Centre of pressure, vertical ground reaction forces and neuromuscular responses of special-forces soldiers to 43km load carriage in the field

Scales, J., O'Driscoll, J., Coleman, D., Giannoglou, D, Gkougkoulis, I, Ntontis, I, Zisopoulou, C and Brown, M.

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Introduction

Occupational load carriage is unique in military settings, as participants are required to carry absolute loads prescribed by the requirements of the task, as opposed to the soldier's physical capacity[1]. Special Operation Forces soldiers have experience and training beyond their infantry trained counterparts and undergo highly demanding training programmes. Such programmes make the chance of neuromuscular function loss during load carriage tasks high, reducing control of joint action and increasing the likelihood of injury[2]. Ankle sprains are one of the most frequent injuries, substantially limiting operational duty days[3]. However, due to the secretive nature of Special Operation Forces, little research examining load carriage injury risk has been reported on this population, with most research focusing on military recruit populations[4,5].

A frequently used method of assessing muscle function is measuring the change in power or the force generating capacity of a muscle group. A commonly used field-based method of assessing muscle function is via a vertical jump test (VJT) due to the minimal equipment required. Indeed, a reduction in lower limb power has been observed in Royal Marine recruits following 12.8km loaded marches via VJT[4]

Ankle injury during can occur via three primary mechanisms. The first is a collapse of the subtalar joint in response reduced lower limb muscle function. Load carriage research has previously demonstrated changes in mean frequency and a shift in recruitment pattern in the peroneus longus when studied by electromyography[6]. The authors concluded that a reduction in ankle stability would follow, exposing soldiers to an increased risk of ankle injury. Indeed, ankle sprain has been viewed as the result of insufficient ankle control by the lower leg muscles for some time[7-9]. When fatigued, laterally placed muscles such as the peroneus longus delay active action by approximately 60ms[9-10] providing reduced support for the ankle during mid-stance. Prior research has used a step up protocol designed to intentionally fatigue shank muscles (defined by a VJT score of 80% max) and subsequently demonstrated that when fatigued participants experienced concurrent Centre of Pressure (CoP) displacement and rate increase (a commonly used method of assessing ankle stability) at mid-stance and delay of peroneus longus activation time[2].

A second mechanism of injury is via increased impact forces through lower limb bone via loss of muscle function during exercise. Overuse injury during load carriage has been understood to occur as a result of deterioration of the muscular ability to generate force[11]. This is principally because the force generating muscles are required to work eccentrically to mitigate the vertical effect of the load[2]. Subsequently the loss in force means the ability to effectively reduce the rate of force application during the foot-ground impact is diminished. Previous research has identified acute increases in key variables of vertical ground reaction forces (VGRF); namely the peak loading force, mid-stance force minimum and late stance thrust maximum in response to load carriage in soldiers[11]. During extended periods of load carriage these elevated ground reaction forces may accumulate into stress fractures.

A third mechanism of injury is eversion ankle sprain. During normal gait, there is a slight medial displacement of CoP as the medially placed muscles activate to reduce the body load during heel contact[12] before bringing the foot back into normal alignment. As it is well documented that load carriage instigates fatigue of the whole lower limb[2-7], which includes a delay in muscle activation time[2,7]. It is possible to postulate that load carriage may significantly increase CoP rate and displacement at immediately at heel contact as the muscles activate slower, which may increase medial deviation at heel contact increasing likelihood of ankle eversion sprain.

The primary aim of this study was to evaluate CoP characterised following an extreme duration load carriage task conducted by Special Operation Forces soldiers with particular focus on medial deviation at heel contact and lateral deviation at mid-stance. Secondary aims of the present study were to assess changes in VJT performance as a measure of estimated neuromuscular function following load carriage, and evaluate changes in VGRF variables that are commonly associated with injury risk.

It was hypothesised that: 1) There will be significantly increased displacement and rate in CoP, characterised by larger displacement and rate at the onset of heel contact. 2) The load carriage task will significantly reduce lower limb neuromuscular function as measured by VJT performance. 3) Load carriage will significantly increase VGRF variables at loading peak.

