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Head-torso coordination in police officers wearing loaded tactical vests during running

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ABSTRACT

Background: The influence of load carriage in operational police officers is not well understood despite a relatively high injury rate. Assessing load related changes in head and torso coordination may provide valuable insight into plausible injury mechanisms.
Research question: Do typical police tactical vest loads alter head and torso coordination during running?
Methods: Thirty-eight UK police officers ran at a self-selected pace (>2 ms^{-1}) on a non-motorised treadmill in four vest load conditions (unloaded, and low, high and evenly distributed loads). Peak head and torso tilt, and peak vest displacement were compared between all four conditions. Timings between vest and torso change of direction were compared between the three loaded conditions. The coupling angle between the head and torso calculated using modified vector coding were compared between unloaded and each loaded conditions using Statistical Parametric Mapping.
Results: No significant differences were found between conditions for peak head or torso tilt alone ($p > 0.05$). Loading equipment low on the vest led to significantly greater mediolateral vest displacements (38 mm) away from the torso than a high (34 mm) or evenly distributed (30 mm) conditions. The vest was found to change direction vertically before the torso in the anterior-posterior direction, and then influence torso motion. The loaded conditions changed the head-torso coupling from in-phase (with head-dominancy) to anti-phase (with torso dominancy) between 55% and 77% stance. Anti-phase with a relatively stationary head and the torso rotating forward likely places a greater concentric demand on the posterior neck muscles relative to unloaded running.
Significance: Current tactical vest designs allow significant extra displacement of load away from the body during running, altering coordination at the head and torso.

1. Introduction

The modern police force is required to carry operational equipment such as body armour, restraining devices, and radios over repeated daily shifts. The equipment carried is determined by operational requirements rather than the capacity of an officer to bear this load. Occupational load carriage is associated with an increased risk of injury [1]. For example, Canadian police populations display high injury rates in comparison to other occupations [2]. Approximately 1047 working weeks are lost per 1000 police officers due to injury with a rate of 90 injuries per 1000 officers, compared to 28 injuries per 1000 workers in non-first-responder occupations [3]. While load was not identified in these studies, associations between load carriage and similar injuries have been observed in military populations [4]. Database analysis of injury within a UK police force identified that 80% of officers experience neck pain in a 12-month period. This was found to be more prevalent in vest users than non-vest users.

The effect of load carriage on biomechanics has been assessed in military populations. Increasing rucksack loading leads to greater anterior torso lean and a more anterior head posture (e.g. [5,6]). Police populations, however, differ in the typical loads carried, load placement, and operational tasks. Military populations will typically carry loads up

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Fig. 1. Left top: Example of actual police loading distribution. Left bottom: example of vest loaded with pouches and sandbags (Distributed condition). Right top to bottom: diagrammatic layout of pouches on vest (High, Distributed, Low). Numbers to the left of items represent item mass (g).

to 54.5 kg, depending on mission requirements [7]. In contrast, police officers carry body armour and multiple light objects required for a shift, totalling approximately 3.5 kg [8]. Whilst there is some assessment of the biomechanical effects of military loads [9], there is limited understanding of the effects of loads typically worn by police officers, and thus limited understanding of the mechanisms linked to the high rate of injury seen in these populations.

Operational police officers in the UK are encouraged to wear equipment distributed on a tactical vest, but may also use a belt, or alternate between belt and vest. The individual approaches to equipment loading further confound understanding of the links between load carriage and injury in police populations. A tactical vest is advantageous as it can be fitted with an industry-standard pouch system (e.g. Modular Lightweight Load-carrying Equipment (MOLLE)) which allows for equipment pouches to be flexibly distributed across the torso, however a vest will load the upper body more than a belt which only loads the pelvis. Given the high rate of injury [2,3], lost work hours, and poor understanding of likely injury mechanisms, investigation is warranted to better understand how typical police loads affect the biomechanics of daily police tasks, such as running. This information would help to inform guidelines for equipment manufacturers, and training to alleviate the burden of injury.

