U.S. Army
Research Institute of
Environmental Medicine

Natick, Massachusetts

TECHNICAL REPORT NO. T23-006
DATE April 2023

3D BODY SCAN PREDICTORS OF INCREASED VENTILATORY RESPONSES TO VEST-BORNE MILITARY LOAD CARRIAGE

United States Army
Medical Research & Development Command

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USARIEM TECHNICAL REPORT T23-006

3D BODY SCAN PREDICTORS OF INCREASED VENTILATORY RESPONSES TO VEST-BORNE MILITARY LOAD CARRIAGE

Erica A. Schafer [1, 2]
Danielle M. Arcidiacono [1, 3]
Hope Y. Soucy [1, 3]
Nicholas J. SantaBarbara [2]
Tunde K. Szivak [2]
Adam W. Potter [4]
Stefan M. Pasiakos [1]
David P. Looney [1]

[1] Military Performance Division, US Army Research Institute of Environmental Medicine, Natick, MA
[2] School of Nursing and Health Sciences, Merrimack College, North Andover, MA
[3] Oak Ridge Institute for Science and Education, Oak Ridge, TN
[4] Thermal and Mountain Medicine Division, US Army Research Institute of Environmental Medicine, Natick, MA

April 2023

U.S. Army Research Institute of Environmental Medicine
Natick, MA 01760-5007

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
26-04-2023

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From - To)*
2023

4. TITLE AND SUBTITLE
3D body scan predictors of increased ventilatory responses to vest-borne military load carriage

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER
MO230031

5e. TASK NUMBER

5f. WORK UNIT NUMBER
H

6. AUTHOR(S)
Erica A. Schafer, Danielle M. Arcidiacono, Hope Y. Soucy, Nicholas J. SantaBarbara, Tunde K. Szivak, Adam W. Potter, Stefan M. Pasiakos, David P. Looney

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Institute of Environmental Medicine
Building 42 - 10 General Greene Ave
Natick, MA 01760

8. PERFORMING ORGANIZATION REPORT NUMBER
T23-006

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Development Command,
Fort Detrick, MD 21702

10. SPONSOR/MONITOR'S ACRONYM(S)
USMRDC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This study sought to quantify the effect of weighted vest mass on respiratory rate (RR) during military load carriage, and analyze 3D body scanner (3DS) measurements to identify anthropometric predictors to explain individual variability. Volunteers included 20 U.S. Army Soldiers and civilians (4 women, 16 men; 17 Soldiers, 3 civilians; age, 28 ± 8 years; height, 174 ± 10 cm; body mass, 81 ± 17 kg). Each participant was assessed using a 3D body scanner before participating in a series of four steady-state loaded walking trials at varying speeds (0.00, 0.45, 0.89, and 1.34 m·s-1) with weighted vests of four randomized weights (0, 22, 44, and 66% body mass). Data suggest larger individuals and those with larger hip circumferences are more likely to exhibit increased ventilatory responses to external loading than smaller individuals with smaller hip circumferences. 3DS measurements may be an efficient tool for predicting potential for increased ventilatory responses to vest-borne load carriage, and can potentially aid in identifying individual Soldiers susceptible to cardiorespiratory strain.

15. SUBJECT TERMS
respiratory rate; whole body scan; physiology; load carriage; morphology

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
Unclassified	Unclassified	Unclassified	Unclassified	18

19a. NAME OF RESPONSIBLE PERSON
David P. Looney

19b. TELEPHONE NUMBER *(Include area code)*
508-206-2357

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ACKNOWLEDGEMENTS

This study was made possible thanks to the time and effort of both our military and civilian volunteers. Additionally, we would like to thank the Human Research Volunteer (HRV) office at Natick Soldier Systems Center (NSSC) for their time, excellence, and dedication. Lastly, we would like to thank the U.S. Army Research Institute of Environmental Medicine (USARIEM) Office of Research Quality and Compliance (ORQC) for their extensive guidance and support.

EXECUTIVE SUMMARY

INTRODUCTION: Military personnel are often tasked with carrying heavy loads over complex terrain in a wide range of environments. Elevated physiological costs of locomotion incurred by the added mass are further compounded by respiratory muscle strain caused by thoracic compression. How individual anthropometrics relate to respiratory responses of individual Soldiers carrying heavy vest-borne load carriage remains unclear. This study sought to quantify the effect of weighted vest mass on respiratory rate (RR) during military load carriage, and analyze 3D body scanner (3DS) measurements to identify anthropometric predictors to explain individual variability.

METHODS: Study volunteers included 20 U.S. Army Soldiers and civilians (4 women, 16 men; 17 Soldiers, 3 civilians; age, 28 ± 8 years; height, 174 ± 10 cm; body mass, 81 ± 17 kg). Each participant was assessed using a 3D body scanner (SS20 Booth Scanner, Size Stream LLC; Cary, NC) before participating in a series of four steady-state loaded walking trials at varying speeds (0.00, 0.45, 0.89, and 1.34 $m \cdot s^{-1}$) with weighted vests of four randomized weights (0, 22, 44, and 66% body mass). Repeated measures analysis of variance (ANOVA) was used to determine differences between RR during each experimental condition. Linear regression analysis was used to analyze the relationships between 3DS measurements and the change in RR with increased vest loading ($\Delta RR/\Delta Load$).