Methods

Participants and ethics statement:

Twenty (n=17 males, n=3 females) soldiers from a Special Operation Forces unit (body mass: 80.72±21.49kg; stature:178.25±8.75cm; age: 26±9yrs) provided written and informed consent to participate in the study. University and the General Military Training Hospital research ethics committees provided study ethical approval. All protocols were performed in accordance with the ethical standards proclaimed in the 2013 declaration of Helsinki. Inclusion criteria required all soldiers to be free from musculoskeletal injury at the time of the study and for up to 3-months prior to the load carriage task, which would visibly prevent normal gait or completion of the load carriage task. All soldiers in the collaborating unit were invited to participate.

Participants completed assessments pre and post a load carriage task. During completion of all pre and post measures the participants wore combat trousers, top and boots; and were unloaded. All post load carriage tests were collected between one and four hours after cessation of the load carriage task due to military demands (participants underwent an assault rifle target shoot carrying no load after the load carriage task). No association was observed between any study variable and time between load carriage completion and the post task testing, suggesting the delay had no effect on recovery.

Load carriage task:

Participants completed a 43km load carriage as part of their unit annual fitness assessment. Participants carried a total external load of 29.80±1.05kg. As participants ate food and drank water from their load carriage system, they were confirmed to have a load of at least 25kg at the end of the load carriage task. The load was spread across a bergen (military style backpack) (20kg minimum), M16 assault rifle (3.5kg) and boots (1.5kg).

The route consisted of mixed gravel tracks and cross-country terrain (duration 817.02±32.66min) comprised of level (11.0km), inclined (17.3km) and declined (14.7km) walking. Participants had a 6-minute rest stop in each hour of the activity. Average speed was recorded as $4.10 \pm 0.24 km \cdot h^{-1}$ including rest stops and was $4.20 \pm 0.18 km \cdot h^{-1}$ excluding rest stops. The march was conducted between 57m and 478m above sea level, consisting of a total gain in altitude of 1048±92m. The average ambient temperature and humidity were recorded at 25.3°C and 45% respectively.

Mean heart rate during the load carriage was 122±13b·min^{-1}. Further assessment showed that heart rate was between 60b·min^{-1} and 80b·min^{-1} for 8.52% of the activity, 80-100b·min^{-1} for 27.84%,100-120b·min^{-1} for 46.38%, 120-140b·min^{-1} for 15.68%, 140-160b·min^{-1} for 1.53% and >160b·min^{-1} for 0.04%. Due to technical failure of some heart rate/GPS monitors, comparisons for heart rate and GPS were made using n=16 (three females, 13 males).

Heart rate and GPS:

Participants wore a GPS/Heart rate monitor (Garmin®, Garmin International Inc, Kansas, USA) for the duration of the load carriage. Heart rate and GPS position were recorded every second for the duration of the task and expressed as an absolute value. All data were downloaded on completion of load carriage using Map Source software (Map Source™, Garmin International Inc, Kansas, USA). The data was then used to define speed of movement, altitude and distance covered.

Vertical Jump Test:

All participants completed three maximal effort VJT pre and post the load carriage event. The VJT is a commonly used assessment of neuromuscular function, as it has been demonstrated to be an effective method of quantifying changes in neuromuscular function[13]. The VJT started with the participants standing in a neutral position with their hands on their hips. The jump commenced with the participants moving down into a squat position without adjusting their feet. After a slight pause at the bottom of the movement they jumped vertically with maximum effort. Participants performed three familiarization practice submaximal jumps immediately before undergoing the maximal effort jumps. Three practice jumps have been shown to not fatigue the lower limb, while providing an opportunity for participants to practice the technique[4]. A camera filmed the participant’s lower limbs in the sagittal plane. The participants completed three maximal effort jumps and the average was recorded.

Jump height was calculated via time off the ground using Quintic Biomechanics (v29, Quintic Consultancy Ltd, UK). Equation (1) was used to identify initial take off velocity by using 0 at as final velocity at the peak of the jump.

Jump height and power were calculated using the following equations:

$$V = u + a.t \tag{1}$$

Equation 1: where V = final velocity ($m.s^{-1}$), u = initial velocity ($m.s^{-1}$), a = gravitational acceleration ($m.s^{-2}$), t = flight time (s).

$$D = u.t + \frac{1}{2}a.t^2 \tag{2}$$

Equation 2: where, D = vertical displacement (m).

$$VJTpower(W) = (60.7 \times D) + (45.3 + BM) - 2055 \tag{3}$$

Equation 3: Equation validated in previously published work[14] used to calculate VJT power (W) derived from jump height (m) and body mass(BM) (kg).

