The Effects of Military Body Armour on Trunk and Hip Kinematics During Performance of Manual Handling Tasks

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Abstract

Musculoskeletal injuries are reported as burdening the military. An identified risk factor for injury is carrying heavy loads, however soldiers are also required to wear their load as body armour. To investigate the effects of body armour on trunk and hip kinematics during military-specific manual handling tasks, 16 males completed three tasks while wearing each of four body armour conditions plus a control. Three-dimensional motion analysis captured and quantified all kinematic data. Average trunk flexion for the weightiest armour type was higher compared with control during the carry component of the ammunition box lift ($p<0.001$) and sandbag lift tasks ($p<0.001$). Trunk rotation ROM was lower for all armour types compared with control during the ammunition box place component ($p<0.001$). The altered kinematics with body armour occurred independent of armour design. In order to optimise armour design, manufacturers need to work with end-users to explore how armour configurations interact with range of personal and situational factors in operationally-relevant environments.

Practitioner summary

Musculoskeletal injuries are reported as burdening the military and may relate to body armour wear. Body armour increased trunk flexion and reduced trunk rotation during military-specific lifting and carrying tasks. The altered kinematics may contribute to injury risk, but more research is required.

Key words: Body armour, Biomechanics, Posture, Injury

INTRODUCTION

Musculoskeletal injuries are a significant concern for military organisations. In Australia, data from the Department of Veterans Affairs listed joint sprains and strains, disorders of muscle, tendons and other soft tissue, and arthropathies amongst the most frequently claimed conditions under the Military Rehabilitation and Compensation Act (Department of Veterans' Affairs Australia, 2014). Data from the U.S Armed Forces in 2013 showed that musculoskeletal injuries resulted in 2.1 million medical encounters annually (Nindl et al. 2013), while recent outpatient data showed that musculoskeletal overuse injuries constituted more than 55% of all injury encounters (Jones et al., 2010). Therefore, identifying strategies to reduce the risk of these types of injuries could immediately benefit military organisations.

Modern military personnel operating in the field perform a diverse range of jobs, many of which encompass some form of manual handling. Indeed, military personnel commonly perform lifting, carrying, pushing, and pulling tasks within their various occupations (e.g., combat engineers, mechanics, infantrymen; Wyss and Mäder 2010, Jaenan 2009, Reynolds et al. 2009), including loading/unloading of munitions from trucks to the ground, building sandbag levees for protection, and periods of intense lifting of materials such as food and medical equipment (Jaenan 2009). High exposure to such tasks has been reported to increase the risk of musculoskeletal injury (Punnett and Wegman 2004).

The high frequency of lifting and carrying loads may increase the susceptibility of soldiers to injury (Kemp et al. 2010); a risk possibly exacerbated in soldiers because they also wear load in the form of body armour. Manual-handling tasks cause alterations in forward flexion, lateral flexion, and axial rotation of the spine that have

been shown to associate with musculoskeletal injuries in manual-handling vocations (Vandergrift et al. 2012). In military personnel, Cohen et al. (2011) recently showed an association between manual handling exposure and musculoskeletal injury incidence. However, quantifying injury risk requires an understanding of the frequency, duration, and magnitude of exposure to the risk factors for injury (Van der Beek & Frings-Dresen 1998). The magnitude of exposure refers to the external load that musculoskeletal structures must resist, and may predict the risk of injury due to mechanical load (Bakker et al. 2009). Magnitude can be estimated from a number of sources, including measurement of changes in joint motion.