Biomechanical assessment of injury risk has typically focused on discrete measures, such as peak forces or single joint or segment kinematics (e.g. lower limb ranges of motion in military load carriage [9]). As limbs connect, work together and interact, further insight can be gained through analysis of segment coordination, which has also proven sensitive in identifying subtle differences [10] and discerning differences in head-trunk co-ordination [11]. Modified vector coding allows for the quantification of coordination between two segments by identifying segment interactions across stance [12]. Assessments of segment coordination could provide useful indicators as to the stress and strain of soft tissue structures connecting two segments [12–14]. The aim of this study, therefore, was to quantify head and torso kinematics and coordination during loaded running in operational police officers. It was hypothesised that load carriage would lead to 1) changes in head and torso coordination during stance, and 2) a more upright torso and head orientation during stance to counterbalance the anterior loading of a tactical vest configuration.

2. Methods

2.1. Participants

Following institutional ethical approval, 38 police officers from a UK police force were recruited (24 males (M); age (years) M 44 ± 7, F 40 ± 9; mass (kg) M 89.6 ± 14.4, F 80.3 ± 16.2; height (m) M 1.78 ± 0.08, F 1.68 ± 0.06). Participants were recruited through a regional police force and represented a range of operational roles. Those reporting current injury affecting running and walking or their normal duties were excluded, but no exclusions were made based on previous injury. Prior to completing experimental trials, mass was measured both in their sportswear, in their own soft body armour, and in body armour plus their equipment setup.

2.2. Experimental Protocol

Following an individual warm up and familiarisation with a motorless treadmill (Woodway Curve, Woodway, U.S.A.) participants undertook unloaded (control) treadmill running at a self-selected pace (>2 ms^{-1}) for 60 s, and then each of three loaded vest configurations in a randomised order for each participant. In addition, participants wore their own soft body armour under the vests. Adequate rest was provided between all trials. Kinematic data for the last 30 s of each trial was recorded at 150 Hz using fifteen Raptor cameras through Cortex software (version 7.02 Motion Analysis Corporation, CA).

Ten, 10.5 mm retro-reflective markers were placed at anatomical locations on the participant. Specifically, a headband containing four markers was placed on the cranium so that the bottom of the band was located approximately level with the eyebrows and in line with the top of the ear. Due to vest obstruction, markers placed on the left and right deltoid centres (from a sagittal view) were used to identify upper torso motion, and markers on both greater trochanters were used to approximate pelvis location. Markers placed on both the left and right lateral malleoli were used to identify stance events. Virtual markers were calculated for the mid-upper-torso as the mid-point between the two deltoid markers and for the mid-pelvis as the mid-point between the two greater trochanter markers. The geometric centre of the head was calculated as the mean of the four marker coordinates of the head. The torso segment was defined from the mid-upper-torso to the mid-pelvis. When participants wore a loaded vest, additional markers were placed on the shoulder straps approximately above both acromion processes and at the lowest point of the zip (bottom of the vest). The upper vest was calculated as the midpoint between the shoulder strap markers, while the lower zip marker represented the lower half of the vest.

Tactical vest trials were conducted using a commercially available vest (Fig. 1), used globally by police forces (P9MPS, Arktis Endurance Textiles Ltd., Exeter, UK). The vest was worn on top of the participant's soft body armour and fitted to manufacturer guidelines. Equipment load across the tactical vest was simulated using customised sandbags replicating the mass of typically worn equipment from a single sample set (Fig. 1). Sandbags were placed in appropriately sized MOLLE pouches (CSM01; MDM02; or TAM15L; Arktis Endurance Textiles Ltd) and attached to the vest in one of the three configurations ($Vest_{Low}$, $Vest_{Dist}$ or $Vest_{High}$; Fig. 1). Specific items are loaded in fixed locations by officers for operational purposes, therefore these were accounted for in the experimental configurations. Specifically, pouches representing the radio, torch and bodycam were positioned on the shoulders in all conditions, and the handcuffs, restraints and incapacitant spray remained on the lowest MOLLE row. The vest was loaded approximately symmetrically in the frontal plane across all configurations. Due to the individual nature of body armour fitting, various brands and sizing of armour were worn in this study (mean armour mass 2.6 ± 0.65 kg).

