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RELATIONSHIPS BETWEEN 3D BODY SCANNER-DERIVED BODY
MEASUREMENTS AND WALKING METABOLIC RATE IN HEALTHY, ACTIVE
MILITARY-AGE MEN AND WOMEN

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MILITARY-AGE MEN AND WOMEN**

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EXECUTIVE SUMMARY

Introduction: Soldiers regularly engage in highly demanding physical training and operational environments. However, an individual Soldier's energy expenditure remains difficult to accurately predict. Leg length has been shown to be a moderate predictor of metabolic cost, but there is conflicting data regarding the validity and reliability of tape measure methods within the open literature. Three dimensional (3D) body scanners have been shown to be highly reliable and valid modern tools for anthropometric measurements of the human body. This work investigates the use of 3D scanner-derived body measurements to predict individual differences in walking metabolic rate.

Methods: Eighteen Soldiers (16 male and 2 females; age 25.6 ± 6.9 years, height 174.3 ± 7.3 cm, body mass (BM) 74.3 ± 12.8 kg) participated in a controlled load carriage study. Volunteers were each assessed by a 3D full body scan (SS20 Booth Scanner, Size Stream LLC; Cary, NC) before completing six minute walking trials on a treadmill at $1.97 \text{ m}\cdot\text{s}^{-1}$. Metabolic rate was measured during walking trials using indirect calorimetry (TrueOne 2400, ParvoMedics; Salt Lake City, UT). Regression analysis was performed to find the coefficient of determination (R^2) values to determine the statistical correlation between 3D scanner-derived body measurements and metabolic rate.

Results: The 3D scanner provided 243 calculated body measurements. Of the 243 measurements, 45 were identified to have moderate correlations (R^2 between 0.14-0.45). Nine of the top ten ranked measurements were either a midsection height or waist circumference. Notably, Outside Leg Length Left showed the highest correlation ($R^2 = 0.277$).

Conclusion: This study highlights a number of midsection height and waist circumference measurements as 3D scanner-derived predictors of individual differences in walking metabolic rate. Further investigations should be conducted with larger and more diverse sample sizes to better represent large military populations.

INTRODUCTION

Soldiers regularly engage in physically demanding training exercises and real-world operations. These physical demands are related to the need for Soldiers to carry heavy loads for extended periods of time (1). Carrying heavy loads increases injury risk and decreases work capacity (2). Calculated metabolic cost estimation is a useful tool to predict performance potential and physiological responses of individual Soldiers (1). Prediction equations can be based on anthropometric measurements such as body composition (3), body mass index (BMI) (3), and leg length (4). Predicting metabolic costs of loaded ruck marches, an integral part of Soldiers' fitness and training, is useful to the training cadre for optimizing safety and work/rest cycles (1).

Anthropometric measurements such as leg length could be an important tool in predicting individualized physiological responses and metabolic rates of Soldiers. Previous studies (4-7) have shown that leg length is a predictor of walking metabolic costs. Metabolic cost increases as stride length increases due to the step-to-step transition costs (4). According to a study performed by Kuo and Donelan (4), individuals with longer leg lengths have longer stride lengths. As humans walk at increasing speeds, stride lengths increase, thereby increasing metabolic costs of these activities (4). Work by Vaughan and O'Malley (6) confirmed these findings through the use of Froude's number to compare walking metabolic power between Pygmy adults and Caucasian adults on a treadmill. Froude's number is equal to $v^2 \cdot g^{-1} \cdot L^{-1}$ where v is velocity, g is gravitational acceleration, and L is a linear dimension, such as leg length (6). Research found that at fast walking speeds and running speeds, Caucasian adults with longer mean leg lengths, exhibited a higher metabolic cost at any given speed. However, techniques utilized by both Kuo and Donelan (4) or Vaughan and O'Malley (6) did not specify the methods used to measure leg length.