Numerous studies have consistently demonstrated a compromise in normal postural kinematics during gait (Attwells et al., 2006, Quesada et al., 2000), and while performing other dynamic tasks (Loverro et al. 2014) when soldiers wear body armour and backpacks. Heavy lifting and carrying of load in addition to wearing body armour may increase postural deviations and, in turn, increase the risk of injury. Phillips et al. (2014) reported that wearing body armour increases the duration with which participants adopt a flexed posture compared to no armour. However, the tasks were not specific to the military, and the small number of participants wore only one size and type of body armour. The body armour design may affect the risk of injury with bulkier armour designs limiting trunk range of motion and altering gait kinematics (Hasselquist et al., 2008; Selinger et al., 2010). Due mostly to extreme environmental conditions (e.g., high heat and humidity), recent body armour iterations afford less coverage than previous armour designs. In addition to maintaining thermal comfort (Caldwell et al. 2011), minimal designs may provide ergonomic benefits for the soldier. For example, a smaller, lighter body

armour design could benefit the soldier by reducing the physical burden of torso-borne load carriage when lifting and carrying heavy items.

To the author's knowledge, no studies have determined the influence of body armour design on postural kinematics during military-specific manual handling tasks. Kinematics of the trunk and hips are often used to associate military task performance with musculoskeletal injury risk (Phillips et al. 2014; Attwells et al. 2006, Birrell et al. 2009). Thus, the aim of this study was to first determine how body armour load could affect trunk and hip kinematics during the performance of two common military tasks and, second, to determine if the design of body armour influences the kinematic response. It was hypothesized that wearing body armour would increase trunk and hip forward flexion during manual handling tasks. In addition, bulkier body armour systems would reduce range of motion at the trunk, but result in greater trunk forward flexion because of their greater mass.

METHODS

Study cohort

The study was conducted using a cohort of 16 active males. Individuals were included in the study if they were aged between 18 and 35 years, presented with no current or recent (within six months) musculoskeletal injury, and were free of any disorder or condition that could affect the normal performance of manual handling tasks. Participants in the study gave informed consent prior to the commencement of any data collection. Ethical approval was obtained from the Deakin University

Human Ethics Advisory Group prior to all participant recruitment and testing procedures.

Experimental protocol

A within-subject study design was used to examine three-dimensional trunk kinematics when wearing different configurations of military body armour. Participants performed three military-specific manual handling tasks for each of the four body armour configurations studied plus a 'no armour' control. These armour configurations included a Modular Combat Body Armour System (MCBAS) and three variations of the Tiered Body Armour System (TBAS), referred to hereafter as TBAS1, TBAS2, and TBAS3. Each body armour configuration comprised a standard torso body armour vest that was fitted to participants' based on their anatomical specifications. All participants wore the vest without the addition of extremity protection which was deemed to contribute minimally to the overall load on the spine (Polcyn et al., 2002). Using the small/medium sizing for comparison, the participants' surface area (mass provided in brackets) covered by the MCBAS, TBAS1, TBAS2, and TBAS3 was 5603 mm²(8.6 kg), 2253 mm² (7.0 kg), 2153 mm² (7.3 kg) and 2153 mm² (6.4 kg) respectively. Participants also wore athletic shorts, leather work boots (Taipan, Australia) and a t-shirt under their armour. This ensemble, without the armour was also used in the control condition. The leather work boots approximated those used by Australian military populations. The participants completed the task battery wearing the five different armour configurations (including no armour) in a randomised order. No familiarization trial was permitted prior to each task. Three minutes rest was provided between each task battery, during which time participants changed their armour configuration.

Within each task battery, the participants performed five repetitions of the ammunition box lift and place, an ammunition box lower and place, and sandbag carry and place. The repetitions were self-paced, and participants were permitted 60 s rest between the fifth repetition of one task before moving onto the first repetition of the next task. Participants were free to choose their handling velocity, however, tape was placed for feet positioning and participants were instructed to lift with a squat technique to standardize posture.

Description of tasks

1. Ammunition box lift and place

On instruction participants lifted one 12.5-kg ammunition box from its central handle in each hand (0.28-m deep × 0.14-m wide × 0.18-m high) from the ground forward 1-m to a 1.3-m shelf. The shelf simulated the height of a standard military truck bed. The left box was first placed on the ground and the right box lifted on to the shelf with assistance from the opposite hand, thereafter, the participant lifted the left ammunition box on to the shelf (Figure 1).