2.3. Data analysis

Analysis was conducted using a custom written MATLAB (R2020a, The Mathworks, MA, USA) script. Raw marker coordinates were filtered using a second order Butterworth filter with a cut-off frequency of 6 Hz. Discrete stance phases were identified for the right leg by defining the points of touchdown and take-off using the right lateral malleolus marker based on [15]. Following the identification of the right leg stance phases, data were extracted and time normalised to 101 frames per stance throughout each 30 s trial. Steps which contained outlying data or unusual movement were identified and removed using a functional median distance depth parameter [16], on average seven steps (23%) were removed per participant, per condition. Examination of curves suggests those discarded to be outliers, potentially those stances where participants were adjusting equipment vests.

2.4. Head and Torso Tilt

Sagittal head and torso tilt were calculated relative to the laboratory reference axes using the Cardan-Euler rotation sequence, with positive representing forward lean relative to the vertical axes in the direction of travel. Peak head and torso tilt and relative displacements were offset using the mean head and torso lean and horizontal displacement in each individual standing trial. The average across all steps was then calculated. The coupling angle between the head and torso in the sagittal plane during stance was calculated using modified vector coding and coupling angles at each time point were classified into one of 8 ranks using the co-ordination classification system proposed by Needham [12].

2.5. Displacement of head geometric centre and Torso Centre of mass

Horizontal displacement between the head and torso segment centres in the sagittal plane was calculated for each stance period, with positive defined when the head centre was further forward than the torso centre.

2.6. Relative vest displacements and timings

Peak displacement of the calculated upper and lower vest segments from the corresponding centres of the torso and pelvis segments in all three cardinal directions relative to the orientation of the body and average displacement across stance was removed from the displacement timeseries to normalise these data. Timings of change of direction of the vest segments were also compared to the corresponding torso segments in the three cardinal directions during stance.

2.7. Statistical analysis

Statistical analysis for the discrete variables was conducted in SPSS

Table 1
Peak head and torso lean relative to vertical and peak horizontal head-torso displacement compared between conditions.

Variable	Mean ± SD				p	F
	Control	$Vest_{Low}$	$Vest_{Dist}$	$Vest_{High}$		
Peak sagittal head tilt (deg)	13 ± 9	10 ± 9	9 ± 9	11 ± 9	0.125	2.015
Peak sagittal torso tilt (deg)	9 ± 6	8 ± 5	7 ± 6	7 ± 6	0.054	2.634
Peak head-torso displacement (mm)	116 ± 36	118 ± 35	117 ± 37	115 ± 35	0.833	0.19

Table 2
Peak displacement between vest and torso segments compared between conditions.

		Peak Displacement (mm)				
Direction	Upper or Lower vest	$Vest_{Low}$	$Vest_{Dist}$	$Vest_{High}$	p	F
Vertical	Upper	8 ± 2	9 ± 3	9 ± 3	0.127	2.502
Mediolateral	**Upper**	**7 ± 5 ***	**9 ± 5 ***	**9 ± 5**	**0.01**	**5.329**
Anterior-posterior	Upper	5 ± 2	6 ± 5	6 ± 2	0.595	0.347
Vertical	Lower	17 ± 4	15 ± 3	15 ± 3	0.252	1.509
Mediolateral	**Lower**	**38 ± 6*+**	**34 ± 8***	**30 ± 8+**	**< 0.001**	**16.714**
Anterior-posterior	Lower	13 ± 6	13 ± 4	13 ± 3	0.973	0.004

Bold text indicates significance ($p < 0.05$), * denotes significance between Vestlow and VestDist; +denotes significance between Vestlow and VestHigh

(Version 25.0, SPSS Inc., Chicago, IL, USA). A Shapiro-Wilk test was used to confirm normality. Discrete means were compared between groups using a one-way repeated measures ANOVA (control and three loaded conditions) for head and torso tilt as well as head, torso, and vest displacement. Vest and torso timing differences were compared using a two by three repeated measures ANOVA (two segment vs three loading conditions). Bonferroni adjusted post-hoc t-tests were used where significant effects were identified. Statistical parametric mapping (SPM; http://www.spm1d.org; [17] with a one-way repeated measures ANOVA control and three loaded conditions) was used to analyse head and torso tilt time-series data. Due to the circular nature of coupling angles, 1D statistical non-parametric mapping (fctSnPM; [18]) was used to analyse categorised coupling angle time-series [19]. For all statistical tests an alpha of 0.05 was set a priori.