RESULTS: Respiratory rate increased in a stepwise manner with added vest mass during all experimental conditions except for two (0 to 22% body mass and 44 to 66% body mass at 0.00 $m \cdot s^{-1}$; $p>0.05$). Correlations between 3DS measurements and $\Delta RR/\Delta Load$ were higher during standing (r, 0.41 ± 0.13) than during walking at 0.45 $m \cdot s^{-1}$ (r, 0.10 ± 0.14), 0.89 $m \cdot s^{-1}$ (r, 0.13 ± 0.14), and 1.34 $m \cdot s^{-1}$ (r, 0.09 ± 0.15). From the 167 3DS measurements, 164 (98.2%) were positively associated with $\Delta RR/\Delta Load$ during standing load carriage. Of these measurements, 41 were identified to have a moderate relationship with $\Delta RR/\Delta Load$ ($r \geq 0.5$).

CONCLUSION: Respiratory rate increases substantially with added vest masses of at least 22% body mass. Data suggest larger individuals and those with larger hip circumferences are more likely to exhibit increased ventilatory responses to external loading than smaller individuals with smaller hip circumferences. 3DS measurements may be an efficient tool for predicting potential for increased ventilatory responses to vest-borne load carriage, and can potentially aid in identifying individual Soldiers susceptible to cardiorespiratory strain.

INTRODUCTION

Standard military operations frequently involve transporting heavy equipment by foot in a variety of environments (1-3). Depending on mission requirements, Warfighters may need to wear body armor, load-carrying vests, or other external loads affixed to their trunk (3). Trunk loading increases physiological strain during Warfighter tasks (4-7). As excessive strain hinders tactical performance and potentially mission completion, identifying individuals at a higher risk for performance decrements secondary to physiological stressors is critical for maintaining readiness (8).

Respiratory rate (RR) is a vital sign and physiological strain indicator that increases with carried external mass (9-14). External loading increases metabolic demands of locomotion (4-7) and imposes a mechanical disadvantage on the Soldier (1). The heavy mass of the vest may compress the upper thorax, limiting chest expansion during inhalation and potentially increasing RR (15-18), compounding the already present respiratory strain incurred during vest-borne loading (9-14). Current literature has established that added load likely increases RR, yet the extent of its impact is not clear. Additionally, increasing the intensity of load carriage (i.e., via added mass, incline, and/or speed) may further increase the degree of respiratory strain (19-21).

Respiratory rate has been used to indicate a change in physical effort and task difficulty (11, 22, 23). Research has found RR to be a good indicator of physical exertion and highly sensitive to glycogen depletion, muscle fatigue, and environmental extremes (i.e., heat stress, hypoxia) (11, 22). During load carriage specifically, RR is known to steadily increase with increases in mass of the load being carried (21, 23-25), supporting the idea that RR is a valuable predictor of physical exertion. Interestingly, RR appears to be more related to the magnitude of external loading rather than proximity to volitional fatigue (23). In other words, RR seems to be a particularly useful method of measuring physiological strain incurred by load carriage (23). Despite its importance, RR is less understood than many other physiological parameters examined by exercise research (11).

Certain anthropometrics (e.g., waist dimensions, body mass) have been identified as moderate predictors of heightened respiratory responses in healthy adults (26). However, methods for obtaining these measurements (e.g., tape measurement, full body casting) are impractical for most applications due to lengthy time requirements and a high probability for human error (27). Dual energy x-ray absorptiometry (DEXA) (28), hydrostatic weighing (29), and BodPod (30) provide insight into parameters such as body fat percentage and fat-free mass, but they cannot provide specific measurements pertaining to individual body dimensions (e.g., lengths, circumferences, surface areas) (30, 31). The tediousness of traditional methods has limited earlier investigations to examining only a select few body measurements; however, emerging three-dimensional body scanner (3DS) technologies enable rapid measurement of many anthropometrics (32-35). In a previous evaluation of relationships between 3DS measurements and the metabolic costs of walking, Holden et al. (35) found the most predictive dimensions were related to the trunk region. Consequently, a 3DS system could similarly be leveraged to explore relationships between RR and hundreds of individual anthropometric dimensions.

This study quantified the effect of varying vest masses on RR to better understand the physiological demands of physical stressors encountered in the operational environment. In addition, this study sought to explore relationships between 3DS measurements and the RR response to added external loads during standing and walking at three different speeds. Findings from this study may expand physiological monitoring interventions in tactical populations, and highlight anthropometrics that may explain increased individual risks of ventilatory strain incurred by thoracic loading.

METHODS

The current study is an exploratory investigation of relationships between RR and 3DS body dimensions in healthy adults during vest-borne loading. A subset of data was analyzed from a multi-iteration U.S. Army Research Institute of Environmental Medicine (USARIEM) research protocol (19-12H: “Modeling the metabolic costs of heavy military backpacking”). Each volunteer completed a series of five visits: familiarization (visit 1), baseline testing including the 3D body scan (visit 2), incremental testing (visit 3), and two experimental visits (visit 4 and 5). On each experimental visit, volunteers were randomly assigned two of the four vest loads (0, 22, 44, and 66% body mass) and asked to complete steady-state trials at four walking speeds (0.0, 0.45, 0.89, and 1.34 $m \cdot s^{-1}$) (**Figure 1**). Each volunteer also completed a fifth trial at an individualized load-specific walking speed that was not included in our analysis since it was not standardized across conditions. The 44% body mass (BM) load was chosen to mirror the relative mass used for an approach load during U.S. Army foot marches (5, 23, 36); while the 66% BM load corresponds with the reported range of an emergency approach load (5, 6, 23). The 22% BM load was chosen to represent an equidistant mass from the standard approach load; while the 0% BM load was used as a control condition (5, 23). Repeated measures analysis of variance (ANOVA) was used to quantify significant differences between each incremental increase and RR measured at each walking speed. The effect of load on RR at each speed, quantified as the slope of the linear trendline between these variables, was subsequently correlated with 3DS measurements.