2. Ammunition box lower and place

Participants were required to lift the right ammunition box in one hand from the 1.3-m shelf and place it on the ground next to them. Following this, participants lowered the left ammunition box to their side with their left hand, picked up the right box with their right hand, turned 180° to their right and walked 1-m to the starting position for task one where they then placed the boxes.

3. Sandbag lift and place

The participant lifted a 10-kg sandbag (0.40-m deep × 0.29-m wide × 0.06-m high), performed a 180° turn to their right, walked 2-m and proceeded to place the sandbag on to a pre-made 'levee' of five sandbags approximately 0.2-m high (Figure 1).

Assessment of posture

Three dimensional motion analysis was performed using a 12-camera, motion capture system (Raptor-E Digital RealTime, Motion Analysis Corporation, Santa Rosa, CA) to determine the instantaneous positions of retro-reflective markers placed on each subject. Each camera collected data at a rate of 100Hz. A total of 29, 15-mm spherical retro-reflective markers were placed by a trained researcher according to a modified Helen Hayes gait analysis arrangement, deemed appropriate for lifting movements (Moniz-Pereira et al., 2010). Relative error was minimised by placing markers close to bony landmarks to reduce skin movement artefacts. The need to place markers directly onto skin precluded the use of military uniforms, the movement of which would introduce movement artefact into range of motion calculations. An exception was made at the sacral position where the body armour covered the required anatomical landmark. It is acknowledged that because the marker was placed over the body armour (drilling a hole in the body armour was not feasible), it is likely that there was an increased movement artefact at this point. Care was taken to minimise the error, through tight fitting of the armour (to limit extraenous movement) and the use of low velocity, though still operationally relevant tasks (Knapik et al., 2011; Knapik and Sharp, 1998). However, the occlusion

of the sacral marker prevented calculation of the relative angle between the trunk and pelvis.

The motion analysis system was calibrated before all trials to orient the cameras with respect to the lab coordinate system, and define the translation and rotation orders for each plane of motion. With the subject in the anatomical position, the longitudinal axis was upward (y), transverse axis to the left (x) and sagittal axis forward (z). The three-dimensional angles selected originated with rotation about the transverse axis (flexion/extension), the second rotation about the sagittal axis (lateral flexion), and the last rotation about the longitudinal axis (rotation/torsion). In cases where markers were visually occluded, cubic and virtual splines were used to predict marker placement and join missing trajectories (Howarth and Callaghan 2010). Once all data points were completely joined, each capture was smoothed using a fourth order, low-pass Butterworth digital filter at a cut off frequency of 6 Hz. This frequency is classically used in human movement studies (Winter et al., 1974; Challis, 1995). Kinematic data including joint centres and segmental parameters was computed using KinTools software (Motion Analysis Corporation, Santa Rosa, CA). The angle between a line from the midpoint of the two anterior superior iliac spine (ASIS) markers and the midpoint of two acromion markers and the line of the laboratory vertical axis in each plane defined trunk angle. Hip joint angles were defined as the relative angle between the pelvis segment and thigh segment. Each task was split into successive execution phases which denoted a lift, lower, carry, and place component that were defined based on distinct movement patterns apparent within each task. Range of motion was calculated as the difference between maximum and minimum flexion angles within each execution

phase. Average angle values were calculated as the mean angle during each execution phase.

Analytical methods

All statistical analyses were performed using the Statistical Package for the Social Sciences (version 20, IBM, Armonk, NY). Descriptive statistics were presented as mean and standard deviation (SD) for participants' height, weight, and age. Prior to analysis, the distribution of data was confirmed normal using Shapiro-Wilks tests. Once normality was confirmed, a three-way analysis of variance (ANOVA) was performed for each dependent variable to assess whether any significant interactions existed between the fixed factors (task component, condition, and trial number). No interaction was found for trial, thus, all trials were aggregated. A two-way within-subject ANOVA with repeated measures for task component and body armour type was performed to compare the ROM spinal angle variables within each task. When an ANOVA identified a significant (task component $\times$ body armour) interaction, simple effects analyses were performed to determine the significance of these interactions. Significance was set at $p < 0.05$.

