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RESEARCH ARTICLE

Carrying a weapon does not change stride-time variability during treadmill-based load carriage

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ABSTRACT
Gait biomechanics during load carriage tasks are a focus of military research aiming to optimise performance and manage injury risk. However, the impact of weapon handling on gait during these tasks remains relatively unexplored. This study investigates non-linear stride time measures, specifically detrended fluctuation analysis (DFA) and sample entropy (SE), which assess the persistence and regularity of stride time. Seventeen Australian Army soldiers completed 12-minute walking trials on an instrumented treadmill, both with and without a replica rifle while carrying 23.2 kg of load at speeds of 3.5 km/h, 5.5 km/h, and 6.5 km/h. Heel contacts were tracked using an 18-camera Vicon system. Mixed-effect model analyses indicated that weapon handling did not significantly affect stride time variability (DFA $p = 0.46$) or regularity (SE $p = 0.42$), suggesting it may not be a critical factor in future studies of stride time variability during load carriage tasks.

Practitioner summary: This study explored how weapon handling impacted gait biomechanics during military load carriage. Advanced analyses (DFA and SE) of stride time data from 17 soldiers indicated that weapon handling had no significant impact on stride time variability, implying that future research might not require the inclusion of a weapon.

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KEYWORDS
Military; gait; biomechanics; army; DFA

Introduction

Gait biomechanics, when carrying body-borne loads, are a focus of military study to optimise performance and mitigate injury risk (Majumdar, Pal, and Majumdar 2010). Load carriage presents as one of the highest causes of musculoskeletal injury in the Australian Defence Force, affecting military readiness and costing over $210 million per year (Orr et al. 2017; Warfe, Jones, and Prigg 2011). Previous studies have shown that adding external load influences several biomechanical gait variables, including stride length, stride frequency, gait variability and trunk lean (Birrell, Hooper, and Haslam 2007; Grenier et al. 2012; LaFiandra et al. 2003). Additionally, studies have shown that both the positioning and type of load can influence these variables during load carriage (Boffey et al. 2019). Carrying a weapon (e.g., rifle) is an essential aspect of load carriage that may influence gait parameters due to restriction of arm swing. Despite this, there is a scarcity of research examining its impact on locomotion, and in particular, gait variability. This gap in the literature is concerning since current military gait research is conducted with (Krajewski et al. 2023) and without carrying a weapon (Nesterovica-Petrikova, Vaivads, and Stepens 2023; Springer, Gottlieb, and Lozin 2016; Ulman, Srinivasan, and Nussbaum 2022; Walsh and Harrison 2022). Arm movement plays a vital role in bipedal walking, with complex neural couplings between the upper and lower limbs contributing to the almost synchronised output of walking (Weersink, de Jong, and Maurits 2022). The restriction of arm swing has been shown to increase metabolic energy

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cost (Umberger 2008), vertical centre of mass movement (Yang et al. 2015), stride velocity and stride length (Takami, Cavan, and Makino 2020), as well as decrease overall gait stability (Delabastita, Desloovere, and Meyns 2016). Additionally, restricting arm movement may have detrimental effects on overall back health (Callaghan, Patla, and McGill 1999; Choi et al. 2021). Further research that has restricted arm swing through carrying a weapon has demonstrated greater ground reaction forces (Birrell, Hooper, and Haslam 2007) and trunk stability (Cofré Lizama et al. 2023), and reduced pelvis and trunk coordination variability (Seay, Hasselquist, and Bensel 2011).

Variability in human movement, especially in repetitive tasks, is often studied to understand performance and distinguish markers that may indicate or predispose dysfunctional movement (Stergiou and Decker 2011). Stride time (ST) variability provides insight into the consistency and control of stride-to-stride fluctuations, which is one of the final outputs of the locomotive system (Beauchet et al. 2009). Increased variability of ST, as categorised by linear measures such as the standard deviation (SD) or coefficient of variation (CV), has been shown to predict falls risk in healthy and pathology-impacted older adults (Kang and Dingwell 2008). However, there is limited literature on the effects of arm restriction on linear measures of gait variability. Roberts et al. (2018) showed that carrying a loaded box in both hands while walking leads to an increase in stride length and the CV of ST. No significant differences were observed between walking with and without an empty box. In contrast, carrying boxes loaded with 5% and 10% of the participant's body weight did increase variability measures. In contrast, Hill and Nantel (2019) reported that step-width variability increased with active arm swing compared with held or normal swing. While these results suggest that restricting arm swing may affect gait variability parameters, they involve actions that are quite different from carrying a weapon, and the impact of carrying a weapon remains unclear.

