RESEARCH ARTICLE

The influence of rifle carriage on the kinetics of human gait

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The influence rifle carriage has on human gait has received little attention in the published literature. Rifle carriage has two main effects, to add load to the anterior of the body and to restrict natural arm swing patterns. Kinetic data were collected from fifteen male participants in four conditions, with 10 successful trials for each condition. Walking speed was fixed at 1.5 $m.s^{-1}$ (± 5%) and data were sampled at 400 Hz. The conditions were: Boot – Used as a control. Fixed Arms – Carrying a lightweight rifle simulator, this restricted arm movements but applied no additional load. Fixed Mass – A 4.4 kg diving belt was worn but allowing the arms to move freely. Rifle – Carrying a weighted replica SA80 rifle (4.4 kg). Results showed rifle carriage significantly alters the GRFs produced during walking, most important are an increase in the impact peak and mediolateral forces. This study suggests that these effects are as a result of the increased range of motion of the body's centre of mass caused by the impeding of natural arm swing patterns. The subsequent effect on the potential development of injuries in rifle carriers is unknown.

Keywords: load carriage; gait analysis; military; rifle carriage

1. Introduction

The biomechanics of military load carriage has received increasing attention in the published literature over the past few decades (Kinoshita, 1985; Martin and Nelson, 1986; Knapik et al, 1996; Harman et al, 2000; Attwells et al, 2006; Birrell et al 2007). In addition to load carriage, rifle carriage is also an essential aspect of military life as a rifle will almost always be carried while on military training and operations. Despite this it is still unknown what effect carrying a rifle has on basal gait patterns. Also, if alterations are observed to what extent these put carriers at an increased risk of injury (either overuse or acute injuries). Rifle carriage has two main effects, to add load to the anterior of the body and to restrict natural arm swing patterns.

The SA80 assault rifle, as used by British troops, represents a relatively small load of 4.4 kg; however, this does result in a forward shift of the body's centre of mass (CoM). The majority of the load carriage literature is concerned with load that is carried on the back (in a backpack) or manually (in the hands either in front or by the side of the body). This literature confirms that, as would be expected, both vertical and anteroposterior ground reaction forces (GRF) produced during gait increase when load is applied to the body. This increase has been suggested to be directly proportional to the applied load (Kinoshita, 1985; Tilbury-Davis and Hooper, 1999; Lloyd and Cooke, 2000; Polcyn et al, 2002; Birrell et al, 2007) or protective mechanisms are activated, such as an increase in double support or greater knee flexion during mid-stance, when carrying heavy loads in an effort to reduce stresses on the lower extremities (Weise-Bjornstal and Dufek, 1991; Harman et al, 2000). Load carriage also has significant effects on the temporal parameters of gait, such as an increase in double and single support time and a decrease in stride length and swing time. Results however are varied and contradictory in some instances.

As well as shifting forward the CoM, rifle carriage restricts natural arm swing patterns as caused by the fixed arm position induced. Early research into the function of the upper limb during locomotion has concluded that the arms do not simply act as pendulums but are driven by muscular activity (Elftman, 1939; Fernandez Ballesteros et al, 1965; Hogue, 1969). It is further recognised that natural arm swing serves to counterbalance horizontal rotation of the trunk and modulate vertical excursions of the body's CoM. Arm swing however is not thought to contribute to the propulsion of the body during walking (Elftman, 1939; Murray et al, 1967; Hinrichs and Cavanagh, 1981). Studies investigating the effects of restricted arm swing patterns during walking have shown that the accompanying pattern of lumbar spine loading and motion could be detrimental for certain injuries and tissues of the lower back (Callaghan et al, 1999). Also, restricted arm movements alter basal spatiotemporal gait patterns by reducing preferred velocity and decreasing stride length (Eke-Okoro et al, 1997).

The principal aim of this research was to determine the effects that rifle carriage has on GRF parameters and establish contributing factors to these effects. To achieve this a laboratory based study collecting kinetic data was adopted, four conditions (boot, fixed arms, fixed mass and rifle) which replicate aspects of rifle carriage were utilised.