Leg length can be assessed using both manual and technical methods. Radiography is widely viewed as the 'gold standard' for measuring leg length (8-11). However, it is costly (8), requires specialized training for operators (12), and involves exposure to radiation (11). Tape measure methods are a more practical body assessment alternative to radiography (13). However, there remains controversy within research as to which leg length measurement is most reliable. Some studies found the distance from the anterior superior iliac spine (ASIS) to the medial malleolus to be acceptably valid and reliable (8, 10, 11, 14); while others suggest measurement from the ASIS to the lateral malleolus as the most accurate methodology (15). Alternatively, it has been proposed that a precise measurement of leg length can be taken from the umbilicus to the medial malleolus (11, 15). A limitation to tape measure methods is poor interrater reliability (16), and common errors with tape measure methods include difficulty and consistency of identifying landmarks, angular deformities, and subject positioning (11, 16). A study performed by Gurney (9) found measurements taken from the ASIS to either the medial or lateral malleolus to be of questionable validity.

Three dimensional (3D) body scanners are a modern anthropometry tool. Scanners have been proven to be cost and time-efficient measurement systems capable of collecting hundreds of measurements from many different angles in a short time (17). Other advantages to using 3D body scanners over tape measure methods include high test-retest reliability, accuracy, ease-of-use, and expedient robust sampling (16). Additionally, these scanners have been shown to have higher validity than tape measure methods (16) and act as an acceptable substitute to manual measurement methods (17). One specific 3D body scanner of interest is the Size Stream SS20 (SS20 Booth Scanner, Size Stream LLC; Cary, NC), which has been proven to be reliable and highly precise (17, 18). Building on the knowledge of 3D body scanner-derived measurements, this study goes on to provide a preliminary analysis of the relationships between Size Stream body measurements and individual differences in walking metabolic rate.