Non-linear measures of gait variability, such as detrended fluctuation analysis (DFA) and sample entropy (SE), assess the temporal structure of ST fluctuations. They quantify the statistical persistence and regularity, respectively (Hausdorff et al. 1995), and appear more sensitive to pathology and age-related changes than traditional linear approaches to measuring gait variability (Hausdorff et al. 1997). Yano et al. (2024) previously showed that step time persistence (DFA α) was unaffected when individuals held a smartphone at chest level in one hand while walking, compared with regular walking. Again, this action is very different from the arm restriction created by carrying a weapon. To date, no research has specifically studied the effect of carrying a weapon on ST variability and regularity. Grasping this relationship will provide important context for interpreting past gait variability literature and may assist future research design regarding the inclusion of a weapon. Non-linear measures may offer additional insight into the influence of carrying a weapon and arm restriction on gait mechanics during load carriage. Consequently, the primary aim of this study was to assess the effect of carrying a weapon on ST variability and regularity during load carriage. Considering the variable speeds inherent in military load-carriage tasks based on mission objectives, the secondary aim was to assess if there were any interactions between speed and carrying a weapon for the ST measures.

Methods

Participants

Seventeen Australian Army soldiers (age: 25.6 ± 5.5 y, height: 1.77 ± 0.09 m, body mass: 80.7 ± 15.8 kg, service: 1.88 ± 1.78 y [0.50 y, 4.83 y]) participated in the study. Each participant was free of neuromusculoskeletal injury for at least six months before participating. All participants provided written, informed consent to ethical procedures, which were approved by the Departments of Defence and Veterans' Affairs Human Research Ethics Committee (Ethics protocol #302-20) and reciprocally approved by La Trobe University's Human Ethics Committee (Ethics protocol #302-20 DDVA HREC).

Experimental overview

The research design of this study was part of a broader investigation aimed at exploring various biomechanical and physiological aspects of load carriage and weapon carriage. Participants attended two sessions, with each session taking place one week apart. Throughout these sessions, participants completed six 12-minute walking trials on an AMTI Compact Tandem Force-Sensing Treadmill (Watertown, MA, USA) at a 0° incline, while either carrying (R) or not carrying (NR) a replica F88 Austeyr rifle (3.2 kg). To simulate the requirements of a Patrol Order (Drain et al. 2012), participants were fitted with 23.2 kg of body-borne load distributed via a weighted vest (anterior load: 13 kg, posterior load: 6 kg). Additionally, they were equipped with a Metamax 3B system (portable spiroergometer) and a Polar heart rate monitor to measure the physiological responses as part of the larger research design (2 kg) (Vickery-Howe et al. 2024). Participants also wore loose active clothing with military boots (2 kg) (Figure 1). This configuration represented body-worn armour along with essential combat equipment such as ammunition. In the R condition, a portion of the anterior load was removed (3 kg) from the vest (anterior load: 10 kg, posterior load: 6 kg) to offset the weight of the weapon.

Before beginning walking trials, participants completed two minutes of walking on the treadmill to familiarise themselves with it and the laboratory environment. Participants completed two trials during the first session at a single speed of 5.5 km/h, and in the second session, they completed two trials at two additional speeds, 3.5 km/h and 6.5 km/h. Both sessions included Rand NR conditions. The order in which participants completed a trial with weapon handling was randomised within each walking speed. When beginning a trial, participants were instructed to walk in the middle of the treadmill for the entire period and were provided with no audible or visual stimuli. To allow for metabolic recovery and reduce the impact of fatigue, participants were given 12 minutes of passive rest between trials.