2. Methodology

2.1 Participants

Fifteen male participants volunteered for the study (mass 83.3 kg ± 13.3 S.D., height 184.4 cm ± 7.9, age 28.9 years ± 5.8). Participants were either left or right foot dominant but all were rear-foot strikers. Ethical approval was granted by the Loughborough University Ethical Advisory Committee (R05/P122). A verbal and written explanation of the study was given, after which a health screen questionnaire was completed by each participant. Informed consent was obtained from all participants before commencing the trial. Participants recruited were physically fit individuals all with extensive load carriage experience, many of whom were either serving or ex-military. This ensured a representative sample of the military population was recruited for the study.

2.2 Equipment

Kinetic data were collected using a Kistler force plate (Type 9286A) in conjunction with a Coda Mpx30 motion analysis system. The force plate was embedded flush in an 8.4 m walkway, situated halfway along the walkway and slightly off centre. This gave adequate distance before and after the force plate to achieve a natural gait pattern. To measure the walking speed of the participants three pairs of infra-red photoelectric cells (Brower Speedtrap II) were used, one set recorded speed on approach to the force plate and the other after the force plate. Both speeds had to be within the desired range thus limiting the potential for acceleration or deceleration that would affect the ground reaction force (GRF) produced.

During the rifle condition (table 1 and figure 1) a weighted replica SA80 assault rifle was carried, this had the same dimensions and weight as the actual SA80 used by British troops. To simulate the fixed arm position induced by rifle carriage a lightweight wooden rifle mock-up with approximate dimensions of the SA80 was used. This restricted natural arm swing, with no addition of load. In the fixed mass condition the weight of the rifle was reproduced by participants wearing a diving belt with a load of 4.4 kg attached. The mass was placed close to the body's neutral centre of mass as it would be if the actual rifle was being carried, but allowing the arms to move freely.

2.3 Protocol

Participants completed all 4 conditions (table 1 and figure 1), with 10 successful trials sought for each condition. The conditions were selected to reflect the 2 main elements of rifle carriage; the addition of mass to the front of the body (fixed mass condition) and the restriction of natural arm swing patterns (fixed arms). In addition to these a control condition was utilised (boot) and a final rifle carriage condition (rifle). Kinetic data were sampled at 400 Hz and the target speed throughout was 1.5 $m.s^{-1}$ (± 5%). A trial was deemed successful if the speed was attained, the foot struck cleanly on the force plate and if an un-adjusted gait pattern was maintained. To ensure participants had familiarised themselves with the condition and walking speed an unlimited number of practice walks were allowed.

Insert Table 1 here

Insert Figure 1 here

2.4 Data Analysis

Participants' kinetic data were normalised, thus allowing between participant comparisons to be drawn. With data expressed as Newton's per unit body weight ($N.BW^{-1}$). Data from the boot and fixed arms conditions were normalised to body weight (including clothes and boots), with the fixed mass and rifle conditions normalised to system weight (this is the weight of the rifle added to that of the participant). All data were expressed as $N.BW^{-1}$, but as explained above this was either body weight or system weight depending on the experimental condition. This ensured that any potential differences in GRF parameters between conditions was not simply as a result of greater load carried in the rifle and fixed mass conditions.

Experimental data from 8 key GRF parameters were measured and collected, these were: Impact peak, thrust maximum, force minimum, maximum braking and propulsive force, vertical and mediolateral impulse and finally stance time. Parameters and terminology adopted for this study were developed using numerous relevant texts, primarily Munro et al, (1987). Mediolateral impulse was calculated as 'total impulse' or absolute values of medial and lateral impulses combined.

The aim of the study was to examine the effects of rifle carriage on GRF parameters. For each parameter measured, a 10-trial mean for each individual participant was used in the analysis. To determine the statistical significance a one-way (repeated measures) ANOVA was conducted. Pairwise comparisons (with Bonferroni correction) gave levels of significance between each of the four conditions. All statistical testing was conducted using SPSS 12.0 and significance was accepted at $p<0.05$.