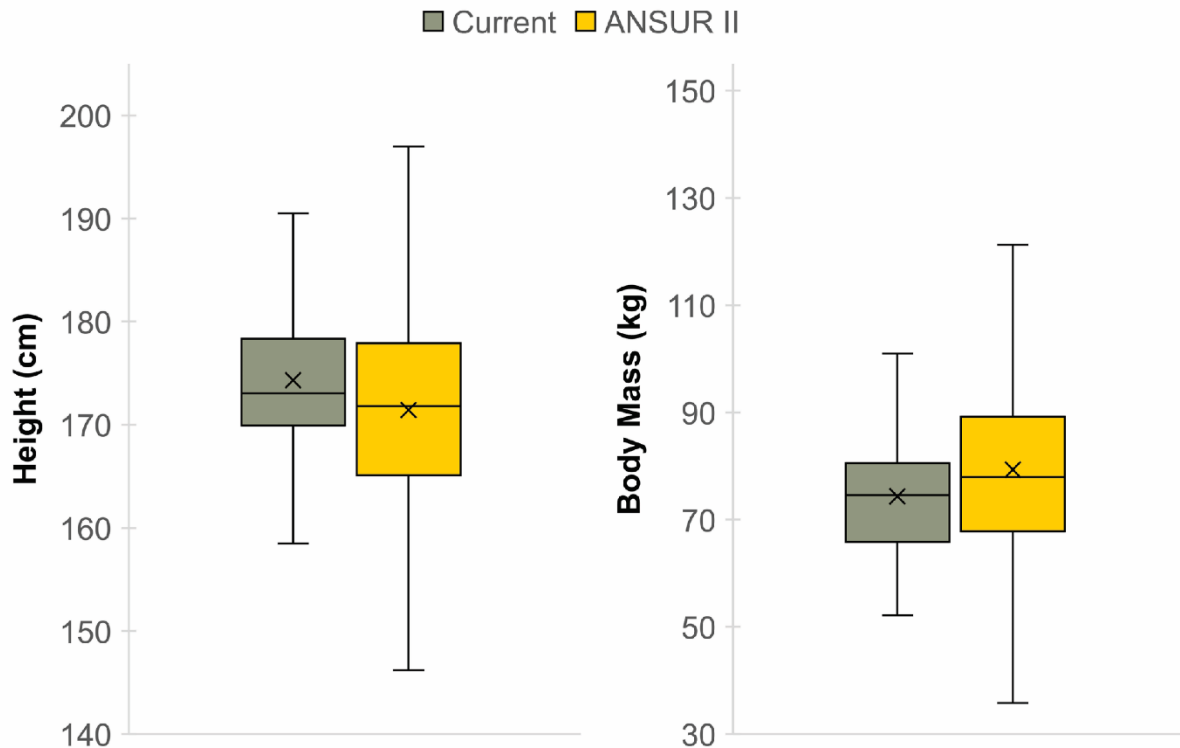
METHODS

We conducted an exploratory, cross-sectional study to investigate the predictive relationships between 3D scanner-derived body measurements and individual walking metabolic rates. Data were analyzed from a subset of volunteer data from an ongoing USARIEM research protocol (Looney 19-12H, "Modeling the Metabolic Cost of Heavy Military Backpacking"). Study volunteers were assessed by a full body 3D scan before completing a six minute treadmill walk at $1.97 \text{ m}\cdot\text{s}^{-1}$. Metabolic costs were measured using indirect calorimetry during the walking trials.

Volunteers

Eighteen volunteers (16 males and 2 females; age 25.6 ± 6.9 years; height 174.3 ± 7.3 cm; body mass (BM) 74.3 ± 12.8 kg) completed the necessary testing for this study's analysis. Figure 1 compares the anthropometrics of the study sample versus 18-44 year old participants in the 2012 US Army Anthropometric Survey (ANSUR II) (19). Volunteers were recruited through the U.S. Army Natick Soldiers Systems Center (NSSC) Human Research Volunteer pool, active duty personnel, and civilian personnel stationed at NSSC. Each volunteer was injury-free and in overall good health. Prior to participation in the study, volunteers were briefed on the purpose of the study as well as potential risks. After briefing, volunteers gave their voluntary informed, written consent. Volunteers also completed medical screening to ensure they met the proper inclusion criteria. During this screening, volunteers completed a background questionnaire to obtain information regarding their demographics, health status, and physical activity. This study was approved by the US Army Medical Research and Development Command Institutional Review Board (MRDC IRB) and the Scientific Review Committee at the U.S. Army Research Institute of Environmental Medicine (USARIEM; Natick, MA).

Figure 1. Comparison of height and body mass of volunteers from current study versus ANSUR II.



Procedures

Prior to each visit, volunteers were instructed to avoid caffeine, nicotine, and were asked to fast for ≥ 10 hours, and to avoid alcohol consumption for ≥ 24 hours. Volunteers were also instructed to avoid vigorous physical activity for ≥ 24 hours prior to their visit. Volunteers were instructed to wear workout clothing to each testing day. To ensure each volunteer was hydrated for the start of each trial, a 500 mL water bottle was provided for them the evening before and the morning of their visit.

Upon arrival to the laboratory each morning, volunteers completed a daily questionnaire. Information was collected on study compliance, pain, and sleep status, and volunteers were asked to provide a urine sample to assess adequate hydration status (urine specific gravity). Volunteers were considered adequately hydrated with a urine specific gravity ≤ 1.03 . Nude body mass was then measured behind a privacy screen using a stationary scale.

Equipment

The Size Stream 3D body scanner (SS20 Booth Scanner, Size Stream LLC; Cary, NC) was used to obtain body measurements of each volunteer (**Figure 2**). Over two million body surface data points are collected in approximately eight seconds, which are used to compute 243 body measurements. This technology has been proven to be

precise (17, 18) and accurate (18). The Size Stream scanner was calibrated before testing each day. Volunteers were instructed to remove any accessories or loose clothing that were not spandex shorts or sports bras to ensure a valid scan. Volunteers with hair longer than shoulder-length were instructed to secure it tightly to the top of their head and all volunteers donned a swim cap to uniform head circumference measures.