RESULTS

Baseline cohort characteristics

In total, data from 16 male participants with anthropometrical characteristics (height; 1.81m, SD 0.08, weight; 74.9 kg, SD 7.5 kg) and age (22 years, SD 1) were statistically analysed. Participants were not military trained, however, these characteristics closely match military recruits (Williams, Rayson, and Jones 2010).

Analysis of task performance

The absolute maximum flexion angle averaged across task components and conditions during the ammunition box lift (58.6° ; 95% CI $53.9 - 63.3^{\circ}$), ammunition box lower (83.5° ; 95% CI $81.5 - 85.5^{\circ}$), and sandbag lift (60.1° ; 95% CI $54.8 - 65.4^{\circ}$), tasks were identified. Trunk axial rotation ROM absolute values across task component and conditions was 13.3° (95% CI $12.4 - 14.3^{\circ}$) for the ammunition box lift, 16.2° (95% CI $15.0 - 17.3^{\circ}$) for the ammunition box lower, and 9.6° (95% CI $9.0 - 10.2^{\circ}$) during the sandbag lift task. No difference in lateral flexion angles between armour conditions was observed during any of the three tasks.

1. Ammunition box lift

A significant interaction between condition and task component was found for trunk axial rotation ROM ($p < 0.001$). During the carry component trunk axial rotation ROM for control was shown to be $5.3^{\circ} \pm 4.8^{\circ}$, $4.2^{\circ} \pm 4.9^{\circ}$, and $4.1^{\circ} \pm 3.3^{\circ}$ higher than MCBAS ($p = 0.005$), TBAS1 ($p = 0.036$), and TBAS2 ($p = 0.002$), respectively. Comparisons between conditions showed average flexion was $3.5^{\circ} \pm 2.4^{\circ}$ ($p = 0.001$) higher for MCBAS, $2.3^{\circ} \pm 2.4^{\circ}$ ($p = 0.009$) for TBAS1, $2.0^{\circ} \pm 2.0^{\circ}$ ($p = 0.009$) for TBAS2, and $1.9^{\circ} \pm 2.0^{\circ}$ ($p = 0.011$) higher for TBAS3 than no armour during the carry component (Fig 2). Comparisons between conditions and the place component revealed that participants trunk axial rotation ROM for control was $11.9^{\circ} \pm 7.7^{\circ}$, $11^{\circ} \pm 8.4^{\circ}$, $11.4^{\circ} \pm 6.2$, and $11.4^{\circ} \pm 6.5^{\circ}$ higher than MCBAS ($p < 0.001$), TBAS1 ($p = 0.001$), TBAS2 ($p < 0.001$), and TBAS3 ($p < 0.001$), respectively (Fig 3). No other variables were significantly different.

2. Ammunition box lower

A significant interaction between condition and task component was found for trunk axial rotation ROM ($p < 0.001$). During the lowering task component trunk axial rotation ROM was $12.1^\circ \pm 5.4^\circ$, $12.7^\circ \pm 6.4^\circ$, $12.8^\circ \pm 4.8^\circ$, and $11.2^\circ \pm 4.7^\circ$ higher in control compared with MCBAS ($p < 0.001$), TBAS1 ($p < 0.001$), TBAS2 ($p < 0.001$), and TBAS3 ($p < 0.001$), respectively. A significant main effect was shown only for condition with maximum hip flexion with MCBAS $9.2^\circ \pm 3.8^\circ$ and TBAS1 $10.6^\circ \pm 4.3^\circ$ higher than no armour ($p < 0.001$).