3. Results

The rifle carriage conditions implemented during this study elicited numerous changes to GRF parameters (table 2). The restriction of natural arm swing patterns (rifle and fixed arms conditions) led to a significant increase in the impact peak, compared to free arm swing (boot and fixed mass conditions). Two thirds of this increase in impact force between the boot and rifle condition is a direct result of restricted arm movements. Similar results were observed regarding the force minimum, with a restriction of natural arm swing significantly reducing the force produced during mid-stance. Carrying a load of 4.4 kg (either rifle or fixed mass conditions) significantly decreased the thrust maximum compared to the fixed arms condition. Regarding the maximum braking and propulsive forces a restriction in arm movement increased both parameters. With mediolateral impulse rifle carriage significantly increased compared to the boot and fixed arms condition. No other significant differences were observed between the stance time and vertical impulse between any of the rifle carriage conditions (table 2).

Insert Table 2 here

4. Discussion

It is important to note that, to the author's knowledge, the kinetic effects of rifle carriage have not been investigated previously. This study highlighted the potential issues and proposes possible mechanisms for these observed differences.

4.1 Impact Peak

Focusing firstly on the effects of rifle carriage on the impact peak, or peak force produced during heel strike phase of gait. Restricted arm movements significantly increased the impact peak compared to the boot condition (figure 2). Two thirds of the increase from the boot to rifle condition was due to the restricted arm movements induced by rifle carriage. The reason for this increase is most likely due to the greater downward acceleration of the CoM just before heel strike. Natural arm movements during walking have been shown to modulate the vertical excursions of the body's CoM (Elftman, 1939; Murray et al, 1967; Hinrichs and Cavanagh, 1981). Therefore, we can assume that restricted arm movements will impede this and result in a greater vertical range of motion travelled by the CoM. During normal walking the body's CoM is at its vertical peak just before heel strike (or during the mid swing phase of gait), and accelerates downward reaching its peak velocity at heel strike. A greater range of motion of the CoM will lead to increased acceleration due to gravity of the CoM towards the ground at heel strike, this will in turn produce a greater impact force (Newton's 2^{nd} Law).

Insert Figure 2 here

The remaining increase in force observed between the boot and rifle condition was a result of load placed on the anterior of the body, namely the rifle; this increase however was not statistically significant. Research into load carriage has shown that when load is carried around the hips (Birrell et al, 2007) and in a front pack (Hsiang and Chang, 2002) a greater impact peak is observed compared to a when load is carried in a backpack. This is due to a forward shift of the CoM, subsequently a greater proportion of the mass is over the striking foot at heel strike. Although the increase was not significant due to the low loads involved (4.4 kg for the rifle compared to 16 kg in the other studies), it does equate to approximately one third of the increase in impact peak between the boot and rifle condition.

Although the increase in the force produced at heel strike may only be small, at around a 2% increase from the boot to the rifle condition. This occurs at every stride taken and is in addition to the load that may be carried, in this case the rifle at 4.4 kg. For the average participant who took part in this study (mass 83.3 kg) carrying the rifle increased the force needed to be absorbed by the supporting leg by 17.2 N per stride. Military recruits can cover up to 11 km per day, which equates to around 9,000 impacts (Jones et al, 2001). As mentioned previously this small but potentially significant increase in force is in addition to other factors such as load carriage or walking / running speed. It is unknown whether an increase in the force needed to be dissipated by the body of 17.2 N for up to 9,000 impacts has any clinical significance, and if so to what extent this may alter the number of overuse injuries sustained by members of the military.