Plantar pressure and ground reaction force assessment:

The participants were required to walk at a pace of 6.5km·h^{-1}±10% across a pressure platform (RSscan International, Belgium, 1068mm x 418mm x 12mm, 7192 sensors), embedded in the middle of a 20m runway. Speed was derived from the time taken to cover 5 metres either side of the pressure platform. Five successful trials were collected at 256Hz. Data was collected in RS Footscan software (RSscan International, Belgium), where the location of the foot strike was defined by the manual designation of masks within the software (Figure 1) to produce a centre mark, from which medial (positive value) and lateral (Negative value) deviations could be assessed. Raw CoP co-ordinates (mm) and raw estimations of force (N) were then exported for analysis in Microsoft Excel (Microsoft: USA). The key variables were extracted via Visual Basic for Applications code and all five trials were then averaged.

Mediolateral displacement was assessed due to its association to global stability of the ankle, while medial and lateral CoP displacement and rate variables were assessed due to their associate with ankle instability at heel contact and mid-stance respectively. Medial displacement was calculated at three very early time points to assess medial shift at a phase when it is highly likely the is no active muscle support. Loading peak and late stance thrust maximum variables were analysed due to their association with overuse injury. Mid-stance force minimum was assessed as it can be used as a proxy for knee flexion. The timing of loading peak, mid-stance force minimum and late stance thrust maximum were recorded from heel contact (as observed by the first measurement over 40N), and were extracted from the raw data and then normalised to total stance time.

Figure 1

Statistical Analysis and sample size:

All data were analysed using the statistical package for social sciences (SPSS v23 for Windows; SPSS Inc., Chicago, Illinois). Shapiro-Wilk tests were used to assess distribution of the measured variables. Differences in means were assessed using paired t-tests with an alpha level set at 0.05. Glass's delta (d_{Glass}) was used to examine the effect size of any statistically significant difference between means. Before VGRF were normalised to body mass the data were log transformed and plotted to ensure that it did not violate the previously proposed scaling guidelines[15]. Sample size was calculated using G*Power[16] using means and standard deviations drawn from previously published work[4].

Results

VJT height decreased significantly following the load carriage task (0.30±0.08m vs. 0.24±0.07m, $p<.001$, $d_{Glass}=0.73$) and power decreased significantly (3429.9±758.3W vs. 3060.0±717.2W, $p<.001$, $d_{Glass}=0.49$).

Loading peak (2.59±0.51BW vs. 2.81±0.61BW, $p=.035$; $d_{Glass}=0.44$) and mid-stance force minimum were significantly increased after load carriage compared to pre measurement (1.28±0.40BW vs. 1.46±0.41BW, $p=.015$ $d_{Glass}=0.45$).

There was no statistically significant change in stance time following load carriage (679.5±77.8 vs, 695.9±89.1, $p=.232$). As such, temporal variables are presented only in relative terms (Table 1). These changes were accompanied by a significant shortening of the time to loading peak following the load carriage task (21.1±2.2% vs 18.5±5.3%, $p=.016$, $d_{Glass}=0.80$).

Table 1

Significant increase in mediolateral displacement of the CoP was observed following the load carriage task (17.0±6.9mm .vs 23.4±9.8mm, $p=.007$, $d_{Glass}=0.77$) which can be further characterised by increased maximum lateral CoP displacement (-2.7±5.7mm vs. -0.3±9.7mm, p=.049, d_{Glass}=0.63) and maximum medial CoP displacement (14.6 ±3.6mm vs. 17.0±3.9mm, p=.029, d_{Glass}=0.64).

Significant increase in rate of medial displacement of the CoP following the load carriage task were observed at 11.86ms (0.5±0.21mm·s^{-1} vs. 1.0±0.9mm·s^{-1},p=.001, d_{Glass}=2.98), at 23.54ms (0.5±0.1mm·s^{-1} vs. 0.8±0.5mm·s^{-1}, p=.015, d_{Glass}=1.89) and at 35.40ms (0.5±0.2mm·s^{-1} vs. 0.7±0.3mm·s^{-1}, p=.014, d_{Glass}=1.20).