Motion capture

Three reflective markers were attached to the right boot of each participant on the calcaneus, first metatarsal and fifth metatarsal. Positions of the markers were tracked via an 18-camera optical Vicon motion capture system (Vantage V16 and V5) that sampled at 120 Hz. The velocity of the calcaneus marker was used to calculate the heel contact times in the Vicon Nexus (Vicon Motion Systems 2023) monitors function. Heel contact was identified via the parameters outlined by Zeni, Richards, and Higginson (2008); we identified a heel contact as the point when the calcaneus marker's velocity vector changed from positive to negative in the x axis (anteroposterior).

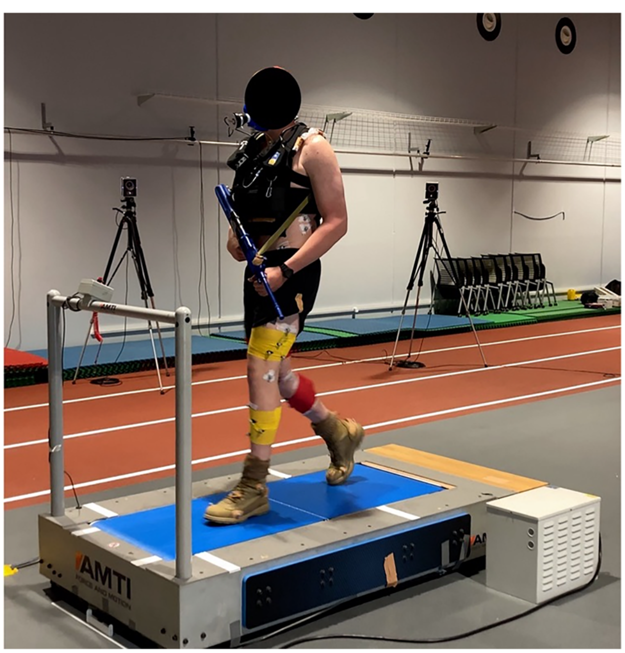

Figure 1. Experimental setup showing a participant on the instrumented treadmill.

Data analysis

After removing the first ten heel contacts to eliminate the effects of gait initiation, 513 heel contacts were used to identify 512 strides. This number has been recommended as the minimum required to reliably quantify non-linear variability measures (Ravi et al. 2020). To assess linear variability, the CV and SD of the 512 strides were calculated in Posit Team (2021). Measures of non-linear variability and regularity, DFA and SE, were calculated using MATLAB 2021a (Matlab 2022). DFA quantifies a measure of persistence within the time series. Persistence refers to the statistical tendency for deviations from a trend or mean value to be followed by further deviations in the same direction. Conversely, anti-persistence occurs when a deviation (from trend/mean) is statistically more likely to be followed by subsequent deviations in the opposite direction (Dingwell and Cusumano 2010). DFA alpha scaling exponents were calculated using an average evenly spaced windows method, which increases the precision of the DFA alpha (Almurad and Delignières 2016). The window size range was set from $nmin = 4$ to $nmax = N/9$ (57) with k (21) estimated using the method described by Liddy and Haddad (2018). SE is another non-linear measure that quantifies the regularity or predictability of a time series by assessing the likelihood that patterns in data will remain similar over time (Ahmadi et al. 2018). SE was calculated using the methods of Richman and Moorman (2000), with parameters of $r = 0.2$ (tolerance ratio) and $m = 2$ (vector length). SE is the negative logarithm of the conditional probability that two sets of data points of length (m) remain similar at the next length ($m + 1$) within a tolerance of r (Kobsar et al. 2020).

Statistical analysis

All measures were confirmed as normally distributed via Shapiro-Wilk's normality test. Levene's test confirmed there was a homogeneity of variances ($p > .05$). The weapon's effect on each measure (SD, CV, SE, DFA), and its interaction with walking speed was examined via linear mixed model analyses, with participant included as

Table 1. Summary statistics of stride-time variables during load carriage with and without weapon carriage across three walking speeds.