3. Sandbag lift and place

A significant interaction between condition and task component was found for trunk axial rotation ROM ($p < 0.001$). MCBAS produced a trunk axial rotation ROM that was $2.8^\circ \pm 3.1^\circ$ and $2.4^\circ \pm 2.7^\circ$ higher than TBAS1 ($p = 0.034$) and TBAS2 ($p = 0.027$), respectively. During the carry component of the sandbag task trunk axial rotation ROM was $5.8^\circ \pm 2.6^\circ$, $5.1^\circ \pm 2.6^\circ$, $4.8^\circ \pm 2.8^\circ$, and $4.8^\circ \pm 3.5^\circ$ higher for control compared with MCBAS ($p < 0.001$), TBAS1 ($p < 0.001$), TBAS2 ($p < 0.001$), and TBAS3 ($p < 0.001$), respectively. The average flexion values for MCBAS ($3.7^\circ \pm 0.5^\circ$; $p < 0.001$), TBAS1 ($2.6^\circ \pm 0.8^\circ$; $p = 0.046$), TBAS2 ($2.4^\circ \pm 0.5^\circ$; $p = 0.003$), and TBAS3 ($2.8^\circ \pm 0.5^\circ$; $p = 0.003$) were higher than control during the carriage component for the sandbag task (Fig 2). No significant differences were shown in hip angles.

DISCUSSION

The primary aim of the current study was to determine how body armour load could affect trunk and hip kinematics during the performance of three common military tasks. The findings confirmed the first hypothesis, with the addition of body armour resulted in greater trunk and hip forward flexion during simulated sandbag transport and ammunition box transfer tasks. The secondary aim was to determine if the design of body armour influences the kinematic response. In contrast to the hypothesis, there were no differences between body armour configurations in trunk flexion or range of motion.

Independent of design, the addition of body armour increased trunk and hip forward flexion during simulated sandbag transport and ammunition box transfer tasks. The magnitude, 2 - 4° is similar to the differences in trunk forward flexion observed in previous studies of trunk posture during load carriage (Attwells et al. 2006, Polcyn et al. 2002). The current data also aligns with the relationship demonstrated by Polcyn et al. (2012), who identified that for every 1-N increase in load there was 0.05° greater trunk flexion. Moreover, the increase in trunk flexion reported here in military-specific manual-handling tasks and across a range of body armour designs, adds to recent work by Phillips et al. (2014) who reported similar findings in a single body armour configuration, during more generic squat and toe-touch tests.

The consensus that body armour, independent of design, increases the time spent in trunk flexion, may provide underlying explanations for military injury epidemiology data (Burton et al., 1996; Konitzer et al., 2008). Cross-sectional survey data of military and civilian armed forces personnel demonstrated positive associations between body armour wear time and lower back pain (LBP; Konitzer et al., 2008)

and LBP-related absenteeism (Burton et al., 1996). Although the current data was collected during very short-duration manual-handling tasks, these tasks can be performed repeatedly across a military shift (Wyss and Mäder 2010, Jaenan 2009, Reynolds et al. 2009). It is possible, therefore, that if the subtle, but significant forward flexion observed in the current study and that of Phillips et al. (2014) is sustained for several hours on duty, then body armour may be placing additional pressure on spinal segments. In particular, prolonged forward flexion under load could create laxity in the lumbar viscoelastic tissues (intervertebral discs, ligaments, facet capsules). The ensuing hypermobility can make the spine more vulnerable to compression and shear force injury (Solomonow et al., 2008). This mechanism may, accordingly, contribute to the high prevalence of musculoskeletal injury observed in modern military forces worldwide (Department of Veterans' Affairs Australia, 2014; Nindl et al. 2013).

Independent of design, the addition of body armour restricted trunk axial rotation by as much as 12° compared with the no armour condition. This novel finding seemingly contradicts previous research that showed no change in ROM when wearing body armour systems (Selinger et al. 2010). Inter-study differences in motion capture systems aside, one possible reason for the contrary results may be single versus multi-plane analysis. Selinger et al. (2010) examined solely ROM in single planes and therefore, may not have captured secondary flexion that increased the total ROM in body armour so there was no difference between conditions. The prospect that body armour wearers may forcefully rotate to overcome movement restrictions (Selinger et al., 2010) and achieve task outcomes may also present

another mechanism by which body armour wear contributes to LBP and musculoskeletal injury.

