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Characteristics of torque production of the lower limb are significantly altered after two hours of treadmill load carriage

Running Head: Prolonged load carriage

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Abstract

Load carriage is seldom completed in isolation, meaning load bearers need to be physically capable of physical activity after the load carriage task. This study aims to examine changes in lower limb muscle strength, as measured by torque production across a range of joint angles as a result of prolonged load carriage. Thirty-four healthy participants underwent two hours of loaded or unloaded treadmill load carriage, with lower limb muscle function variables assessed pre and post activity. The loaded group had a mass of (Mean(range)) 76.45 (27.12)kg, stature: 178.56 (17.63)cm, age: 23(6)yrs, and comprised of 13 males and 3 females. While the unloaded group had a body mass of 73.69(24.19)kg, stature: 178.89(18.49)cm, age: 22(5)yrs and comprised of 14 males and 4 females. Significant reductions across a range of parameters were observed. Characterised by reductions at the optimum muscle length for torque output, with all aspects demonstrating large (knee extension at $180^{\circ}\cdot s^{-1}$: 0.51 Standardised SD, knee extension at $60^{\circ}\cdot s^{-1}$: 0.98 standardised SD) or extremely large individual differences (knee flexion at $180^{\circ}\cdot s^{-1}$: 2.17 standardised SD). These findings suggest after the completion of the load carriage task participants are in a significantly reduced physical state, which may have implications for secondary tasks.

Key words:

Joint angle, Muscle length, Torque curve, Prolonged exercise, Military

Introduction

The capacity to safely carry external loads is a requirement in many occupational settings, including the military [1], firefighting and other emergency services [2]. In these settings there are frequently secondary tasks which require substantial exertion, such as moving over obstacles [3], climbing ladders or evacuating casualties [4]. Furthermore, load carriage is seldom completed in isolation, meaning upon completion of the load carriage, the load carrier needs to be physically capable to undergo occupational tasks such as setting up military positions or to execute attacks involving high intensity activity, such as sprinting or skilful activities, such as shooting[5], while emergency services personnel may be required to undertake lifesaving activities. Consequently, this study will assess the impact of prolonged load carriage on the torque producing capacity of the major muscle groups associated with locomotion.

Muscular function is accurately assessed by measuring the ability of a muscle or muscle group to generate force. While electromyography analysis provides a commentary on muscle fibre recruitment it cannot directly report the change in force produced by the muscle. Isokinetic dynamometry is commonly used to study changes in the muscles force producing capability[6] as the findings can be related directly to ability to complete real world tasks, making it a uniquely relevant tool to study load carriage.

It has previously been demonstrated that externally carried loads cause a number of acute changes to lower limb muscle torque output, which are cited as markers for injury risk [7]. These alterations are characterised by a reduction in ankle plantarflexion and knee extension and flexion, as measured by peak torque, following a two hour bout of treadmill load carriage task [7,8]. These findings are important, as it has been previously identified that plantarflexion peak force output is associated with braking impulse and energy cost and knee peak torque output has been associated with energy cost [9]. The use of peak torque as a measure of force producing capacity of the muscle could be viewed as an oversimplification, given that previous research has shown the timing and muscle length (as measured by joint angle) at which peak torque occurs can change with movement velocity and fatigue, as such if peak torque shifts from the optimum position it suggests there is a delay in muscle activation suggesting less economical gait and a greater injury risk [10,11]. Therefore, it may be useful to support peak torque assessment with torque measurements at multiple joint angles.

This work aims to use an occupationally relevant model of load carriage[7] to assess the torque output of the knee flexors and extensors and the ankle plantarflexors and dorsiflexors throughout the torque curve. It is hypothesised that as a result of load carriage peak torque will be reduced characterised by a reduction of torque across the range of the movement and by a shift in the angle of peak torque. This will be the first study to conduct an assessment of torque-length relationship following load carriage. This method will provide a greater understanding of the change in muscle behaviour as a result of an occupationally relevant load carriage task.

Materials and Methods

Participants

Voluntary, informed consent was collected from 34 healthy participants. Participants were matched according to gender, body mass, lower limb strength (all measures), stature, and age. The loaded group had a mass of (Mean(range)) 76.45(27.12)kg, stature: 178.56(17.63)cm, age: 23(6)yrs, and comprised of 13 males and 3 females. While the unloaded group had a body mass of 73.69(24.19) kg, stature: 178.89(18.49)cm, age: 22(5)yrs and comprised of 14 males and 4 females (Lower limb strength of both groups are presented in table 1). When assessed via t-tests no statistically significant differences were observed between groups.