Figure 2. Size Stream SS20 Booth Scanner.



All treadmill walking tests were performed on a laboratory treadmill (Trackmaster® TMX428; Full Vision, Inc.; Newton, KS). Volunteers warmed up with 6 min walks at 0.45, 0.89, and 1.34 $\text{m}\cdot\text{s}^{-1}$ interspaced by 2 min rest intervals. Subsequently, each volunteer was required to walk for 6 min at 1.97 $\text{m}\cdot\text{s}^{-1}$ while maintaining a respiratory exchange ratio (RER) < 1 and without transitioning into a running gait.

Each volunteer was fit-tested to the respiratory mask at the start of each visit. A stationary metabolic cart (TrueOne 2400, ParvoMedics; Salt Lake City, UT) was used to perform indirect calorimetry while the volunteers performed a 6 minute walk at 1.97 $\text{m}\cdot\text{s}^{-1}$. The metabolic cart was calibrated before each testing session began in accordance with the manufacturer's instructions. Gas measurements were continuously collected to measure the volume of oxygen uptake ($\dot{V}\text{O}_2$) and volume of expired carbon dioxide ($\dot{V}\text{CO}_2$). Using these measurements, metabolic rate was calculated via indirect calorimetry using the equation from Kipp et al. (20), derived from Péronnet and Massicotte's updated nonprotein respiratory quotient table (21).

Statistical Analysis

Data are reported as mean \pm standard deviation (SD) unless noted otherwise. All data reported in this exploratory, cross-sectional study were analyzed using Excel statistical software (Microsoft Excel for Office 365, Microsoft Corporation; Redmond, WA). Linear regression analysis was performed to find the coefficient of determination (R^2) values between each 3D scanner-derived body measurement and the walking metabolic rate. Coefficients of determination were interpreted by squaring the correlation classification criteria from Taylor (22). An R^2 value ≤ 0.12 indicating a weak association, between 0.14 and 0.45 indicating a moderate association, and ≥ 0.46 indicating a strong association.