Figure 1. Outline of steady-state walking trial procedures.

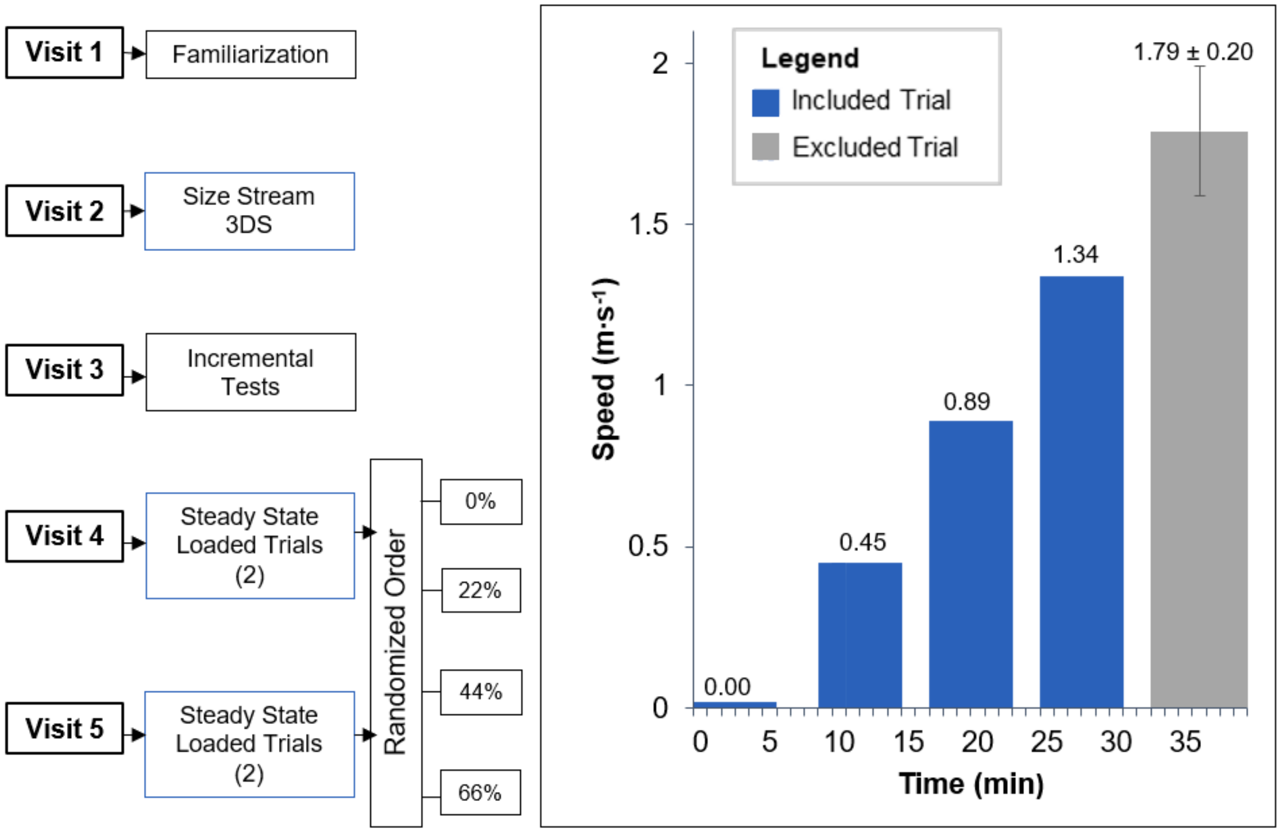

Figure Legend: Sequence of protocol events detailing when Size Stream scans were collected and when steady-state trials were performed. 0, 22, 44, and 66%, percent of body mass (BM) carried during steady state loaded trials.

Volunteers

Twenty U.S. Army Soldiers and civilians (4 women, 16 men; 17 Soldiers, 3 civilians; age, 28 ± 8 years; height, 174 ± 10 cm; body mass, 81 ± 17 kg) voluntarily participated in this study. Volunteers were recruited from the Natick Soldier System Center (NSSC) Human Research Volunteer Pool, and from active-duty personnel and civilian employees of NSSC. Each volunteer was informed of the study purpose and the potential risks, and if still interested provided written informed consent before participating. Volunteers were asked to complete a questionnaire to ensure overall health and absence of injury. Inclusion criteria for this study required individuals to be between 18 and 44 years of age, physically active at least twice per week for ≥ 30 minutes, and able to sustain a walking pace of 1.34 $m \cdot s^{-1}$ while wearing a vest equal to 66% of their overall body mass. The study was approved by the Scientific Review Committee at the U.S. Army Research Institute of Environmental Medicine (USARIEM), and by the US Army Medical Research and Development Command Institutional Review Board (MRDC IRB).

Procedures

Volunteers completed a series of four loaded walking trials of varying speeds and vest masses. Prior to each visit, volunteers were asked to avoid caffeine, nicotine, and food for at least ten hours before the start of the visit, and to avoid alcohol and vigorous exercise for at least 24 hours. Each volunteer was required to maintain hydration by drinking ≥ 500 mL of water the night before and the morning of each visit. A questionnaire was administered before each visit regarding sleep, pain, and study compliance, followed by a test of urine specific gravity to ensure adequate hydration (≤ 1.030). Nude body mass was obtained with a calibrated stationary scale (Model WSI-600; Mettler Toledo, Toledo, OH).