4.2 Force Minimum

An interesting occurrence was seen regarding the force minimum. Restricted arm movements as caused by the rifle and fixed arms condition produced a significantly lower force minimum compared to free arm movements in the boot and fixed mass condition. There was no significant difference between the rifle and fixed arms or between the boot and fixed mass condition (figure 2). Even though the difference with the force minimum produced some of the clearest and most significant results, mechanisms behind the observed differences are uncertain. During mid-stance (at which the force minimum occurs) the body’s CoM reaches its vertical peak. The assumption is that restricted arm movements will cause the CoM to attain a higher peak compared to free arm movements. The force produced during walking is a product of the mass and acceleration of the body. For the vertically higher CoM to be reached the acceleration of the body does not necessarily have to be increased. If this is the case then the time taken for the body to reach its peak will have to increase with a constant or reduced acceleration. Kinoshita (1985) showed that when load of either

20 or 40% of bodyweight was carried in a double-pack, then the relative time for the force minimum to occur increased with little change in the other vertical time parameters. Another reason for the reduced force minimum may be in response to active momentum being generated in the initial phase of the gait cycle. This leads to reduced forces being needed to facilitate forward propulsion, in accordance with the inverse pendulum model of gait as proposed by Winter (1980).

4.3 Thrust Maximum

The carrying of load in front of the body (rifle and fixed mass condition) produced a trend for a decreased thrust maximum, or force produced at toe-off. Significant differences were observed with the fixed arms conditions producing a higher force compared to the fixed mass and rifle conditions (figure 2). This observation is more difficult to explain as a decreased thrust maximum may be as a result of active momentum being produced earlier in the gait cycle (Winter, 1980). Other potential mechanisms are reduced extension of the knee during push-off or the potential of load carried to alter the forward lean of the participant. Neither of these explanations is sufficient to explain the decrease in thrust maximum observed here. Further research is needed to corroborate and explain this finding.

4.4 Maximum Braking and Propulsive Force

Restricted arm movements, as caused by the rifle or fixed arms condition, resulted in an increase in both the maximum braking and propulsive force produced during walking. The rifle condition displayed a significantly greater maximum braking force compared to the fixed mass condition (figure 3). This was the only significant difference between the conditions adopted, this is despite the fixed arms condition producing a greater (more negative) mean force. Therefore it can be suggested that restricted arm movements (fixed arms or rifle condition) produce a greater maximum braking force compared to the boot and fixed mass condition. Although no main statistical effect was observed. A potential reason for this again may be due to the increased vertical acceleration of the body's CoM caused by restricted arm movements. The CoM is slowed during mid-stance and then propelled forward again during toe-off. The greater the acceleration of the body at heel strike may lead to greater braking forces being needed to slow the body, hence the increased braking force with restricted arm movements.

Insert Figure 3 here

Changes to the maximum propulsive force were clearer with respect to the effect of rifle carriage. Significant differences (figure 3) were only observed with the boot (or control condition) displaying lower forces compared to the fixed arms and rifle condition (in other words restriction of natural arm swing). Some research has suggested that arm swing does not contribute to the drive (or the forward propulsion of the body) during walking (Murray et al, 1967) or running (Hinrichs, 1990). Reasons given for this are that the forward drive produced by the forward swinging arm is negated by that produced by the opposite arm swinging backwards. This idea of the arms not contributing to the propulsion of the body is one that this paper challenges; reasons for this are: 1 – Gutnik et al (2005) suggest that the energy of flexion in the upper limb in each cycle was several times greater than the energy of extension during human walking. 2 – The muscles involved in flexion of the upper limb are bigger and more powerful than those of extension. 3 – The drive produced by the arms is an essential part of successful performance in running and jumping events. Arm swing during vertical jumps increases the upward lift of the body (Feltner et al, 2004; Lees et al, 2004). 4 – Finally, if arm swing does not contribute to the forward propulsion of the body, this current study may not have shown significant differences as a result of restricted arm swing due to rifle carriage.

