as participants opted out of the exercise far earlier in the full protective clothing condition, thereby not allowing rectal temperature to continue to rise.¹⁵ The study also does not report comparable rectal temperatures at set time points, making it impossible to discern like for like comparisons between the two protective ensembles. Similarly, as sweat rate values were not adjusted for walking time, the results obtained were, most likely, due to the shorter working period completed by participants when wearing the full protective outfit.¹⁵ Making specific inferences from the results obtained by Montain et al¹⁵ to military personnel is problematic; this research focused on general protective clothing, and it is unknown whether the burden imposed on the wearer by such protective clothing is directly comparable to that of military body armor. The results obtained from both studies are also only applicable to certain tasks identified as important in military occupations (i.e., marching and load carriage).¹⁹⁻²¹ Moreover, as the exercise completed was of low-to-moderate intensity, the results obtained give little insight into the effect that military body armor configurations might have during high-intensity work tasks. A further limitation is the lack of a "no armor" control condition, which makes the interpretation of the findings difficult as readers are unable to assess the global thermal changes caused by the armor or personal protective clothing.

Payne et al¹⁶ examined the effect of personal protective clothing on physiological and subjective responses during simulated firefighting work. Participants wore three different types of protective uniforms throughout the study, each over a standardized uniform of a T-shirt, underwear, shorts, and socks.¹⁶ Participants completed a 30-minute work simulation, comprising tasks, such as walking while pulling a charged hose, moving 200-L chemical drums, and moving 20-L car

buoys and stacks.¹⁶ While completing this work simulation, participants' rectal temperature and body fluid loss were used as major indicators of the degree of heat stress being imposed during the respective conditions.¹⁶ Rectal temperatures and body fluid loss did not differ between the type of suit worn.¹⁶ Although the work completed was intermittent, it was relatively low in intensity, thereby making it difficult to extrapolate these results to reflect the often high-intensity nature of military work.²⁶ Additionally, as garment weight was not specified, it is not clear whether the imposed load was equivalent to that of the various configurations of military body armor.¹⁰

Although not widespread in military body armor research, the use of subjective rating tools can also be utilized as an indicator of thermal stress.^{39,42-46} The perceptual responses individuals have to their working conditions may, however, be important as they may limit the amount of work time one can spend on a task.⁴⁷ Northington et al⁴⁸ utilized a thermal sensation index in their study exploring the impact of chemical protective clothing during a high-intensity treadmill exercise. No differences were found in thermal sensation values between the personal protective clothing condition and the control condition of shorts and a T-shirt.⁴⁸ It is possible that the short duration of the exercise (~10 minutes), however, was not long enough for differences in the subjective evaluation of the work to become apparent. Furthermore, it is unclear whether the added burden of the chemical protective clothing ensemble employed in the study is equivalent to that elicited by military body armor.

It is apparent that none of the research investigating military body armor truly incorporates all the variables necessary to give an accurate assessment of thermal strain elicited by such garments. It is also highly possible that the personal protective clothing utilized in much of this research does not reflect the load imposed by military body armor (and ancillary equipment). Further research into this area utilizing job-specific tasks, various body armor and equipment configurations, adequate participant numbers, and a defined control condition is, therefore, required.

PHYSICAL EXERTION AND BODY ARMOR USAGE

Physically demanding occupational tasks, such as those undertaken in the military, impose significant physiological strain on the worker.⁴¹ Further, exertion increases with additional load.^{49,50} Oxygen uptake (VO_2) is one method that has traditionally been used to quantify physiological strain during heavy occupational work.⁴¹ Hasselquist et al¹² found VO_2 to be 17 and 7% higher during the walking and running activities employed in their study, respectively, with the three extremity armor conditions when compared to the control and "vest only" conditions. This indicates that participants were required to work harder to maintain the set work pace when the extremity armor was in place, suggesting that these armor configurations elicited a degree of resistance upon the wearer above and beyond that of the tactical vest alone.¹² Surprisingly, DeMaio

et al¹³ actually observed decreased VO_2 for the armored condition during the uphill maximal walking element of their research. The authors attributed these findings to possible constriction of chest wall motion when wearing the Kevlar vest¹³; however, it is also possible that as participants withdrew from the trial earlier when wearing the vest, VO_2 did not have the same opportunity to rise as during the control trial. It is clear that further research utilizing oxygen consumption as a measure of physiological exertion is required before firm conclusions can be drawn.