Equipment

Three-dimensional body measurements (3DS) were obtained using the Size Stream SS20 (SS20 Booth Scanner, Size Stream LLC; Cary, NC) (**Figure 2**). The system takes approximately 8-10 seconds to capture 243 precise and accurate measurements (32, 33). The Size Stream SS20 provides highly reliable body surface measurements (32, 33, 37). Volunteers were asked to remove any accessories and clothing except for spandex shorts or sports bras (for women) and secure their hair with a swim cap before being scanned. They were then instructed to stand in a standardized position and remain still during the scan. The 3D body scanner collected 243 body measurements for each volunteer (35). Unilateral measurements were averaged from both sides for data reduction and to focus analyses on regional body dimensions irrespective of limb dominance or asymmetries.

Figure 2. Size Stream SS20 Booth Scanner.

Each walking trial was performed on a treadmill (Trackmaster® TMX428; Full Vision, Inc.; Newton, KS) for six minutes at each of the designated speeds (0.00, 0.45, 0.89, and 1.34 $m \cdot s^{-1}$). Volunteers were allotted a two-minute rest in between speeds and 12-minute rest between load conditions. Respiratory rate was averaged during the final minute of each trial. Indirect calorimetry was collected by a stationary metabolic cart (TrueOne 2400, ParvoMedics; Salt Lake City, UT) and a fitted respiratory mask. The metabolic cart was calibrated before each trial per the manufacturer's instructions. A double-layered vest (V-MAX™ Weight Vest; Weightvest.com, Inc.; Rexburg, ID, USA) was used for testing of 22, 44 and 66% BM loads. The designated vest masses were measured including the weight of the vest itself. The load was packed using standard plates, starting at the bottom layer moving incrementally to the top layer with increasing weight to ensure that the mass was evenly distributed. Plates were arranged symmetrically front to back and laterally on the vest.

Statistical Analysis

All data are reported as mean ± standard deviation unless noted otherwise. Data were analyzed using R statistical software (Version 3.3.1; R Foundation for Statistical Computing; Vienna, Austria). Repeated measures analysis of variance (ANOVA) was conducted to determine interactions between load and RR. If the omnibus test was significant, planned pairwise contrasts were analyzed between loads at each separate speed. Issues with multiple comparisons were addressed by restricting analysis of statistical differences to planned contrasts between load conditions at each speed. No further adjustments for multiplicity were made since these planned contrasts collectively evaluate the extent to which varying levels of external loading affects respiratory rate. The level of statistical significance was set a priori as $p \leq 0.05$.

Multiple step analysis was used to evaluate the influence of 3DS measurements on individual variability of RR during load carriage. For each volunteer at every speed, we fit a separate linear regression equation that predicted RR as a function of load and then extracted the slope coefficient (**Figure 3**). Subsequently, we analyzed the correlation between the coefficients extracted from all volunteers at a given speed and each of the 3DS measurements one by one. This approach enabled identification of individuals with more exaggerated respiratory responses to loading and to examine whether relationships were consistent across standing and walking trials at various speeds. Linear regression analysis was used to calculate the Pearson's correlation coefficient (r) between each 3DS measurement and the change in RR with increased loading (ΔRR/ΔLoad). Values near zero represent the absence of a relationship between two variables, while values close to +1 and -1 represent near-perfect direct and inverse relationships. Any r value outside of ±0.5 indicates a moderately strong relationship (38).

Figure 3. Example slope coefficient extracted from a volunteer's 1.34 m·s^{-1} walk trials.

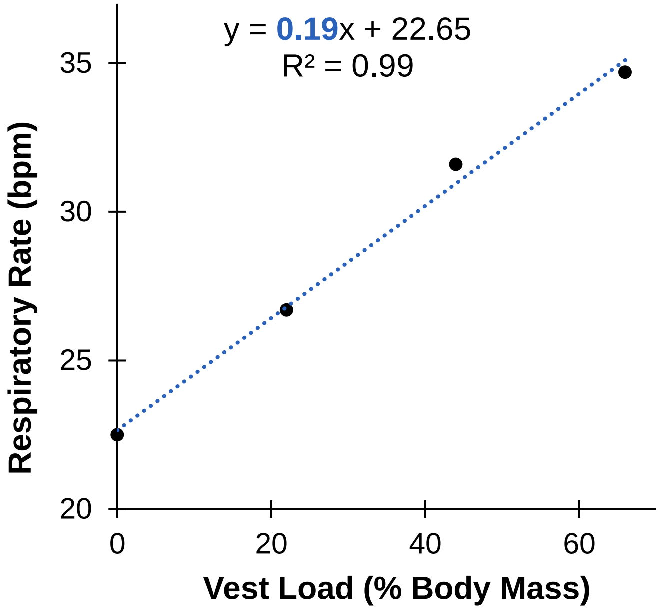

Figure Legend: Points representing a volunteer's recorded average respiratory rate for each vest mass at 1.34 m·s^{-1}. Slope coefficient was extracted from the line of best fit.

RESULTS

Mean RR across all conditions was 25 ± 7 bpm. RR for each experimental condition is reported in **Figure 4.** Main effects of load and speed as well as a significant interaction between load and speed were detected ($p<0.01$). Respiratory rate was higher ($p<0.05$) for the heavier load condition in every comparison excluding two occurrences, 0 to 22% body mass and 44 to 66% body mass at 0.00 $m \cdot s^{-1}$ ($p>0.05$).