4.5 Mediolateral Forces

Changes to the mediolateral forces during gait are generally regarded as the least important of the three axes, with much research into load carriage regarding them of limited consequence (Kinoshita, 1985; Lloyd and Cooke, 2000; Harman et al, 2000). This research however has highlighted observable differences that occur in the mediolateral axes during rifle carriage, or conditions that replicate rifle carriage. Rifle carriage significantly increased the mediolateral impulse compared to the boot and fixed arms condition (figure 4). However, no significant difference was seen between the rifle and fixed mass condition.

Insert Figure 4 here

The differences observed with the mediolateral impulse may be as a result of an increased horizontal excursion of the body's CoM, leading to a decrease in stability or increased need for greater postural control. As mentioned previously, natural arm swing patterns serve to counterbalance horizontal rotation of the trunk and also help to modulate the CoM in both the vertical and horizontal direction (Elftman, 1939; Murray et al, 1967; Hinrichs and Cavanagh, 1981). Therefore it is assumed that restricted arm movements will impede this stabilising factor. The greater range of motion of the body's CoM in the horizontal plane may lead to increased mediolateral forces. Greater mediolateral force may indicate either a decrease in stability of the participant or, in order to maintain stability, greater postural control will be needed. Increasing the work needed to be done by the muscles of the trunk may increase the stresses or strain placed on this musculature and also increase energy cost. In clinical terms an increased mediolateral minimum force (or force in the lateral direction, away from the mid-line of the body) at heel strike may be related to an increased inversion of the foot during initial impact. If this force is excessive enough or repeated many times this may lead to problems or injury to the ankle and knee joints (Sacco et al, 2006). Increased mediolateral impulse may also indicate a decrease in stability while walking and this could increase the likelihood or severity of potential falls. This becomes more important when we consider the high loads carried by members of the military and the additional risk of injury as a result of a fall whilst carrying these loads. This however cannot be substantiated during the current study.

4.6 Other Parameters

No significant relationships were observed for other GRF parameters that were measured, namely vertical impulse and stance time. The lack of change in the vertical impulse is not surprising given the significant increase in impact peak and decrease in force minimum. These changes will cancel each other out somewhat. Also, with no changes to stance time it can be suggested that rifle carriage does not affect single support time parameters. This is supported by Eke-Okoro et al (1997) who also found that restricted arm swing led to no alterations in stance time.

5. Conclusions

Findings from this study suggest that rifle carriage does alter basal gait patterns. Most important is an increased impact peak (or force produced at heel strike) with rifle carriage. Other significant effects of rifle carriage were also seen, including increases in maximum propulsive force and mediolateral impulse, and a decrease in force minimum. This study suggests that these differences are as a result of the restriction in natural arm swing patterns. These restrictions in natural arm swing have been shown previously to increase both the horizontal and vertical range of motion of the body's centre of mass. This in turn is suggested to be the principal mechanism behind the changes to kinetic parameters observed in this study. Rifle carriage is essential within the military but the subsequent possible effect on the potential development of injuries remains unknown. This study has highlighted and scientifically showed that rifle carriage alters basal gait patterns, a previously unreported aspect of military load carriage.

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Figure 1: Illustration of the rifle or load carriage conditions used in this study.