3. Results

3.1. Discrete analysis

On average 23 ± 5 stances were analysed per condition per participant. In contrast to hypothesis 2, no significant differences were found for peak head or torso tilt between conditions (Table 1). There were also no significant differences in head-torso peak displacement (Table 1). When comparing peak vest-torso displacements, significant differences were found in the mediolateral direction between conditions for both the upper and lower vest (Table 2). Post-hoc analysis highlighted significant differences between the $Vest_{Low}$ and $Vest_{Dist}$ conditions ($p = 0.047$), and $Vest_{Low}$ and $Vest_{High}$ ($p < 0.001$). No significant differences, however, were identified between $Vest_{High}$ and $Vest_{Dist}$ conditions in the mediolateral direction for the lower vest and torso. Significant interaction effects were also identified in the upper vest displacement in the mediolateral direction (Table 2). Post hoc analysis showed the distributed condition had greater displacement than the low load condition ($p = 0.008$), but no differences in the other directions.

Significant main effects were found between the vest and torso motion change of direction timing, both in the upper and lower torso vest pairings for all three loading distributions (Table 3). In the vertical orientation, the vest lags behind the respective body segment when shifting from a downward to an upward motion (mean 1.9% and 2.3% of stance later for upper and lower vest respectively). In contrast, in the anterior-posterior direction the vest changes direction from forwards to backwards before the torso (mean 7.7% and 8.0% of stance earlier for upper torso and pelvis respectively). No significant main effects were found for load distribution in any direction. A significant interaction effect was found in the vertical direction of the upper vest ($p = 0.001$, $F=8.23$), showing that the timing differences between the vest and torso were smaller in the $Vest_{Low}$ condition (1.4% stance) compared to the $Vest_{High}$ (2% stance) or $Vest_{Dist}$ (2.1% stance) conditions in the upper vest-torso region.

3.2. Timeseries analysis

Statistical parametric mapping (SPM) analysis of the head tilt timeseries revealed no significant differences between any of the loading conditions. Torso tilt revealed a significant difference between conditions from 36% to 56% of stance ($p = 0.044$). Visual inspection of the

Table 3
Timing of vest and torso segments changing direction compared between conditions.

		Time of direction change (% Stance)				
		Load Distribution				
Direction	**Segment**	$Vest_{Low}$	$Vest_{Dist}$	$Vest_{High}$	$P_{vest\text{-}torso}$	F
Anterior-posterior	**Upper Vest**	**33.8 ± 9.0**	**34.2 ± 10.9**	**33.9 ± 10.6**	**0.001**	**14.64**
	Upper Torso	**40.6 ± 10.0**	**42.6 ± 12.5**	**41.9 ± 12.2**		
	Lower Vest	**64.2 ± 7.9**	**62.2 ± 7.7**	**61.0 ± 5.2**	**0.027**	**6.95**
	Pelvis	**72.2 ± 7.5**	**69.8 ± 7.9**	**69.5 ± 7.9**		
Vertical	**Upper Vest**	**43.1 ± 3.9**	**43.3 ± 3.9**	**43.5 ± 3.9**	**≤ 0.001**	**50.13**
	Upper Torso	**41.6 ± 3.1**	**41.2 ± 3.3**	**41.5 ± 3.2**		
	Lower Vest	**42.7 ± 3.5**	**43.2 ± 4.1**	**42.7 ± 3.9**	**0.004**	**14.17**
	Pelvis	**40.9 ± 6.1**	**40.7 ± 4.5**	**40.1 ± 4.2**		

Bold text indicates significance ($p < 0.05$), timing differences were different between vest and torso in all directions. Note: The vest was found not to change direction during stance in the mediolateral direction, and therefore these results are not included here.