Figure 4. Mean ± SD of respiratory rate (RR) at each speed and vest mass.

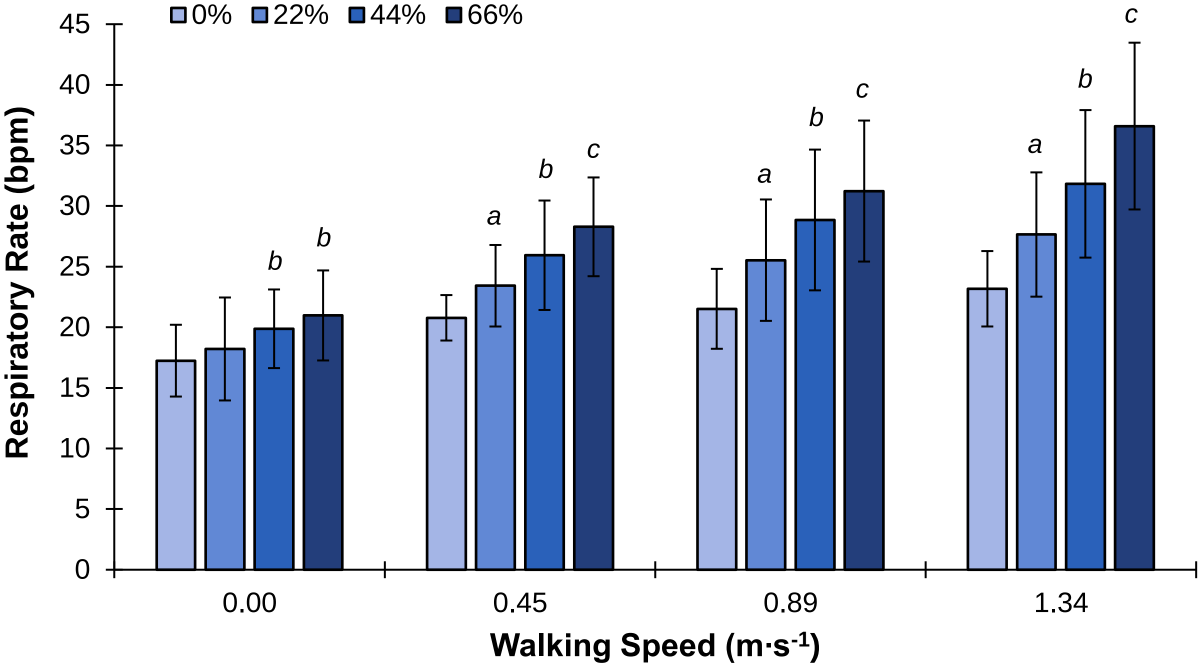

Figure Legend: *a*, significantly greater than 0% BM; *b*, significantly greater than 0 and 22% BM; *c*, significantly greater than 0, 22, and 44% BM.

Extracted slope coefficients for the effect of load on RR were higher at faster walking speeds (0.00 m·s^{-1}, 0.06 ± 0.04 bpm/%BM; 0.45 m·s^{-1}, 0.11 ± 0.08 bpm/%BM; 0.89 m·s^{-1}, 0.15 ± 0.10 bpm/%BM; 1.34 m·s^{-1}, 0.20 ± 0.11 bpm/%BM). **Figure 5** shows the relationships between 3DS measurements and extracted slope coefficients of the ∆RR/∆Load. During standing trials, 164 3DS measurements (98.2%; r, 0.41 ± 0.13) were positively associated with the ∆RR/∆Load. This is much higher than the number of positive correlations identified for the walking trials at 0.45 m·s^{-1} (n = 126, 74.6%; r, 0.10 ± 0.14), 0.89 m·s^{-1} (n = 145, 85.8%; r, 0.13 ± 0.14), and 1.34 m·s^{-1} (n = 138, 81.7%; r, 0.09 ± 0.15). **Tables 1** and **2** reports moderate correlations found between 41 measurements (**Figure 6**) and ∆RR/∆Load across the four speeds.

Figure 5. Pearson's correlation coefficient (r) values between 3DS measurements and individual slope coefficients.