Ethical approval was attained from the university ethics committee and all procedures were performed in accordance with the Declaration of Helsinki (2013). To participate in the laboratory studies the participants were required to meet the following inclusion criteria: 18-32 years old, be free from musculoskeletal injury and disorders, which may obviously alter gait, must sufficiently complete a pre-exercise physical activity questionnaire, must be taller than 163cm and must weigh more than 50kg. These criteria ensured participants reflected physical characteristics of a military cohort[12].

Experimental Design

The study was conducted in a parallel controlled group design with both conditions running concurrently. Participants walked on a level motorised treadmill (Woodway ELG, Birmingham, UK)(0% gradient) for 120minutes, at 6.5km·h^{-1}, which is a commonly used speed and duration as it reflects the pace and task duration used in the British Army annual load carriage task[12].

Participants consumed water with no restrictions during the treadmill protocol, which reflected the occupational military setting. The bottle from which the water was drunk was not carried within the load carriage system.

(Insert Figure 1 about here)

The loaded condition consisted of a 32kg external load spread across, webbing (10kg), bergen (15kg) and a dummy rifle (7kg) (Figure 1), this load was chosen as it reflects the load carriage system carried during the annual British Army and US Marine Corps load carriage test.

However the load is heavier than the load carried by Greek Soldiers (17kg) who carry the load for a longer distance (21km) during their annual load carriage test. During the task, participants wore their own walking boots, shirt, and shorts. Participants were advised to wear a polo neck shirt to avoid the rifle sling rubbing the neck causing skin sores.

Before and after the treadmill protocol, participants underwent isokinetic and isometric testing. The test order was the same on each occasion and conducted at approximately the same time of day (early morning) to control for diurnal variation in the force producing capabilities of the muscles[13].

Lower Limb Strength

Isokinetic knee assessment was conducted on the right limb using a Biodex System 3 Pro (Biodex: New York: USA). The right leg was chosen for all measurement to allow comparison to previous research[7]. The set up followed BASES guidelines as they were seated in the chair and secured with straps 5cm above the lateral malleolus, with their hips and knee joints at approximately 90°, with the inclusion of placing the left leg behind a restraining webbing strap to limit a countermovement swing. Before testing participants were instructed to undergo the entire protocol at a submaximal effort (self-perceived 30% effort- confirmed post hoc from a subsample of five participants) to familiarise the participant with the test protocol.

For ankle assessment, participants were seated in the chair and secured with straps. The thigh supporting attachment was used to ensure a hip angle of approximately 80° and a knee angle of approximately 170°, again the right limb was used.

The test protocol consisted of a maximal voluntary isometric knee extension and flexion and then one set of eight maximal contractions of the knee extensors and flexors at speeds of $60°·s^{-1}$ and $180°·s^{-1}$. The ankle test protocol consisted of maximal voluntary isometric plantarflexion contraction followed by one set of eight maximal contractions of the ankle during dorsi and plantar flexion at speeds of $60°·s^{-1}$ and $120°·s^{-1}$. These speeds were chosen to ensure relevant to previous work in the field[7,8].

The tests were conducted in the order of isometric flexion, 30 second rest, isometric extension, 60 second rest, isokinetic knee flexion and extension at $60°\cdot s^{-1}$, 30 second rest and isokinetic knee flexion and extension at $180°\cdot s^{-1}$. Ankle testing was conducted in the same order with $120°\cdot s^{-1}$ being the final measurement. The testing order was chosen as it has been observed that when participants who have a limited experience of isokinetic dynamometry are tested, higher reliability scores are observed when lower rotation speeds are used first[14].

Maximal voluntary contraction score for isometric contractions were considered the single highest recorded value. For the isokinetic contractions, visual basic code was used to highlight the start and end of each repetition, then for each repetition the highest torque value registered was extracted from each of the eight repetitions on the condition that the target velocity was attained. The highest five out of eight values were averaged to be presented as the peak torque score. This method of averaging was chosen as it was frequently observed that participants took three trials to present accurate and reliable results[10]. However, during data analysis it was highlighted that a small number of participants achieved higher torques in the first three repetitions, this method allowed for both events to be accurately portrayed.