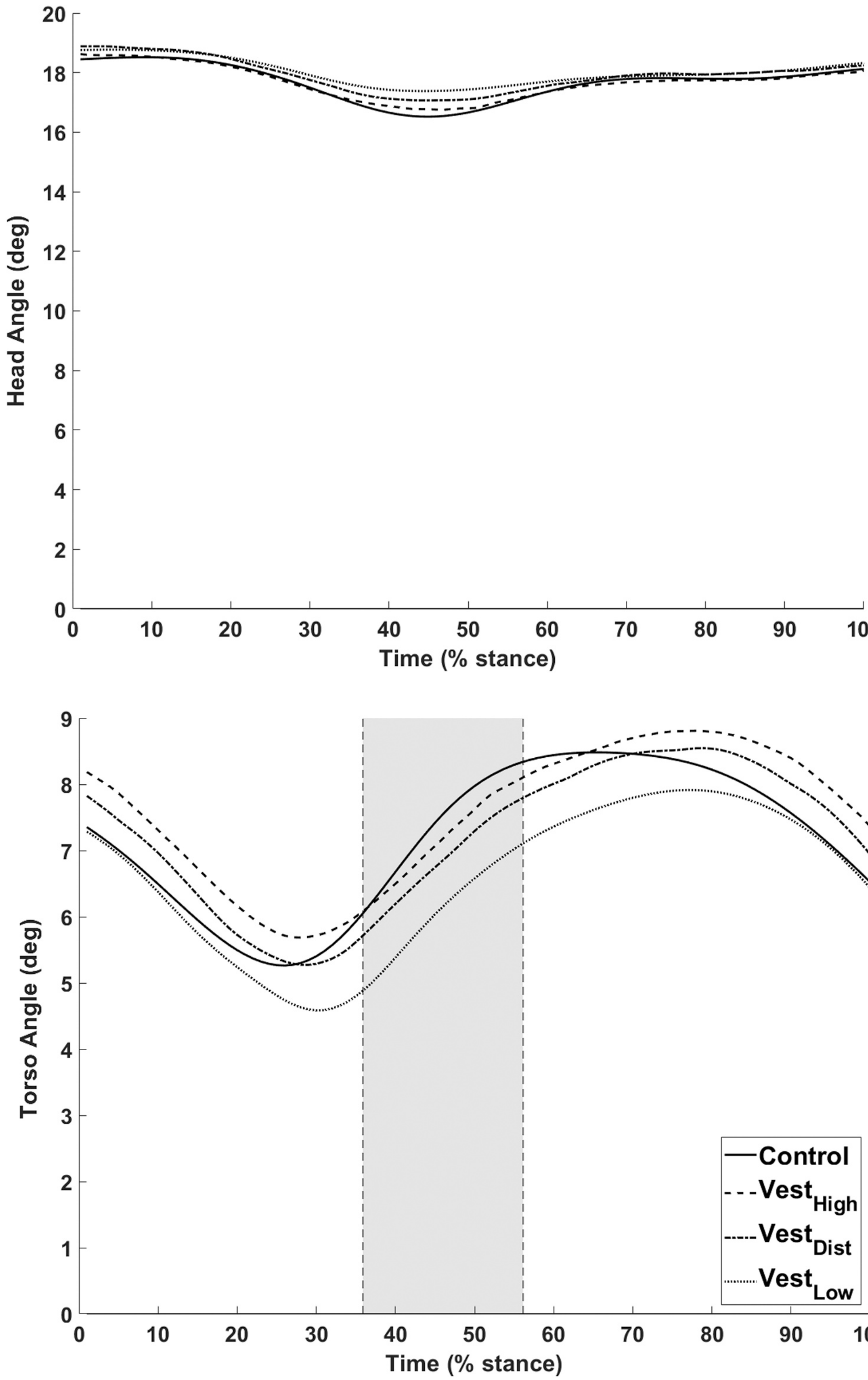

Fig. 2. Top: Mean timeseries for head forward lean compared to vertical (positive represents forward lean) Bottom: Mean timeseries for torso forward lean compared to vertical (positive represents forward lean). Vertical shading represents period of significant difference between conditions as identified using SPM.

mean timeseries reveals the control condition to have a steeper gradient during the period of significance, and an earlier peak than when compared to the loaded conditions (Fig. 2). fctSnPM analysis of coupling angle categories identified a significant difference between conditions from 56% to 77% of stance ($p = 0.045$) (Fig. 3), post-hoc tests showed that the Control condition was significantly different to other conditions (p values; $Vest_{High}$=0.01, $Vest_{Dist}$=0.005, $Vest_{Low}$=0.005) but no differences between loaded conditions.