Speed	3.5 km/h			5.5 km/h			6.5 km		
Condition	R	NR	MD	R	NR	MD	R	NR	MD
SD (ms)	16.2 ± 2.7	15.8 ± 3.2	−0.4	14.6 ± 2.7	14.3 ± 3.0	0.3	11.1 ± 1.2	11.9 ± 1.5	0.9
n	14	14	–	16	16	–	8	8	–
CV (%)	1.50 ± 0.23	1.45 ± 0.29	−0.06	1.39 ± 0.23	1.36 ± 0.29	0.03	1.15 ± 0.14	1.24 ± 0.15	0.08
n	14	14	–	16	16	–	9	9	–
DFA (α)	0.778 ± 0.071	0.785 ± 0.081	0.006	0.765 ± 0.106	0.756 ± 0.098	0.009	0.683 ± 0.084	0.744 ± 0.086	0.061
n	14	14	–	16	16	–	9	9	–
SE (S)	1.68 ± 0.20	1.69 ± 0.17	0.01	1.60 ± 0.17	1.57 ± 0.16	0.03	1.45 ± 0.09	1.46 ± 0.05	0.01
n	14	14	–	16	16	–	8	8	–

R: with rifle; NR: without rifle; MD: mean difference; SD: standard deviation; CV: coefficient of variation; DFA: detrended fluctuation analysis; SE: sample entropy; n: sample size.

a random effect. Given that no interactions between speed and weapon were found, the Akaike Information Criterion (AIC) score was used to refine the models, thereby minimising overfitting and focusing on the main effects of the models. A Wald test was used to test for the significance ($p < .05$) of each fixed effect. Pairwise *post-hoc* multiple comparisons were completed for each significant effect identified.

Table 2. Linear mixed model results: the effect of weapon handling on stride time variability measures.

Measure	numDF	denDF	*F* value	*p*
SD (ms)	1	75	0.69	0.416
CV (%)	1	75	1.26	0.262
DFA (α)	1	77	0.54	0.458
SE (S)	1	75	0.66	0.421

SD: standard deviation; CV: coefficient of variation; DFA: detrended fluctuation analysis; SE: sample entropy.

Table 3. Linear mixed model results: the effect of speed on stride time variability measures.

Measure	numDF	denDF	*F* value	*p*
SD (ms)	3	75	79.18	<0.001
CV (%)	3	75	43.56	<0.001
DFA (α)	3	77	3.71	0.020
SE (S)	3	75	78.82	<0.001

SD: standard deviation; CV: coefficient of variation; DFA: detrended fluctuation analysis; SE: sample entropy.

Results

Due to technical difficulties (software malfunction) and participant availability, 17 participants completed 80 trials (40 [R], 40 [NR]). After outlier removal using the boxplots method (Tukey 1977) a total of 388/400 calculated variables (stride time mean, SD, CV, SE, DFA) were included in the analysis. The number of participants with complete paired data varied across walking speeds: 14 for 3.5 km/h, 16 for 5.5 km/h, and 9 for 6.5 km/h. For the variables SD and SE, there was one less paired data point for each respective condition. Table 1 displays the summary statistics of all descriptive, linear and non-linear measures of ST variability in both R and NR conditions. Table 2 displays the results of the linear mixed model analysis related to weapon carriage, demonstrating no significant main effect of weapon on any measure of ST variability. Table 3 presents the linear mixed model analysis for the effect of speed, demonstrating a significant main effect on CV, SD, SE, and DFA measures. To visually represent the paired observations of R and NR walking trials, Figures 2 and 3 present paired boxplots. Figure 2 illustrates SD and CV, while Figure 3 displays SE and DFA; however, no statistically significant differences were observed between conditions for any of these measures.

Discussion

The aim of this study was to examine the effect of weapon carriage on ST variability and regularity during load carriage across a range of locomotor speeds. The data demonstrates that weapon carriage did not significantly affect linear and non-linear measures of ST variability and regularity. Additionally, no significant interaction was observed between weapon carriage and speed for any linear or non-linear ST measure. However, there were significant main effects of walking speed for CV, SD, SE and DFA, which supports past research (Brach et al. 2001; Chien et al. 2015; Kang and Dingwell 2008). Taken together, the current results demonstrate that weapon carriage is not required in treadmill walking trials when undertaking analysis to quantify measures of ST variability and regularity during load carriage.