Figure 2

Significant increases in magnitude of the medial displacement following the load carriage task were observed at 11.86ms (3.8±2.2mm vs. 14.9±15.3, p=.001, d_{Glass}=5.22), at 23.54ms (8.6±4.8mm vs. 13.6±9.6mm, p=.029, d_{Glass}=1.05) and at 35.4ms (12.7±5.4mm vs. 16.2±10.5mm, p=.023, d_{Glass}=1.01).

Discussion

The present study demonstrates statistically significant reductions in neuromuscular function following the load carriage task. Concurrent increases were observed in VGRF and deviations across all measured CoP variables in a Special Operation Forces cohort following a 43Km load carriage task. These findings suggest it is possible to accept all three hypotheses, highlighting that prolonged load carriage alters gait and VJT variables, which are associated with increased injury risk.

Statistically significant (18.62%) reductions in VJT height were observed, corresponding to a 10.34% reduction in vertical jump power following the load carriage event. These findings are larger than the 8% reduction in neuromuscular function previously reported[4], which is likely due to the longer distance covered by the Special Operation Forces soldiers in this study. The large variance of VJT scores is comparable to other studies in the field and is believed to be partly in response to the absolute load carried by the soldiers[4]. As soldiers with lower total body weight experience greater physical challenge to carry the load.

The force generating capacity of the lower limb muscles have been shown to be associated with increased VGRF during load carriage. The current study observed an increase in loading peak and late stance thrust maximum following the load carriage task, corroborating previous work[6]. Increases in the magnitude of impact peak and the shortening of time to loading peak highlights an increase in rate to loading peak, which are commonly cited as biomechanical risk factors for lower limb extremity overuse injuries [17-19]. These findings are possibly due to a reduction of neuromuscular function of the lower limb, specifically the knee extensor muscles, which work eccentrically during heel contact to reduce the magnitude of the foot ground interaction. Future physical training programmes could consider developing knee extensor muscles, to increase the body's capacity to reduce the vertical impact of the load.

An increase in mid-stance force minimum following the load carriage task was observed indicating a possible decrease in knee flexion. A possible reason for this observed change is the significant reduction in neuromuscular function (observed by a VJT height loss of 18.62%) as the body attempts to reduce the eccentric loading on the quadriceps, as a protective mechanism against further neuromuscular function loss and possible injury. It should be considered that occupational load carriage is seldom completed in isolation with soldiers usually engaging in further activities such as conducting reconnaissance, setting up defensive positions or assaulting an enemy position. These findings highlight that soldiers are exposed to increased injury risk during load carriage, but also during subsequent unloaded occupational activities.

Total CoP displacement and mediolateral displacement was increased following load carriage, and there was no corresponding increase in stance time observed, suggesting a reduction in global stability of the ankle[20]. This can be further characterised as a significant increase maximum medial CoP displacement, signifying a reduction of control of the ankle at heel contact[2]. While plantar pressure has been examined during unloaded running following load carriage[21], the novel aspect of these findings is that the largest change in CoP rate and displacement was observed early in the gait cycle with an increase in displacement of 288.7% at 11.86ms, 56.5% at 23.54ms and 43.2% at 35.4ms during unloaded walking. The change in displacement and rate early at heel contact is possibly as a result of reduced muscular control from reduced muscle strength and delayed activation time. This is supported by the concurrent loss in neuromuscular function following the load carriage task. These findings suggest resistive force is greatly reduced during initial contact, consequently the soldiers are exposed to significant ankle sprain risk.

In line with studies that artificially fatigued the lower limb[2] this study observed increased lateral shift of CoP at mid-stance. Previous work has suggested this may be due in part to fatigue in laterally placed muscles such as the peroneus longus[2]. While this study did not examine shank muscle activation via electromyography, the concurrent reduction in VJT score provides some support for this postulation. Future physical training programmes may choose to investigate the efficacy of different training modes to improve the stability of the ankle and the laterally place shank muscles.