4. Discussion

This study compared head, torso and tactical vest kinematics, as well as segment coordination, during loaded running in operational police officers wearing typical loads. The research aim was to investigate how tactical vest loading may alter kinematics that may increase the risk of injury in police officers. Differences were found in head-torso coupling angles in the sagittal plane when officers ran with loaded tactical vests

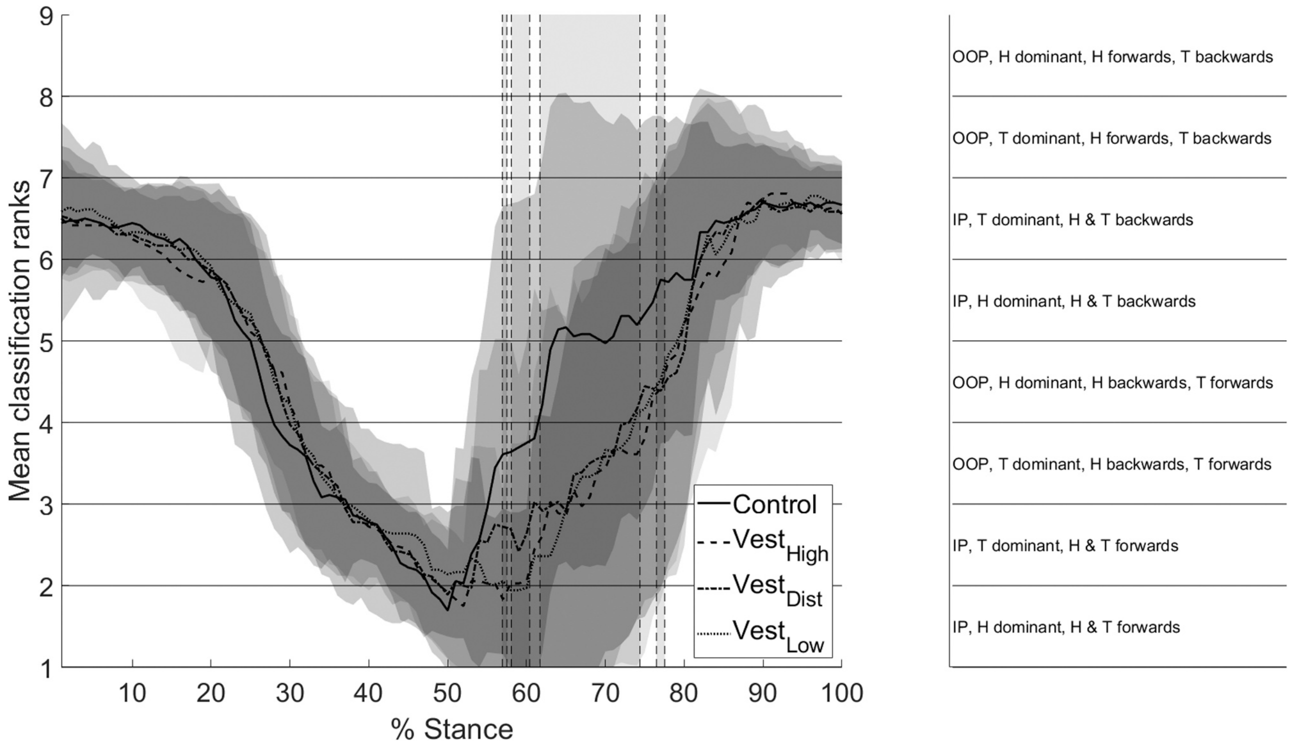

Fig. 3. Mean timeseries of coupling angle categories of head and torso sagittal segment orientations for control and the three loaded conditions. Vertical shading represents periods of significant difference between conditions. Coordination frequency bins (Needham et al., 2015) and segment directions are labelled on the axes to the right of the classification timeseries; H= head, T = torso, IP=In Phase, OOP= Out of Phase.

compared to when they ran unloaded. The results of the current study show that whilst loads typically worn by police officers do not affect head displacement during running, the torso orientation is altered. Further, head-torso coupling was altered with tactical vest loading during running between 56% and 77% of stance which is when the weight of the vest is accepted by the body. Previous studies of military populations have found a change in torso lean and head posture with heavy loading (8–50 kg), usually involving a rucksack [6,7]. Results from Attwells et al. [6] demonstrated that forward torso lean increases by as much as 17° between the lightest and heaviest conditions, with similar findings in head tilt. However, in these military studies the loads are much heavier than the loads used in this study therefore kinematic changes with loading may be subtler in police populations.