Weapon carriage did not significantly affect the amount, structure or regularity of ST variability during treadmill walking with load. However, adaptions might occur higher up the kinetic chain closer to the constraint of the weapon, with these adaptations not being apparent in spatiotemporal measures of gait. For example, Cofré Lizama et al. (2023), who performed their analysis using data collected concurrently with the present study, concluded that local dynamic

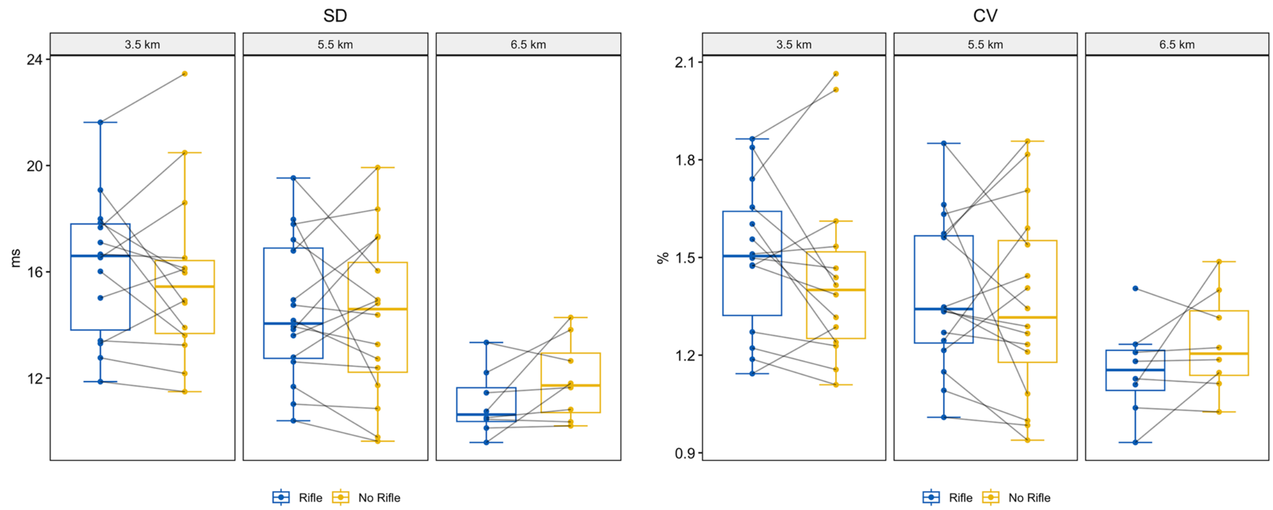

Figure 2. Box plots of linear of stride-time variables (SD, CV) during load carriage with and without weapon carriage across three walking speeds.