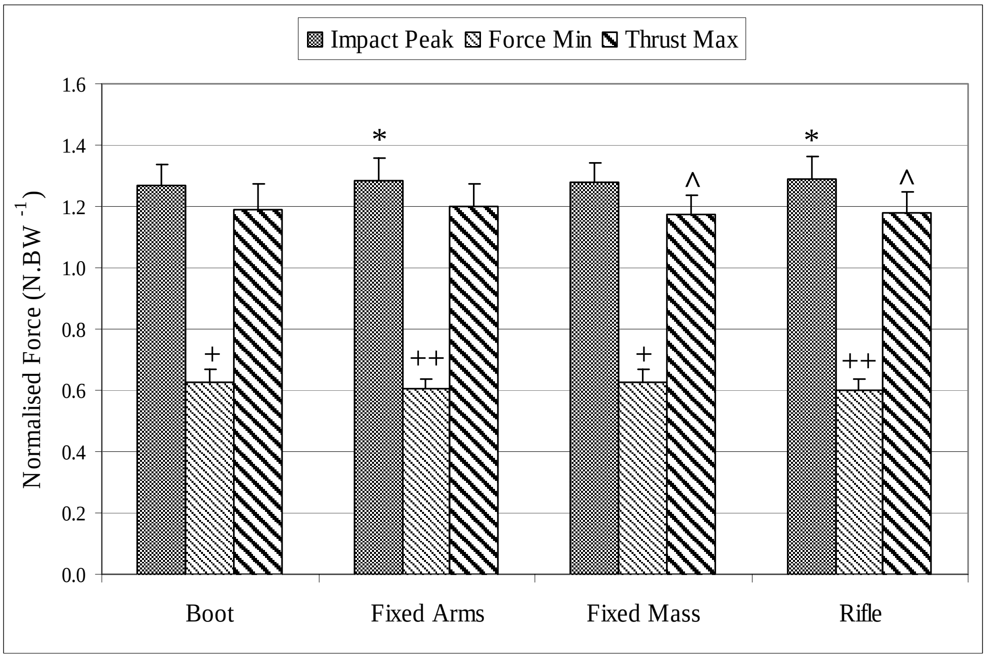

Figure 2: Mean vertical GRF parameters, (error bars represent standard deviation).

* indicates significant difference with the impact peak from the boot condition.

^ significance with the thrust maximum from fixed arms condition.

+ significance from fixed arms and rifle condition, ++ from boot and fixed mass condition with the force minimum.

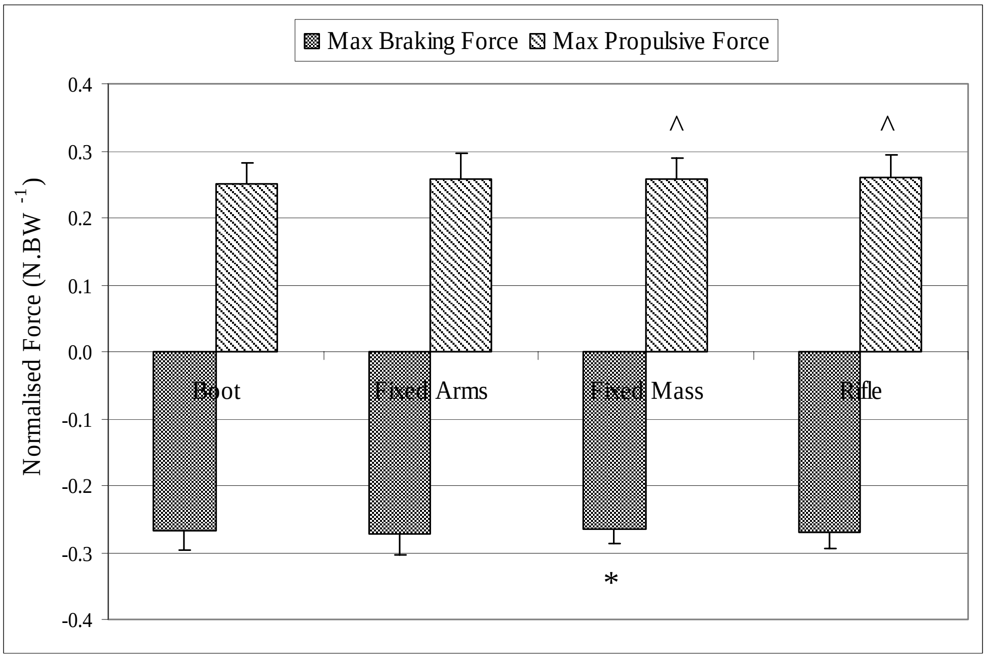

Figure 3: Mean mediolateral impulse, (error bars represent the standard deviation).

* indicates significant difference from the rifle condition.

^ indicates significant difference from the boot condition.