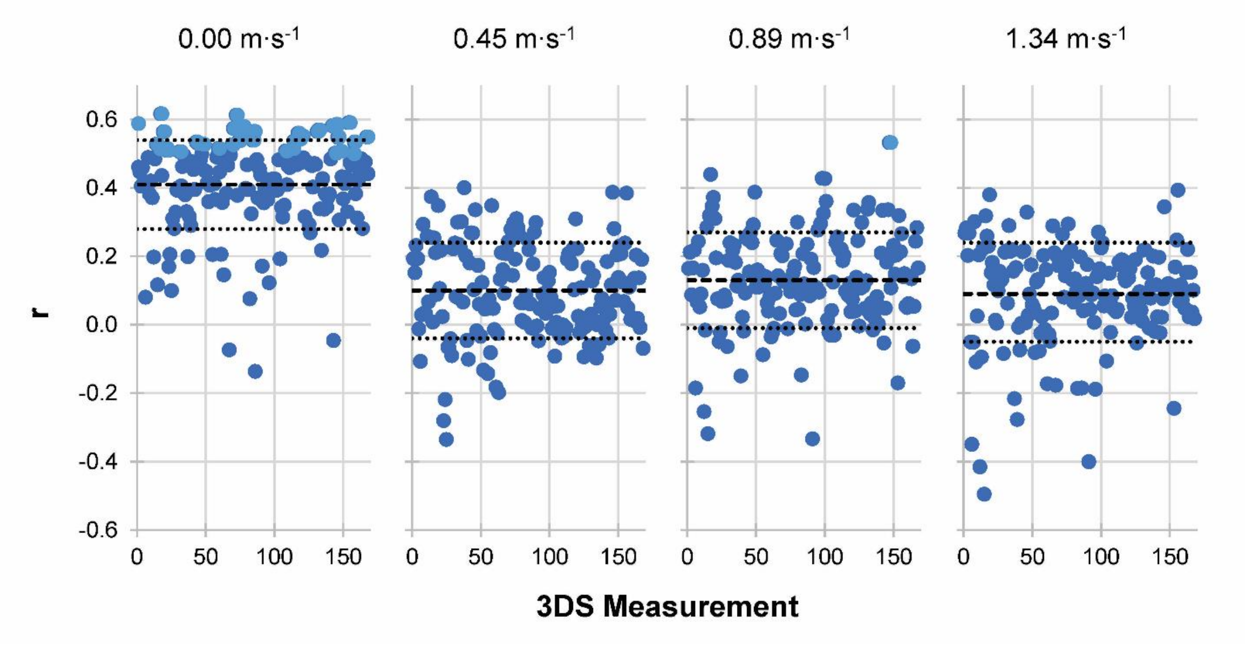

Figure Legend: Pearson correlation coefficients (r) between 167 3DS measurements and ∆RR/∆Load. Across all speeds, 41 measurements reflected moderate relationships (r>0.5, r<-0.5) with the ∆RR/∆Load (highlighted in light blue).

Table 1. Descriptive statistics for 3DS measurements with moderate relationships to the ΔRR/ΔLoad in alphabetical order.

Name	Region	r	Mean ± SD	Min, Max
Actual Mid-Thigh Circum	LE	0.53	51 ± 4	43, 58
Arm Hole Circum	UE	0.51	55 ± 6	45, 65
Arm Length	UE	0.62	60 ± 4	50, 67
Arm Volume (cm^3)	UE	0.51	4,510 ± 736	3,281, 6,132
Axilla Chest Circum TM	TR	0.52	106 ± 10	88, 127
Back Crotch Length	TR	0.51	39 ± 4	29, 46
Bust Girth With Drop	TR	0.51	102 ± 11	85, 129
Chest/Bust Circum	TR	0.53	106 ± 11	88, 129
Chest/Bust Circum TM	TR	0.53	105 ± 11	88, 129
Collar Circum	HN	0.53	40 ± 4	33, 46
Front Jacket TM	TR	0.52	77 ± 6	68, 87
Hinged Bust Circum TM	TR	0.53	107 ± 9	89, 125
Hip Circum	TR	0.57	107 ± 8	94, 125
Hip Circum TM	TR	0.57	107 ± 8	94, 125
Hip Circum TM Back	TR	0.61	28 ± 2	24, 32
Hips 8 Inches Down From Small Of Back	TR	0.58	105 ± 7	93, 117
Hips Two Inches Above Crotch	TR	0.57	106 ± 7	93, 121
Hip Widest Circum TM Front	TR	0.54	26 ± 2	23, 30
Hip Widest Circum TM Back	TR	0.54	66 ± 5	58, 80
Hip Widest TM Circum	TR	0.55	26 ± 2	23, 30
Leg Volume (cm^3)	LE	0.54	10,345 ± 1,614	7,869, 13,351
Low Hip	TR	0.57	107 ± 8	94, 129
Optimal Small Waist Back Height	TR	0.51	105 ± 7	89, 117
Outer Arm Hole Circum	UE	0.57	51 ± 6	41, 62
Over Arm Circum TM	UE	0.52	124 ± 8	111, 142
Over Arm Circum	UE	0.54	126 ± 8	113, 143
Seat Circum	TR	0.55	104 ± 8	89, 119
Seat Circum TM	TR	0.56	104 ± 8	89, 119
Seat Circum TM Back	TR	0.54	28 ± 2	25, 34
Sleeve Length	UE	0.57	80 ± 6	67, 87
Sleeve Length TM	UE	0.57	82 ± 6	70, 90
Surface Area Arm (cm^2)	UE	0.58	1,801 ± 221	1,292, 2,079
Surface Area Torso (cm^2)	TR	0.50	6,482 ± 786	5,189, 8,231
Surface Area Total (cm^2)	WB	0.59	19,257 ± 1,934	15,486, 23,240
Thigh Circum	LE	0.55	62 ± 5	53, 70
Thigh Height $(0.89\ m \cdot s^{-1})$	LE	0.53	74 ± 11	63, 115
Torso Volume (cm^3)	TR	0.51	53,055 ± 11,818	37,497, 85,661
Under Knee Height	LE	0.59	42 ± 3	36, 47
Vertical Trunk Circum	TR	0.50	173 ± 12	148, 192
Volume (cm^3)	WB	0.53	82,856 ± 16,079	60,496, 126,426
Wrist Circum	UE	0.55	17 ± 1	15, 20

Table Legend: Units are displayed in centimeters (cm) unless otherwise noted. Circum, circumference; LE, lower extremity; UE, upper extremity; TM, tape measure; TR, torso; HN, head/neck; WB, whole body.

Table 2. 3DS measurements with moderate relationships to the ΔRR/ΔLoad arranged in descending order by r value.