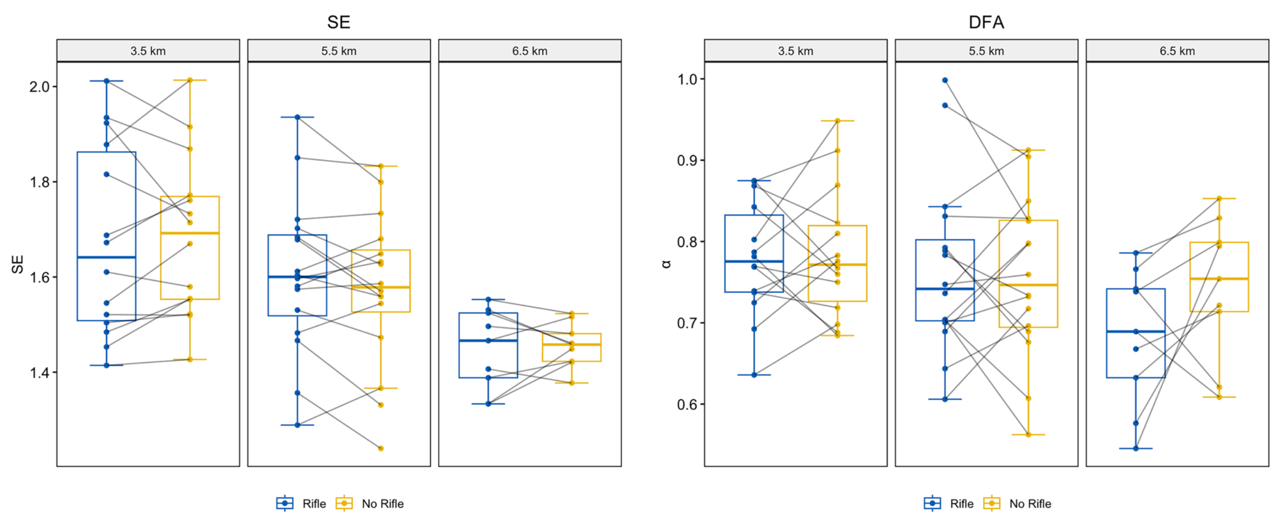

Figure 3. Box plots of non-linear of stride-time variables (DFA, SE) during load carriage with and without weapon carriage across three walking speeds.

stability was increased at the sternum but not at the sacrum with weapon carriage during walking gait. Carrying a weapon shifts the centre of mass anteriorly and necessitates increased muscular activation of the upper body (Brown, Vera-Garcia, and McGill 2006), which could be the key factor contributing to the greater trunk stability that has been previously observed (Stokes, Fox, and Henry 2006). Furthermore, Dingwell, Salinas, and Cusumano (2017) has suggested that the human motor system may utilise compensatory mechanisms to preserve stability while adapting variability in different aspects of gait. The Goal Equivalent Manifold (GEM) concept is one of the best examples. Applying the GEM to treadmill walking, individuals can choose a variety of different stride times and stride lengths to maintain their stride speed and remain on the treadmill (Cusumano and Dingwell 2013). Therefore, it is possible that individuals preserve the magnitude and structure of ST variability while regulating other gait parameters not observed, such as stride length or stride speed.

Previous research has shown changes in ST variability and persistence for populations with altered arm swing, such as Parkinson's disease (PD), Huntington's disease, and older adults (Hausdorff 2009). However, it's important to acknowledge these populations are characterised by a myriad of concurrent health conditions and limitations that are likely to contribute to alterations in ST variability. For example, dopamine medication such as Levodopa has reduced ST variability in PD patients, highlighting the influence of dopaminergic pathways on gait variability (Schaafsma et al. 2003). Huntington's disease is associated with neuronal loss in the basal ganglia, often accompanied by chorea, resulting in loss of motor control and jerky movement. Additionally, as humans age, there is a decrease in muscle control, muscle strength, flexibility, balance, sensory input, and cognitive function (Hosokawa et al. 2022). These are believed to be some of the primary factors contributing to changes in gait variability. It is also important to note that the limited mobility of these population groups also restricts their walking capacity. Given the limited mobility of these groups, researchers have been forced to quantify ST measures on short series lengths of less than 512 strides, potentially undermining the reliability of the findings (Marmelat, Reynolds, and Hellman 2018).

Alternatively, changes in ST variability measures may have occurred when carrying a rifle but were not detected due to the resolution of the capture device. Non-linear measures that examine the temporal structure of ST can be influenced by the resolution of the signal (Fallahtafti, Wurdeman, and Yentes 2021; Liddy et al. 2019), with a lower-resolution signal potentially providing a binning effect for SE, increasing the signal's regularity (Fallahtafti, Wurdeman, and Yentes 2021). Further, a lower resolution signal for DFA can artificially introduce a period of anti-persistent behaviour, decreasing the alpha (Liddy and Haddad 2018). As such, the ST signal observed may not best represent true movement at lower resolutions. However, a change in ST measures was demonstrated with speed and a resolution rate of at least 120 Hz was used, as is recommended for non-linear measures (Ravi et al. 2020).

The anterior distribution of external load may have influenced the results of the current study. Previously, Birrell and Haslam (2010) demonstrated that load positioning affected some basic outcomes of gait. When testing 13 common military load carriage conditions whilst carrying a weapon, they observed that a greater posterior load distribution resulted in a reduced toe-off force. In contrast, an evenly distributed load (anterior and posterior) decreased the maximum braking force of the gait cycle. Therefore, an alternative load distribution (even or posterior) may affect the biomechanical responses to weapon carriage, which may subsequently alter measures of ST variability.