VO_2 measurement, particularly during high-intensity tasks, can impede performance,⁵¹ so is often substituted with less invasive methods of exertion measurement. Heart rate monitoring can be used to provide information on the intensity of the activity being performed; for instance, the physiological strain involved with completing an occupational task,^{41,51} without impairing task performance.

The effect of body armor on participants' heart rate has been investigated during both continuous^{10,14} and intermittent¹⁷ treadmill walking lasting from 30 minutes to 4 hours. Ricciardi et al¹⁰ conducted 30-minute continuous treadmill walking exercises with and without body armor, at both slow and moderate paces.¹⁰ Significantly higher heart rate values were observed for both the slow (118 ± 16 compared to 107 ± 14 beats per minute) and moderate (180 ± 13 compared to 164 ± 16 beats per minute) paces of the treadmill testing when wearing body armor when compared to the control condition.¹⁰ These results indicate that the added exertion of wearing body armor persists with increases in exercise (work) intensity. Cheuvront et al¹⁷ conducted a study in which participants completed 4 hours of intermittent treadmill walking wearing either U.S. army fatigues alone or U.S. army fatigues plus a protective vest. Participants' heart rate was found to be 7 beats per minute higher for the protective vest condition when compared to the control condition after the first hour of exercise and 19 beats per minute higher after completing the 4-hour exercise protocol.¹⁷ This study illustrates, then, that not only does performing exercise (work) while wearing personal protective clothing elicit higher heart rate values, but this effect may also be exacerbated over prolonged periods.¹⁷ Additionally, it is possible that, as only a protective vest was worn in this study, the results obtained may only represent a fraction of the physiological strain induced by full military body armor and associated equipment. In contrast to Cheuvront et al,¹⁷ Cadarette et al¹⁴ found no significant differences found between heart rate values for any of the six body armor configurations tested. Such results infer that each armor design elicits a similar level of physiological strain upon the wearer during continuous treadmill walking.¹⁴ As previously discussed, however, the low-intensity walking protocol used may inhibit the application of these results to the high-intensity military work tasks performed intermittently on the battlefield.²⁶

Because of the relatively limited availability of research surrounding military body armor, general protective clothing research may provide broad insight into the possible

consequences of body armor on physiological exertion. Dorman and Havenith⁵² and Dreger et al⁵³ reported 2.4 to 20.9% higher VO_2 during all tasks performed (comprising lifting and moving crates, crawling on hands and knees, and moving under and over obstacles) for the protective clothing ensembles utilized in their study when compared to the control condition. It is possible, however, that the measurement of VO_2 during these protocols, particularly the obstacle course, may have impaired physical performance,⁵¹ so the true change in physiological exertion with and without body armor or personal protective clothing during such tasks remains unknown.

It is apparent that there are gaps in the literature in relation to the objective exertion measures observed when wearing protective garments such as body armor during high-intensity, intermittent exercise or work tasks. Subjective scales, such as Borg's rating of perceived exertion (RPE),⁵⁴ may, however, provide further insight into the physiological exertion experienced when wearing body armor.^{10,55} Though not yet reported for high-intensity, repeated military work tasks, RPE and the effects of personal protective clothing and equipment have been examined during various types of activity, including slow and moderate treadmill walking,¹⁰ measurements of gross arm movement,⁵⁵ and during simulated urban firefighting¹⁶—the latter sharing the repeated, intermittent material-handling profile of military work, albeit at a lower intensity. Participants' RPE values during a "target touching task" and a "cranking task" increased with load, with RPE values significantly higher for the heaviest garment condition (2.75 kg) when compared to the lightest garment (0.06 kg).⁵⁵ This seemed to be particularly evident during the "cranking task," where subjects rotated a handle on a hand ergometer at a moderate pace.⁵⁵ This task, which utilizes upper body strength and endurance, may serve as a proxy (albeit a weak one) for how military manual-handling movements such as "lift" and "carry"¹⁹⁻²¹ may be affected by weighted garments, such as body armor. It gives little insight, however, into how other tasks pertinent to military success (i.e., running, crawling, climbing)¹⁹⁻²¹ would be impaired (if at all). Ricciardi et al¹⁰ also observed significantly higher RPE values for both the slow and moderate treadmill walking test conditions when wearing body armor compared to the without armor condition. Although this is a good indicator of how prolonged load carriage will be impaired by body armor, it gives no insight into how the performance of other tasks identified by military task analyses¹⁹⁻²¹ will be affected.