Rank	Name	Region	r
1	Arm Length	UE	0.62
2	Hip Circum TM Back	TR	0.61
3	Under Knee Height	LE	0.59
4	Surface Area Total (cm^2)	WB	0.59
5	Surface Area Arm (cm^2)	UE	0.58
6	Hips 8 Inches Down From Small Of Back	TR	0.58
7	Hip Circum	TR	0.57
8	Hip Circum TM	TR	0.57
9	Hips Two Inches Above Crotch	TR	0.57
10	Sleeve Length TM	UE	0.57
11	Sleeve Length	UE	0.57
12	Low Hip	TR	0.57
13	Outer Arm Hole Circum	UE	0.57
14	Seat Circum TM	TR	0.56
15	Seat Circum	TR	0.55
16	Wrist Circum	UE	0.55
17	Thigh Circum	LE	0.55
18	Hip Widest TM Circum	TR	0.55
19	Hip Widest Circum TM Back	TR	0.54
20	Seat Circum TM Back	TR	0.54
21	Leg Volume (cm^3)	LE	0.54
22	Hip Widest Circum TM Front	TR	0.54
23	Over Arm Circum	UE	0.54
24	Volume (cm^3)	WB	0.53
25	Chest/Bust Circum	TR	0.53
26	Thigh Height *($0.89\ m \cdot s^{-1}$)*	LE	0.53
27	Chest/Bust Circum TM	TR	0.53
28	Actual Mid-Thigh Circum	LE	0.53
29	Collar Circum	HN	0.53
30	Hinged Bust Circum TM	TR	0.53
31	Front Jacket TM	TR	0.52
32	Axilla Chest Circum TM	TR	0.52
33	Over Arm Circum TM	UE	0.52
34	Arm Hole Circum	UE	0.51
35	Arm Volume (cm^3)	UE	0.51
36	Back Crotch Length	TR	0.51
37	Opt Small Waist Back Height	TR	0.51
38	Torso Volume (cm^3)	TR	0.51
39	Bust Girth With Drop	TR	0.51
40	Surface Area Torso (cm^2)	TR	0.50

Table Legend: Units are displayed in centimeters (cm) unless otherwise noted. Circum, circumference; LE, lower extremity; UE, upper extremity; TM, tape measure; TR, torso; HN, head/neck; WB, whole body.

Figure 6. Human body rendering highlighting the 41 3DS measurements moderately correlated with the ∆RR/∆Load across all speeds.

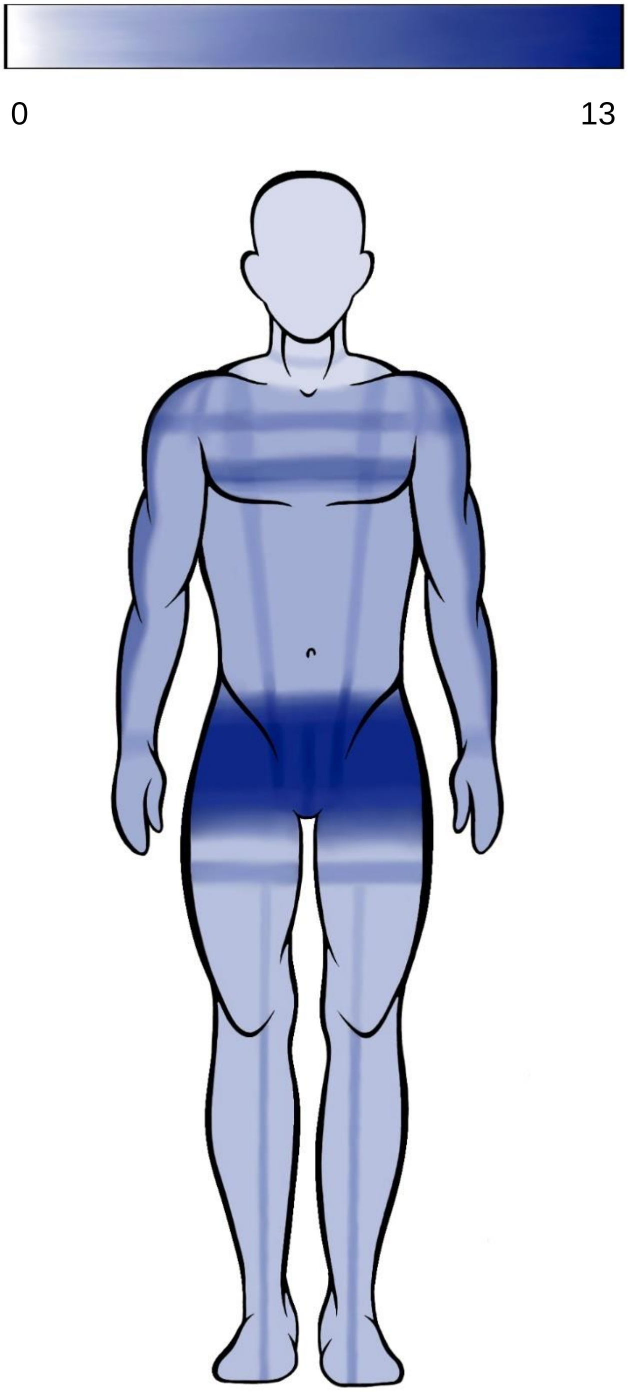

Figure Legend: Human body marked with actual measurement dimensions according to the Size Stream manual. Color gradient representing density of overlapping measurements (0, none in given area; 13, most in given area).