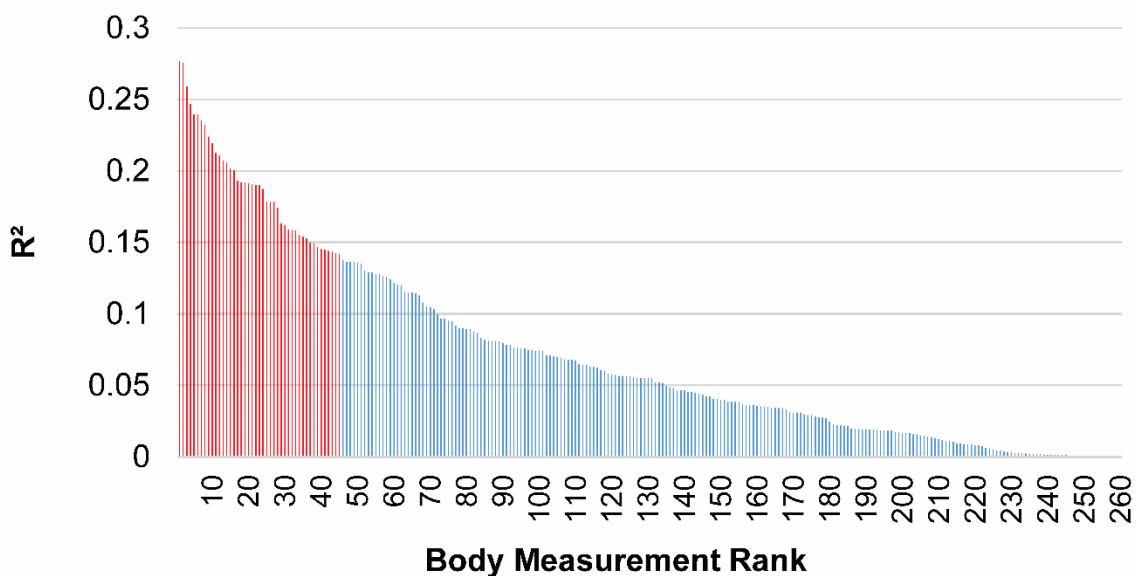
RESULTS

The mean walking metabolic rate across all 18 volunteers was $8.02 \pm 0.70 \text{ W}\cdot\text{kg}^{-1}$. Coefficient of determination (R^2) was used to determine the proportion of variance for each body measurement assessed by the Size Stream 3D body scanner (**Figure 3**). Measurements are listed in order from greatest to smallest R^2 values. In total, forty-five measurements had a moderate correlation with walking metabolic rate while the remaining 198 measurements had weak associations. The seventh ranked measurement, Muscularity Index, is the ratio of the sum of the bicep, calf, and thigh circumferences to the maximum circumference of the stomach and can be calculated using the following equation:

$$\text{Muscularity Index} = \frac{(\text{Bicep Left} + \text{Bicep Right} + \text{Calf Left} + \text{Calf Right} + \text{Thigh Left} + \text{Thigh Right})}{\text{Stomach Max}}$$

where each input is the circumference measured by the Size Stream 3D body scanner at that specific site.

Figure 3. Coefficient of determination (R^2) values between SizeStream 3D body scanner measurements and walking metabolic rate ranked in descending order.



The top ten measurements with the highest R^2 are all displayed in **Table 1**, which displays the measurement number, name, mean \pm SD, minimum, maximum, R^2 , and a reference image. The names and descriptions of each measurement are taken directly from the Size Stream SS20 Measurements & Landmarks Definitions manual. Measurements are listed in order of highest to lowest R^2 .

Table 1. Descriptive data from body measurements with highest association with walking metabolic rate.




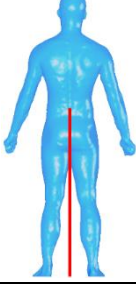

Rank	Name	Mean \pm SD (cm)	Min, Max (cm)	R ²	Image
1	Outside Leg Length Left	41.5 \pm 1.9	[37.8, 45.3]	0.277	
2	Optimal Small Waist Left Height	41.2 \pm 1.9	[37.6, 45.1]	0.275	
3	Optimal Formula Waist Tape Measure Front Right	24.2 \pm 3.2	[16.9, 29.0]	0.259	
4	Optimal Formula Waist Back Height	41.3 \pm 1.9	[37.8, 45.9]	0.247	
5	Waist Height	41.2 \pm 1.9	[37.7, 45.1]	0.240	

Table 1 (continued). Descriptive data from body measurements with highest association with walking metabolic rate.





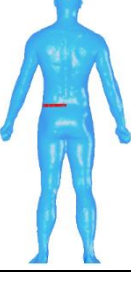
Rank	Name	Mean \pm SD (cm)	Min, Max (cm)	R ²	Image
6	Stomach Front Point Circumference Tape Measure Back Left	7.9 \pm 0.9	[6.5, 10.0]	0.235	
7	Muscularity Index	3.0 \pm 0.2	[2.7, 3.4]	0.232	
8	Outside Leg Length Right	41.4 \pm 1.9	[38.0, 45.4]	0.224	
9	Arm Under Length Left	17.9 \pm 1.1	[15.4, 19.5]	0.219	
10	Stomach Max Circumference Tape Measure Back Left	8.17 \pm 0.9	[6.7, 10.2]	0.213	

Figure 4 displays scatter plots of the top ten measurements with the highest association with walking metabolic rate organized in order from highest to lowest R^2 .

Figure 4. Walking metabolic rate across top ten ranked body measurements with highest association with walking metabolic rate ($W \cdot kg^{-1}$).