Torque at specific joint angles was extracted at 5° intervals including all measurements at which the participant achieved target velocity. Knee joint angle was defined as the internal measurement of the knee angle. For example, if the leg is fully extended the angle would be 180°, while a seated position would present a joint angle of approximately 90°. Joint angles were derived from the lever position reported by the isokinetic dynamometer, values which occurred during the target velocity were exported in raw format and were processed in excel.

Environmental Conditions

Environmental temperature and humidity were monitored (ATP: UK) during all the testing periods. No statistically significant differences in environmental temperature were observed during testing (Mean: SD), with a temperature of 18.7:2.8°C and humidity 50.1:9.4%.

Statistical Analysis

SPSS for windows version 23 (SPSS, Chicago, USA) and Excel (Microsoft: USA) was used for statistical analyses. Distribution of the data was assessed using the Shapiro-Wilk test for normality. Subsequently, differences between groups were assessed using independent group t-tests with an alpha level set at 0.05. Analysis of the change score enabled normalization to baseline. Before change scores were compared and normalized to body mass the data was log transformed and plotted to ensure that it did not violate scaling guidelines[15]

Analysis of the torque at joint angles was examined by three way mixed methods ANOVA of the change scores once normality was confirmed. Post hoc pairwise analysis was conducted to confirm the significant differences at individual joint angles. Effect sizes were presented as d_{Glass}. The primary measure of individual differences was conducted using standardised standard deviations[16]. Qualitative thresholds were taken from Smith, Hopkins [17]. Sample size was calculated using G*Power[18] using means and standard deviations drawn from the live data to confirm the study was sufficiently powered. The variable examined was taken from previous work within our lab and recruitment was stopped when sufficient sample size was met for the variables of knee extension $60^{\circ}s^{-1}$ (n=9 participants per group).

Results

Adverse Events

No participants experienced any major injury as a result of this study. However, six participants experienced blisters on their feet as a result of the load carriage protocol and three participants noted hotspots due to the load carriage equipment rubbing on their shoulders and hips. Grannuflex (a hydrocolloid, moisture retentive wound dressing) and zink-oxide tape were provided to the participants during and after the study, and the participants were advised to wear polo neck shirts. Participants reported that these were very useful in mitigating the skin sores.

Sample Size Profile

Three participants failed to complete the load carriage task, these consisted of two females and one male. All three participants stated the reason for withdrawal was excessive pain across their shoulders as a result of the load.

Lower limb Muscle Strength

(Insert Figure 2 about here)

Figure 2 presents significant differences in the knee flexors at 180°·s^{-1} were observed between 95°-125°, while knee extensors demonstrate reductions between 95°-105° at 60°·s^{-1} and 95°-125° at 180°·s^{-1}.

Seventeen participants completed the unloaded protocol and 16 completed the loaded protocol, however some participants (n presented in table 1) were not able to achieve the target velocity so were excluded from the analysis. Large effect sizes were observed for all significant variables.

(Insert Table 1 about here)

(Insert Table 2 about here)

A statistically significant change was observed in the angle of peak torque in the knee flexors at 60°·s^{-1} (Table 2), despite no change in torque at individual joint angles or peak toque magnitude.

(Insert table 3 about here)

Table 3 presents individual differences observed for knee flexion.

Discussion

This is the first study to demonstrate an overall reduction in torque across multiple joint angles in both the knee extensors and flexors, as a result of two hours of treadmill load carriage (fig.2). This can be further characterised by a reduction in peak torque and a statistically significant shift in the position of peak torque from a number of variables in the knee but none in the ankle, suggesting that load carriage instigates a reduction in torque output, while table 3 explains that individual differences were observed in these findings. As such it is possible to accept the hypothesis that peak torque is reduced in the knee extensors and flexors and ankle plantarflexors as a result of two hours of load carriage. This can be defined by changes in the position of peak torque and the profile of the curve from multiple triangulatory measurements.

Peak Torque

Reductions in peak torque (table 1) were observed for most measures of knee flexion and knee extension for both isometric and isokinetic contractions supported by large effect sizes, the observed changes across a range of velocities and contraction types provides strong triangulatory support for the changes. Furthermore, while reductions of peak torque between 9% and 15.1% in the load carriage group were observed for knee flexion in alignment with previous work[19], and increases from baseline were observed for the unloaded group, which suggests greater decrements than previously documented.