An increase in load carriage CoP variation following load carriage suggests significant individual variance was experienced following the load carriage task. While the large effect sizes observed suggest the changes can be considered with confidence. These findings suggest there is significant individual variance in gait parameters in response to the load carriage task. During the load carriage task participants wore a uniformly issued boot, therefore military commanders should consider providing a range of footwear options to allow for differences in gait kinetics in order to increase ankle support at heel contact.

Due to military requirements, participants were not able to complete the laboratory testing with their bergens on, meaning that changes in gait measured across the force platform were not representative of possible gait changes with the load considered. However, there were significant alterations to unloaded gait following the removal of the external load. This novel finding implies that injury risk increase from load carriage is not confined to the duration over which the load is carried. Conversely, it appears there is significant impact on normal function even after the load is removed.

A limitation of this study is that a control condition was not included in this study (walking with no load). As such, while the findings are relevant to the soldier, it is not possible to determine whether the changes occur as a result of the additional carrying of the load or the load carriage task. Laboratory work completed has shown that two hours of prolonged load carriage causes a reduction in neuromuscular function of the lower limb, compared to no change during unloaded walking, suggesting the findings from this study are likely due to the impact of the load[22]. Further controlled studies are required to confirm whether changes in the observed parameters are as a result of the load or walking task.

Due to the occupational nature of the load carriage, participants underwent a static rifle target shoot after the load carriage task, which meant participants underwent the post testing at different times. No association was observed between any variable and the time they underwent post testing.

This study provides an original understanding of the physiological and mechanical stress experienced by a hard-to-reach population of Special Operation Forces soldiers undergoing a substantial and prolonged load carriage task in an occupational setting. This study presents a number of novel findings, chiefly, the onset of significant CoP medial shift very early in the gait cycle, increased lateral displacement of the CoP and the increased VGRF following the load carriage task suggesting significant loss of control of the ankle joint at heel contact.

Since participants wore standard issue military boots, these findings may have significant implications for future military footwear design. Boot design could be more specific, targeting greater medial stability supporting the side of the foot at heel contact and lateral support of the ankle during mid-stance. This work has also demonstrated that very early assessment of medial displacement could serve as an injury-screening tool for large-scale assessment of eversion strain risk, further development of the tool could be used to examine subpopulations such as foot valgus, high/low arch structure as a risk for eversion sprain.

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Table 1: Means and SD of GRF and timing variables supported by standardised effect sizes and significance levels for VGRF values

Variable	Pre	Post	*p*-Value	d_{Glass}
Stance Time (ms)	679.45 (77.84)	695.91 (89.15)	0.232	
Total CoP Displacement (mm)	309.09 (17.49)	325.49 (26.17)	<0.001*	0.94
Loading Peak (BW)	1.95 (0.37)	2.11 (0.44)	0.035*	0.44
Mid-stance Force Minimum (BW)	0.96 (0.30)	1.10 (0.31)	0.015*	0.45
Late Stance Thrust Maximum (BW)	1.64 (0.42)	1.73 (0.42)	0.362	
Time to Loading Peak (%)	22.08 (2.38)	19.70 (5.23)	0.037*	1.00
Time to Mid-stance Force Minimum (%)	52.84 (3.95)	50.97 (6.27)	0.356	
Time to Late Stance Thrust Max (%)	79.31 (2.25)	75.93 (9.20)	0.265	
Average Vertical Impulse (BW·S)	1062.13 (264.67)	1170.87 (324.79)	0.032*	0.41
Total Vertical Impulse (BW·S)	189558.55 (66176.34)	211488.30 (70302.65)	0.052	

*Effect observed at $p<0.05$. CoP: Centre of Pressure. Time values are presented as percentage of total stance time.

Figure 1: A typical centre of pressure line of progression, along with a diagram presentation of key points. Markers were extracted from the raw data via Microsoft Excel: A) Maximum medial CoP displacement, B) maximum lateral CoP displacement. Medialateral displacement is recorded as A+B.

Figure 2 Mediolateral displacement of the centre of pressure before and after load carriage at heel strike. Means with standard deviation bars are presented. Three time points represent first three frames from heel contact. Statistically significant differences (*p*<0.05) were observed post load carriage for all time points compared to pre load carriage.