DISCUSSION

The primary purposes of this study were to quantify how RR increases with added vest mass and to evaluate the strength of relationships between individual anthropometrics and RR during military load carriage exercise. We identified increases in RR with added vest masses of 22% or more during all but two experimental conditions ($p<0.05$). Additionally, we uncovered stronger relationships between 3DS anthropometric measurements and the ΔRR/ΔLoad during stationary load carriage than during locomotion. We were able to isolate 41 3DS measurements as having moderate correlations to ΔRR/ΔLoad across four walking speeds. These results have a variety of applications beyond military load carriage (e.g., occupational medicine, recreation, strength and conditioning) (39-41) and may be used to further develop military load carriage equipment. Future studies should examine the degree of the compressive forces of the vest on RR compared to the increased metabolic demands of walking, in addition to load carriage strategies to minimize physiological strain (e.g., vest model, load distribution).

Our study identified a stepwise increase in RR with added vest masses. Differences ($p<0.05$) were detected between 14 of the 16 experimental conditions, excluding the differences between 0 to 22% ($p=0.058$) and 44 to 66% body mass ($p=0.076$) during standing ($0.00\ \mathrm{m\cdot s^{-1}}$). These findings indicate added vest masses of 22% or more increase the degree of cardiorespiratory strain experienced by individuals during walking load carriage. Increases in vest mass raise metabolic activity to sustain the demand of exercise (1-3), further manifesting in increased RR (12, 13). The lack of significant change between two of the experimental conditions (0 to 22% BM and 44 to 66% BM at $0.00\ \mathrm{m\cdot s^{-1}}$) could be contributed to the relatively small sample size of the trials. A larger sample size may detect a more significant change in RR with loading; however, the difference may not be physiologically important.

We identified stronger relationships between 3DS measurements and change in RR with loading at $0.00\ \mathrm{m\cdot s^{-1}}$ than at any of the other three speeds studied. Of the 167 individual measurements, 164 (98.2%) were determined to have a positive relationship with the ΔRR/ΔLoad. The strong positive nature of these interactions indicates a directly proportional relationship between the ΔRR/ΔLoad and the overall size of the individual. The vest masses used in this study were relative to the individual's body mass, meaning that larger individuals were tasked with carrying larger vest masses. Based off our results, one can expect that ventilatory responses during stationary load carriage will increase with the size of the individual. Stronger correlations between the ΔRR/ΔLoad and individual 3DS measurements were only observed during standing. During standing, any increase in RR can only be driven by the compressive forces of the vest mass and the subsequent respiratory muscle strain to adequately expand the thoracic cavity (24). Any increase in RR during walking load carriage is driven by both thoracic compression as well as the increased metabolic cost of walking (1, 5, 23). Thus, the body type more susceptible to the compressive effects on the trunk (e.g., larger hip circumferences) may be less susceptible to the effects of load on locomotor-induced respiratory strain. This would explain why the correlations were so high during standing but were near zero during walking.

We were able to isolate 41 3DS measurements that expressed moderate positive correlations to the $\Delta RR/\Delta Load$ ($r \geq 0.5$). Of these measurements 10 referred to the upper extremity (24.4%), 5 referred to the lower extremity (12.2%), 23 referred to the torso (56.1%), 1 referred to the head/neck (2.4%), and 2 referred to the whole body (4.9%). Only one of the 41 measurements displayed a moderate correlation during walking (thigh height, $0.89\ m \cdot s^{-1}$), while others were only observed during standing ($0.00\ m \cdot s^{-1}$). Of note, 13 measurements (31.7%) are found in the hip region, 10 of which are circumferences. These results enable the conclusion that individuals with larger hips (e.g., circumferences), experience heightened respiratory strain when standing with a weighted vest. Additionally, it is possible that sex differences may influence these relationships (i.e., anatomical differences between male and female hip structure) (42). However, hip measurements recorded from male and female volunteers that participated in the present study were similar (hip circumference*:* male, 106.7 ± 7.6 cm; female, 106.7 ± 9.1 cm). Consequently, the moderate relationships between hip circumferences and $\Delta RR/\Delta Load$ are not simply a consequence of sex differences.

Pre-emptive anthropometric screening could identify specific Soldiers likely to experience greater respiratory strain, indicating a higher level of physical exertion (11). An increased degree of physical exertion may not only result in performance decrements, but also in physiological and perceptual strain (43, 44). Beyond military load carriage, the results of this study could also apply to areas of occupational performance that utilize load carriage such as firefighting, law enforcement, and search and rescue (39). Additionally, recreational activities such as hiking and strength training also utilize frequent, heavy load carriage exercise (40, 41). The ability to predict heightened cardiorespiratory responses to load carriage is an important contribution to the understanding of military performance and exercise physiology (1, 5). Understanding the influence of anthropometrics on the degree of physical exertion experienced by Soldiers or other tactical athletes enables further comprehension of the physiological costs of load carriage, a frequent and demanding military task (3, 5, 23). Predicting each individual Soldiers' tolerance to loading allows for adequate planning by military leadership to reduce Soldier fatigue and increase mission readiness. By better understanding physiological responses to military practices, we can improve training regimens to enhance performance during real-world mission requirements (45). Results of this study may be used to optimize military load carrying equipment and enhance physiological monitoring interventions in tactical populations.

CONCLUSION

This study sought to quantify the relationship between heavy vested load carriage and RR, and investigate the influence of individual anthropometrics on the degree of cardiorespiratory strain experienced during vest-borne military load carriage. Our results have determined that RR increases significantly with added vest masses of at least 22% during walking. We also observed that larger individuals experience increased ventilatory responses to vest-borne stationary load carriage as compared to smaller individuals, with the strongest anatomical predictor being larger hip circumferences. These collective findings provide a better understanding of the physiological costs of load carriage and how to predict which Soldiers may be most affected by disproportionate cardiorespiratory responses.

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