When the joint angle of torque was assessed and presented in table 2, this study observed that peak torque occurred at a larger angle in the load carriage group compared to unloaded control at both baseline and for change scores, for both knee flexion (p=0.03) and extension at $60^{\circ}\cdot s^{-1}$ (p=0.008) with a trend for knee extension at $180^{\circ}\cdot s^{-1}$ (p=0.08). These results suggest that while peak torque is reduced during load carriage, the working muscle also requires a greater distance to achieve peak torque suggesting a shift from optimal muscle length. It is noteworthy that the angle of peak torque changed in knee flexion at $60^{\circ}\cdot s^{-1}$, while no differences were observed in peak torque or the torque profile curve, highlighting a change in torque producing capacity which would have been missed by peak torque testing. Due to reduced specificity of isokinetic dynamometry it is unclear what impact this shift in angle of peak torque will have on the participant's locomotive ability.

Significant reductions in ankle plantarflexor peak torque across all parameters were observed as a result of the load carriage in agreement with previous work[8], which were supported by moderate to large effect sizes (Table 1). As previous work has shown that the ankle plantarflexors provide propulsive force to propel the body forwards during locomotion[20], it is likely that this reduction in muscle strength will increase the energy cost of the task. Moreover, a number of muscles such as the peroneus longus that are involved in plantarflexion have secondary roles providing mediolateral support for the ankle protecting against ankle inversion injury. However, further research is required to examine this in more depth.

Torque angle relationship

The examination of knee extension and flexion at multiple joint angles is novel to load carriage study. It is clear that the faster joint movements displayed reduced torque output over a larger proportion of the joint angle (Fig.2). In all instances, the peak torque values occurred during the optimal muscle length for force, displayed by a flattening of the curve around its peak of the loaded post-test measurements. It is notable that these are muscle lengths (95°-125°) which do not occur during load carriage. So when the muscle is at lengths which are reflective of locomotion (130°-180° [21]) there appears to be no significant change between loaded and unloaded groups. These findings suggest that while changes in torque and peak torque can be observed by isokinetic dynamometry of the whole muscle action, it is unclear whether this loss will have a pronounced effect on the muscle's ability to produce force at muscle lengths relevant to walking with or without external load.

This study assessed lower limb strength as a result of a two hour occupational load carriage task to highlight that the reduction in peak torque (Table 1), change in the torque profile (Fig2) and that the position of peak torque shift as a result of load carriage (Table 2). These findings suggest a delay in muscle fibre recruitment, potentiating the body's ability to mitigate the effect of the load suggesting the participant may be exposed to greater injury risk and reduced movement economy. Interestingly, large inter individual responses were observed for most isokinetic dynamometry testing with large standard deviation. This suggests that there is merit in future research examining the profile of the torque curve, both in an experimental design study supporting load carriage and in a clinical setting. These findings suggest that the load carrier may be exposed to reduced ability to produce for in the low limb suggesting they are less able to move economically and are exposed to increased injury risk. Further studies examining impact forces are required to confirm this.

Limitations

This study highlights the benefit of assessing knee torque output at specific joint angles. However, it was not possible to evaluate ankle torque output in the same manner due to the limited range of movement of the ankle joint. Future work could be conducted at a lower velocity and would increase the range of movement for which the participants are at the target velocity.

Perspectives

This paper analyses torque output of the knee extensors and flexors at multiple joint angles which highlighted that reductions in torque output occur at muscle lengths not typically used during locomotion. This suggests that the change in output is likely to be greater than previously thought. Future research should focus on analysis of torque at specific joint angles, to provide comprehensive assessment of the muscle action. In an applied setting, load carriage instigates significant alteration to lower limb strength which could influence injury risk through changes in impact forces and energy cost of the task to the participants.

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Table 1 Means and change scores for knee and ankle peak torque