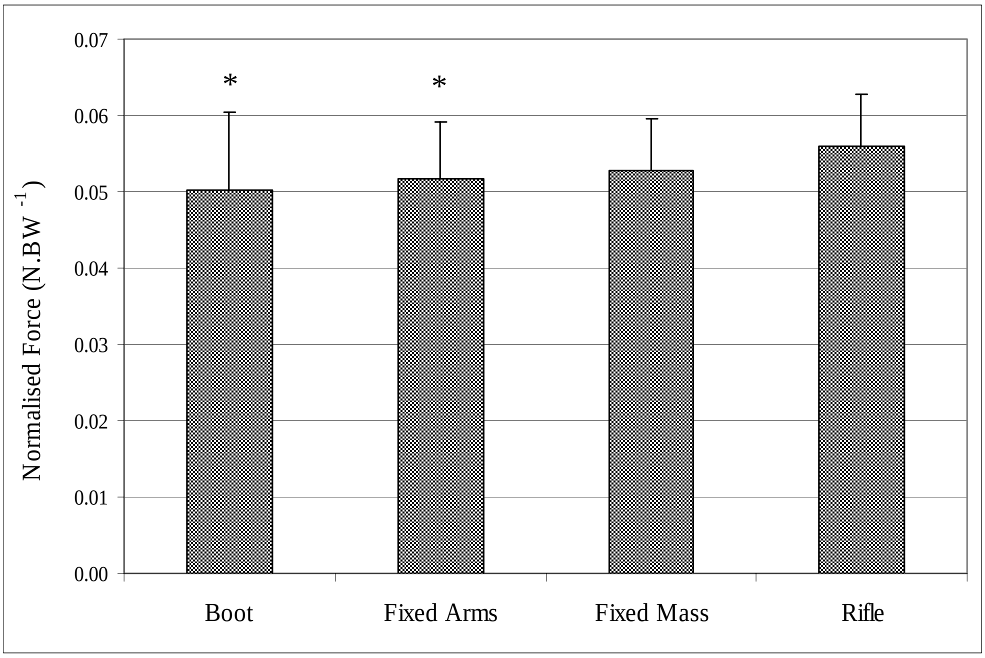

Figure 4: Mean mediolateral impulse, (error bars represent the standard deviation). * indicates significant difference from the rifle condition.

Table 1: Conditions used during the study

Condition	Description
Boot	Wearing non-restrictive clothing and military boots
Fixed Arms	As boot, but carrying a lightweight wooden rifle mock-up
Fixed Mass	As boot, with the addition of a 4.4 kg diving belt
Rifle	As boot, but carrying a weighted replica SA80 rifle

Table 2: Changes to mean GRF parameters, standard deviation in parentheses. Forces measured in ($N.BW^{-1}$), Impulses (($N.BW^{-1}$).s) and Time in (s).

GRF Parameter	**Condition**				**Level of Significance**
	Boot	Fixed Arms	Fixed Mass	Rifle	
Impact Peak	1.226 (0.07)	1.284 (0.07)	1.277 (0.07)	1.292 (0.07)	$p < 0.01$
Force Minimum	0.626 (0.04)	0.604 (0.04)	0.627 (0.04)	0.602 (0.04)	$p < 0.01$
Thrust Maximum	1.191 (0.08)	1.202 (0.07)	1.171 (0.06)	1.179 (0.07)	$p < 0.001$
Max Braking Force	-0.267 (0.03)	-0.273 (0.03)	-0.266 (0.02)	-0.270 (0.02)	NS
Max Propulsive Force	0.249 (0.03)	0.259 (0.04)	0.259 (0.03)	0.261 (0.03)	$p < 0.01$
Vertical Impulse	1.110 (0.04)	1.108 (0.03)	1.099 (0.03)	1.099 (0.02)	NS
Mediolateral Impulse	0.050 (0.01)	0.052 (0.01)	0.053 (0.01)	0.056 (0.01)	$p < 0.01$
Stance Time	0.677 (0.02)	0.675 (0.02)	0.670 (0.02)	0.672 (0.02)	NS