Comparison of vest and torso kinematics show that both the upper and lower portions of the vest change directions at different times to the torso. On average the lower part of the vest changes direction in the anterior-posterior direction 8.03% earlier in stance than the torso and 2.3% later than the torso in the vertical direction (Table 3). The differences in head-torso coordination, identified with the coupling angles in the second half of stance, are likely part caused by the later impact timing of the vest pulling on the torso and altering torso kinematics whilst the head stabilises the visual field [20]. The torso accepts the weight of the vest moving vertically down and against the direction of travel whilst the torso is moving up and forwards towards toe off. At this point, the torso positioning is pulled out of position by the mass of the vest impacting the torso and moving against it. In order to keep the head level during gait, the smaller postural neck muscles must be engaged appropriately in accordance with the gait cycle [20]. Alterations to this pattern, likely resulting in excessive loading of these small muscles, could suggest a plausible mechanism for the higher prevalence of injuries seen by police populations. Differences in upper and lower vest displacements relative to the torso also highlight areas where a tactical vest may not appropriately fit the torso. These findings are suggestive of the need for location specific fitting mechanisms to support the loading requirements in the police population. Based on the findings within this study, however, it is possible that the location of the load may not be as important as the way the load is fitted to the torso when considering smaller loads such as those seen in this study.

The vest had large displacements of up to 38 mm away from the torso in the mediolateral direction, particularly with the lower vest. Peak vest displacement occurs at the time of the vest changing direction (Table 3). These displacements were significantly different between loading conditions, and greatest in the low loading (Vest$_{Low}$) condition. Neither the upper or lower vest changed direction in the mediolateral direction during stance, suggesting that it was still moving laterally at toe off and reached the end of its motion in the flight phase, thus changing direction prior to touchdown. Displacements in the anterior-posterior direction also help to explain the vest and torso interaction. During the gait cycle, at foot contact the torso begins to decelerate. At this point in time the vest continues to move separately to the torso. The vest then reaches the end range of the inelastic fabric and stops by pulling on the torso. In this study the vests were all fitted and adjusted as specified by the manufacturer's guidelines, but even with appropriate fitting there is up to 38 mm of movement relative to the torso. Pairing these findings with the lack of differences in head-torso coordination between loaded conditions, it supports the notion that the fit of tactical vest load carriage vest is more important than the specific load distribution. Specific recommendations for operational load placement locations on a tactical vest remain unclear, however it is evident that load carriage equipment should be well fitted to the torso.

The lack of any significant differences in the discrete biomechanical variables, and even single time-series analysis, supports the importance of coordination analysis with the human-equipment interaction. Previous work supports that timeseries coordination analyses can provide effective methods to detect subtle biomechanical changes as shown in this study [11,21].

Care was taken to enhance the ecological validity of the data collected in this study by using typical loads, equipment and distributions. However, there are a number of factors that may influence the injury risk in police populations that were not accounted for here. The running task was conducted on a non-motorised treadmill, and whilst there is evidence that there are different mechanical and physiological effects when compared to a motorised treadmill [22-24], it remains unclear how comparable this is to overground running. Additionally, police may wear other equipment which may affect running gait further and therefore increase the risk of developing a neck, shoulder, or back injury. Lastly, officers undertake many varied other tasks not investigated here such as driving, apprehending a suspect on the ground, and desk work, all of which may contribute to injury risk [25,26]. Additionally, the methods for modelling the torso segment are simplified due to the difficulty of placing markers whilst participants wear both armour and tactical vest although we are confident that the variables calculated here adequately represent the torso motion for comparison between the conditions.

Despite these limitations, this work demonstrates the changes in head-torso coordination seen with loaded gait when compared to unloaded. This suggests possible avenues for future research into neck pain from vests used by police officers, such as altering of load carriage equipment and re-assessing changes in coordination dynamics.

Declaration of Competing Interest

This project formed part of a Knowledge Transfer Partnership, funded through Innovate UK in partnership with Arktis Endurance Textiles Ltd. The sponsors were not involved in the study design, collection, analysis or interpretation of data. The sponsor did not have a role in the writing or submission of this manuscript. The authors have no financial conflicts of interest to disclose.

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