Variable	Condition	n	Baseline ($N \cdot M^{-1}$)	Change (%)	*P*-Value	Effect Size (d_{Glass})
Knee Flexion 180°·s^{-1}	Unloaded	13	72.0 (27.5)	4.5 (17.2)	0.008*	1.10
	Loaded	16	92.0 (39.3)	-10.9 (15.6)		
Knee Flexion 60°·s^{-1}	Unloaded	13	86.7 (30.1)	-4.9 (13.9)	0.154	
	Loaded	16	105.8 (38.2)	-12.2 (13.1)		
Knee Flexion 0°·s^{-1}	Unloaded	14	90.1 (29.5)	0.3 (10.2)	0.248	
	Loaded	16	101.3 (32.7)	-5.8 (13.7)		
Knee Extension 180°·s^{-1}	Unloaded	13	130.2 (33.1)	2.1 (10.6)	0.009*	1.06
	Loaded	16	146.5 (41.8)	-9.1 (11.6)		
Knee Extension 60°·s^{-1}	Unloaded	13	172.8 (40.0)	-2.2 (9.5)	0.022*	1.04
	Loaded	16	195.0 (75.7)	-12.1 (12.8)		
Knee Extension 0°·s^{-1}	Unloaded	14	225.2 (70.9)	0.8 (14.6)	0.005*	1.25
	Loaded	16	269.9 (110.7)	-11.9 (14.1)		
Ankle Dorsiflexion 120°·s^{-1}	Unloaded	13	10.8 (24.1)	-2.9 (30.5)	0.224	
	Loaded	16	14.7 (5.4)	-12.2 (33.8)		
Ankle Dorsiflexion 60°·s^{-1}	Unloaded	13	17.8 (5.8)	7.2 (24.6)	0.617	
	Loaded	16	21.9 (5.0)	2.2 (19.6)		
Ankle Plantarflexion 120°·s^{-1}	Unloaded	13	46.8 (20.9)	-1.6 (9.1)	0.052	
	Loaded	16	45.5 (17.3)	-11.0 (13.4)		
Ankle Plantarflexion 60°·s^{-1}	Unloaded	13	67.2 (4.7)	2.8 (18.9)	0.045*	0.62
	Loaded	16	70.6 (16.9)	-14.6 (14.9)		
Ankle Plantarflexion 0°·s^{-1}	Unloaded	14	77.6 (28.4)	7.0 (26.5)	0.004*	0.89
	Loaded	16	113.4 (37.3)	-19.9 (6.6)		

Table presents means with standard deviation in brackets. * highlights significance to $P<0.05$.

Table 2 The position of peak torque for knee extension and flexion

Action	Group	Baseline (Degrees)	Post (Degrees)	Change score (%)	*P*-Value	Effect Size (d_{Glass})
Knee Flexion 180°·s^{-1}	Unloaded	130.3 (12.5)	132.8 (16.4)	1.2 (45.9)	0.65	
	Loaded	123.9 (17.1)	131.2 (10.8)	8.1 (27.7)		
Knee Flexion 60°·s^{-1}	Unloaded	129.4 (11.6)	127.2 (17.7)	-6.3 (36.4)	0.03*	0.64
	Loaded	122.0 (13.5)	134.6 (7.8)	19.1 (17.3)		
Knee Extension 180°·s^{-1}	Unloaded	108.3 (8.6)	108.6 (7.8)	0.0 (12.3)	0.08	
	Loaded	109.6 (7.5)	104.6 (7.2)	-7.8 (12.4)		
Knee Extension 60°·s^{-1}	Unloaded	105.0 (7.7)	103.5 (8.1)	-2.4 (10.1)	0.008*	0.19
	Loaded	106.4 (5.0)	97.5 (5.8)	-12.9 (11.2)		
Ankle Dorsiflexion 120°·s^{-1}	Unloaded	11.1 (14.2)	12.1 (15.3)	2.2 (2.1)	0.88	
	Loaded	13.7 (17.5)	14.9 (19.2)	4.1 (7.4)		
Ankle Dorsiflexion 60°·s^{-1}	Unloaded	5.7 (17.8)	9.8 (13.0)	7.8 (18.1)	0.35	
	Loaded	5.3 (31.1)	16.2 (21.4)	23.2 (55.3)		
Ankle Plantarflexion 120°·s^{-1}	Unloaded	22.2 (11.4)	21.3 (7.2)	-2.5 (2.9)	0.76	
	Loaded	19.5 (5.0)	19.9 (3.6)	5.2 (9.2)		
Ankle Plantarflexion 60°·s^{-1}	Unloaded	38.7 (18.5)	31.8 (7.0)	-10.0 (2.1)	0.07	
	Loaded	27.9 (6.2)	36.2 (19.8)	35.2 (42.1)		

Table presents means with standard deviation in brackets. * highlights significance to P<0.05.

Table 3 Individual differences, SD confidence intervals and standardised standard deviations

Table presents individual differences with qualitative description

Variable	S_{dir}	SD Upper CI	SD Lower CI	Standardised SD	Qualitative Description
Knee Flexion 180°s^{-1}	9.23	10.28	-4.83	2.17	Extremely Large
Knee Extension 180°s^{-1}	4.62	0.51	-9.26	0.51	Large
Knee Extension 60°s^{-1}	8.64	13.70	-6.21	0.98	Large