Importantly, this study employed treadmill walking during load carriage, which has been shown to affect measures of ST variability (Dingwell et al. 2001; Hollman et al. 2016). The treadmill may have influenced stride fluctuations to become more persistent, damping the effects of weapon carriage on gait variability. The current results show that the DFA alpha ranged between 0.68 - 0.78 for all conditions, representing highly persistent stride fluctuations. Future studies should also include overground walking within their methodologies, which may allow for more natural stride fluctuations. Finally, the participants recruited for the current study were soldiers with prior rifle-carriage experience, meaning they may have developed motor strategies to limit gait variability during load carriage tasks when carrying a weapon. An extension of the current study would be to explore measures of ST variability before and after training to see if experience affects soldiers' gait variability while carrying a weapon. It is important to note that the findings of this study are specifically applicable to the carriage of personal rifles similar to those used in standard Australian military operations. It remains unclear whether heavier or longer weaponry, such as light or heavy machine guns, would impact these measures. However, the use of a replica F88 Austeyr rifle in this study makes the findings highly relevant to standard operational conditions for Australian soldiers.

Our findings imply that linear and non-linear measures of gait variability are robust to weapon carriage during loaded walking across various military-relevant locomotor speeds. As such, prior studies on locomotion that did not include a weapon, do not require reinterpretation. Additionally, future studies examining gait variability on load carriage locomotion may proceed without a weapon. Overall, this enhances research accessibility, as researchers will not need to seek approval, gain access, or manage the risks of conducting studies involving a weapon.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendix
Model results.

Predictors	Mean			SD			CV		
	Estimates	CI	*p*	Estimate	CI	*p*	Estimates	CI	*p*
(Intercept)	0.15	−0.11 – 0.42	0.243	−0.06	−0.39 – 0.27	0.717	0.02	−0.27 – 0.31	0.884
Speed [SS (~5 km)]	1.45	1.29 – 1.61	**<0.001**	1.24	0.90 – 1.58	**<0.001**	1.33	1.04 – 1.62	**<0.001**
Speed [5.5 km]	−0.36	−0.50 – −0.22	**<0.001**	−0.35	−0.65 – −0.05	**0.022**	−0.40	−0.65 – −0.14	**0.003**
Speed [6.5 km]	−1.43	−1.60 – −1.27	**<0.001**	−0.70	−1.06 – −0.34	**<0.001**	−1.04	−1.35 – −0.73	**<0.001**
Weapon [Weapon]	−0.07	−0.17 – 0.04	0.194	0.15	−0.08 – 0.37	0.198	0.10	−0.10 – 0.30	0.310
Random effects									
σ^2	0.07			0.32			0.24		
τ_{00}	0.24 Participant			0.22 Participant			0.16 Participant		
ICC	0.94			0.77			0.78		
N	17 Participant			17 Participant			17 Participant		
Observations	100			98			98		
Marginal R^2 / Conditional R^2	0.408 / 0.967			0.244 / 0.830			0.368 / 0.859		

Predictors	SE			DFA		
	Estimates	CI	*p*	Estimates	CI	*p*
(Intercept)	0.00	−0.29 – 0.30	0.985	0.27	−0.16 – 0.71	0.212
Speed [SS (~5 km)]	1.35	1.08 – 1.61	**<0.001**	0.01	−0.51 – 0.54	0.959
Speed [5.5 km]	−0.31	−0.54 – −0.07	**0.011**	−0.24	−0.70 – 0.22	0.300
Speed [6.5 km]	−0.88	−1.16 – −0.61	**<0.001**	−0.82	−1.38 – −0.27	**0.004**
Weapon [Weapon]	0.09	−0.09 – 0.27	0.312	−0.13	−0.49 – 0.22	0.455
Random effects						
σ^2	0.20			0.78		
τ_{00}	0.21 Participant			0.18 Participant		
ICC	0.51			0.19		
N	17 Participant			17 Participant		
Observations	100			98		
Marginal R^2 / Conditional R^2	0.579 / 0.796			0.093 / 0.262		