Payne et al¹⁶ utilized the RPE scale in their study examining the effect of personal protective clothing on physiological and psychological responses during simulated firefighting work. RPEs were made by each participant following the completion of certain firefighter-specific work tasks, at minutes 6, 11, 20, and 27.¹⁶ No statistically significant difference was observed in RPE values between the different types of suits worn.¹⁶ However, it is unclear whether the additional load imposed by the firefighters personal protective clothing

and equipment is comparable to the load imposed by military body armor.¹⁰ Further research of the subjective exertion experienced when wearing different body armor ensembles during repeated, intermittent and high-intensity, military-specific tasks is, therefore, required.

SUMMARY

Armed forces worldwide utilize some form of body armor as part of their personal protective system in operational situations.¹⁰ This situation has been exacerbated by the advent of unconventional warfare and the use of IEDs.^{2,5} These hazards now form a new threat to the modern soldier.^{2,5} Unfortunately, the successful performance of military tasks and the protection against hazards often have conflicting requirements.^{10,14,27} There is some evidence to show that the performance of prolonged treadmill walking is adversely affected by body armor,^{12,13,15} as well as high-intensity maximal efforts on a military-style obstacle course.¹¹ It is also possible that the observed performance decrements may be exacerbated when soldiers are carrying their full combat load in addition to their protective body armor, but the precise relationship between the degree of performance decrement with increasing equipment load is yet to be identified. The effect that body armor has on the performance of intermittent or repeated high-intensity military work and the physiological and subjective responses to such work also remains unknown. As these types of tasks have been shown to be paramount to successful military performance,^{11,26} research into this area is necessary and warranted.

FUTURE DIRECTIONS

Further research into the performance decrements incurred by body armor and the physiological and subjective mechanisms behind such decrements (should they occur) across a range of military-specific tasks is required to ensure the highest possible level of safety and effectiveness of armed forces. Researchers in this area should endeavor to utilize adequate participant numbers to give statistical power to the research, therefore ensuring meaningful trends become apparent. Additionally, researchers should employ a control condition in their study design to allow for a global assessment of the performance consequences, physiological and subjective responses caused by the use of body armor. Further, exploring the effects of body armor during a range of environmental conditions (i.e., temperature, wind speed) will allow for the extrapolation of results to specific areas and populations of interest.

Aside from the acute performance and physiological decrements incurred by body armor, little is known about the long-term impacts for soldiers repeatedly and extensively wearing armor during deployment. Chronic body armor wear may contribute to the increasing incidence of noncombative, musculoskeletal injuries. In contrast, it may be possible that personnel undergo subjective physiological or performance adaptations that allow them to perform their daily tasks adequately

although having maximum protection. Longitudinal evidence from the field is likely to be associative at best given the absurdity of assigning soldiers to a "control" group who perform their duties without armor. Though such research would be more achievable away from the battleground, whether the intervention period could last long enough for adaptation or injury to occur (and the ethical concerns over the latter) is debatable. Nonetheless, the persistent tension between increased thoracic protection in combat vs. decreased physical performance and increased physiological, thermal, and subjective stress remains to be resolved and compels armor manufacturers to design less cumbersome garments with the same level of protection.

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