The increased trunk flexion and restricted trunk rotation in the current study occurred independent of the four different body armour design employed. These findings were in contrast to our secondary hypothesis. These observations are, however, most likely attributable to the small variations between MCBAS and TBAS body armour systems. Across the four designs, the difference in surface coverage ranged 0 to 2450 mm², whilst the difference in load was 0.3 to 2.4 kg. It is possible that such subtle differences do not elicit meaningful differences in trunk kinematics at least when worn in isolation. It is not clear whether these small variations become more meaningful when combined with the often heavy (> 50 kg; Drain et al., in press) load carriage requirements of modern military personnel. If body armour variations do not influence kinematics within a certain load range, this conclusion should not preclude military organisations and body armour manufacturers continuing to advance their design. Instead, it may be that, for a given load, end-user decision making regarding optimal armour configurations depends on other variables. Indeed, our group has recently shown that body armour configurations can differentially affect the wearer's speed across a range of job-specific tasks (Larsen et al., 2014). These recent results, together with those reported in the current study suggest armour manufacturers need to invest in multi-variate evaluations of their designs, to maximise user acceptance.

The current study examined the range of motion of healthy civilians wearing the different configurations of body armour. The value of this approach was to isolate the impact of the armour on task-specific movements, without introducing

confounders from any adjustments in technique that may be associated with years of wearing the armour and / or injuries sustained in service. Furthermore, the results in the current study are, therefore, applicable to military recruits experiencing their first exposure to body armour which may come through a) job-specific task assessments (Silk and Billing, 2013) or b) early in their military service. From the foundations laid in the current study, an obvious next step is to extend this research into more operationally relevant environments. Two immediate candidates could be confined working spaces where restrictions in trunk rotation could meaningfully inhibit task performance or long duration shifts where prolonged forward flexion could increase injury risk. In the latter case, future research could explore how movement fatigue interact with different body armour conditions to impact range of motion, task performance and injury risk. A related area of research would be to explore how incumbent (either full-time or reservist) workers perform their duties over a shift in different configurations. It is possible, however, that over a prolonged deployment, the lifting technique and therefore, their range of motion, could change. Such comparisons may not only need to take into account fatigue across a shift, but also the impact of task experience and any pre-existing injury that could be interacting with the body armour to influence range of motion and task performance. These factors were not a focus of the current study. Capturing the possible influence that personal and situational factors have on an individual's range of motion will require much larger sample sizes. The increase in statistical power is not only required to quantify possible moderating factors, but also to absorb the likely increase in measurement error associated with a field environment, where markers can be occluded due to uniforms and equipment positions, for example.

Researchers need to carefully weigh these trade-offs when balancing precise measurements against high fidelity testing environments.

Conclusion

It is evident from this study that wearing body armour alters trunk and hip kinematics when performing manual handling tasks. While fundamental for protection, body armour may increase the risk of developing musculoskeletal injuries,. Both time spent in a flexed posture during lifting tasks and average flexion during load carriage increased with the addition of body armour. Additionally, body armour restricted multi-planar movement. Although the addition of body armour altered movement kinematics relative to control conditions, there were no differences observed between the armour configurations trialled. These latter findings could indicate that more subtle variations in body armour mass or coverage may not be influential in posture or movement kinematics. However, evaluation of other dependent variables, particularly in more operationally-relevant environments, with incumbent personnel, should be the focus of researchers seeking to assist manufactures and end-users striving to optimise body armour configuration for health and safety.

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A

B

Figure 1 – Laboratory setup during completion of the ammunition box lift (A) and sandbag lift (B) tasks

Figure 2 – Comparisons between conditions for trunk flexion during the carry component of the ammunition box lift (A) and sandbag lift (B) tasks

Ammunition box place component

Figure 3 – Comparisons between conditions for trunk rotation ROM during the ammunition box lift task