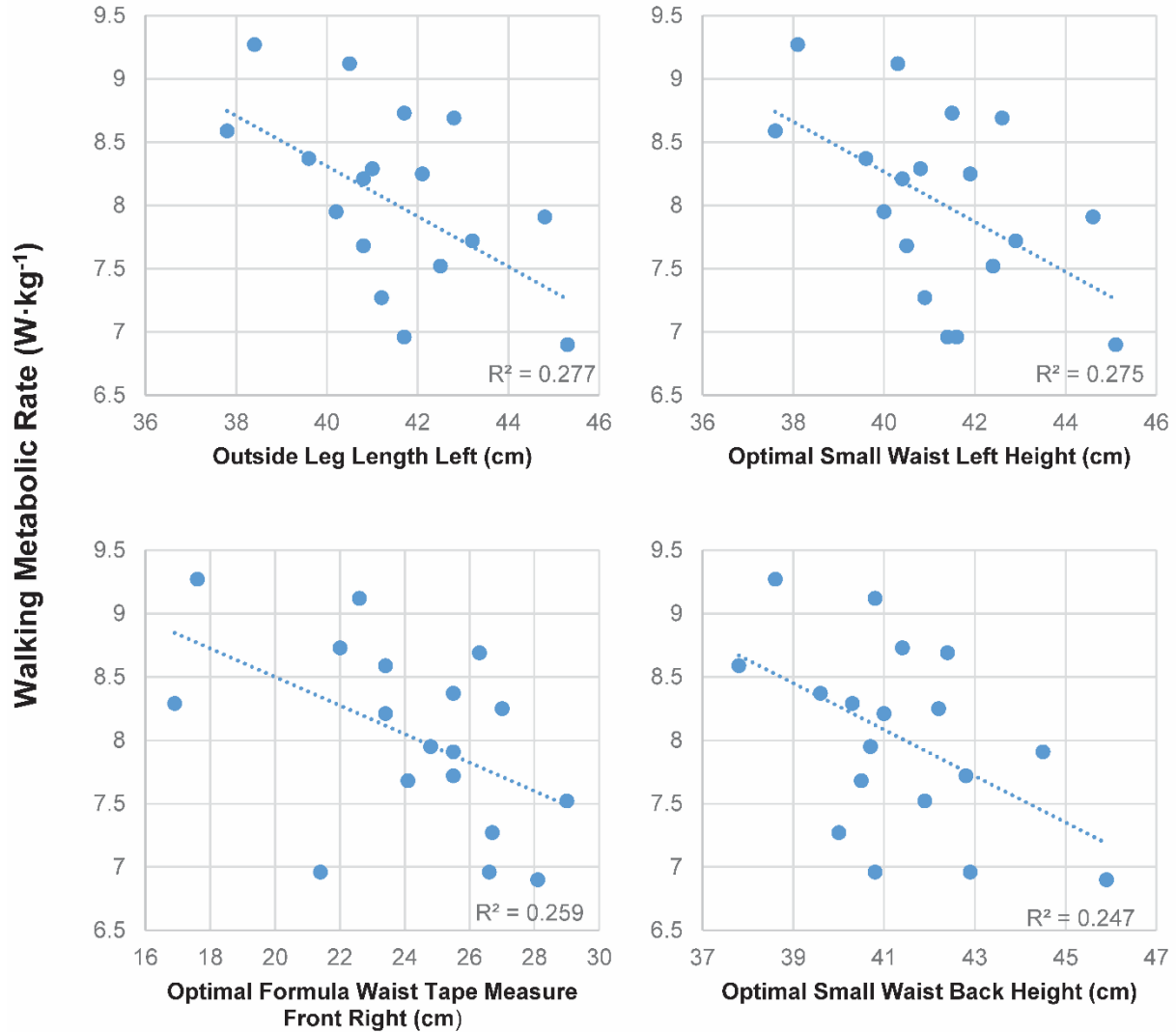
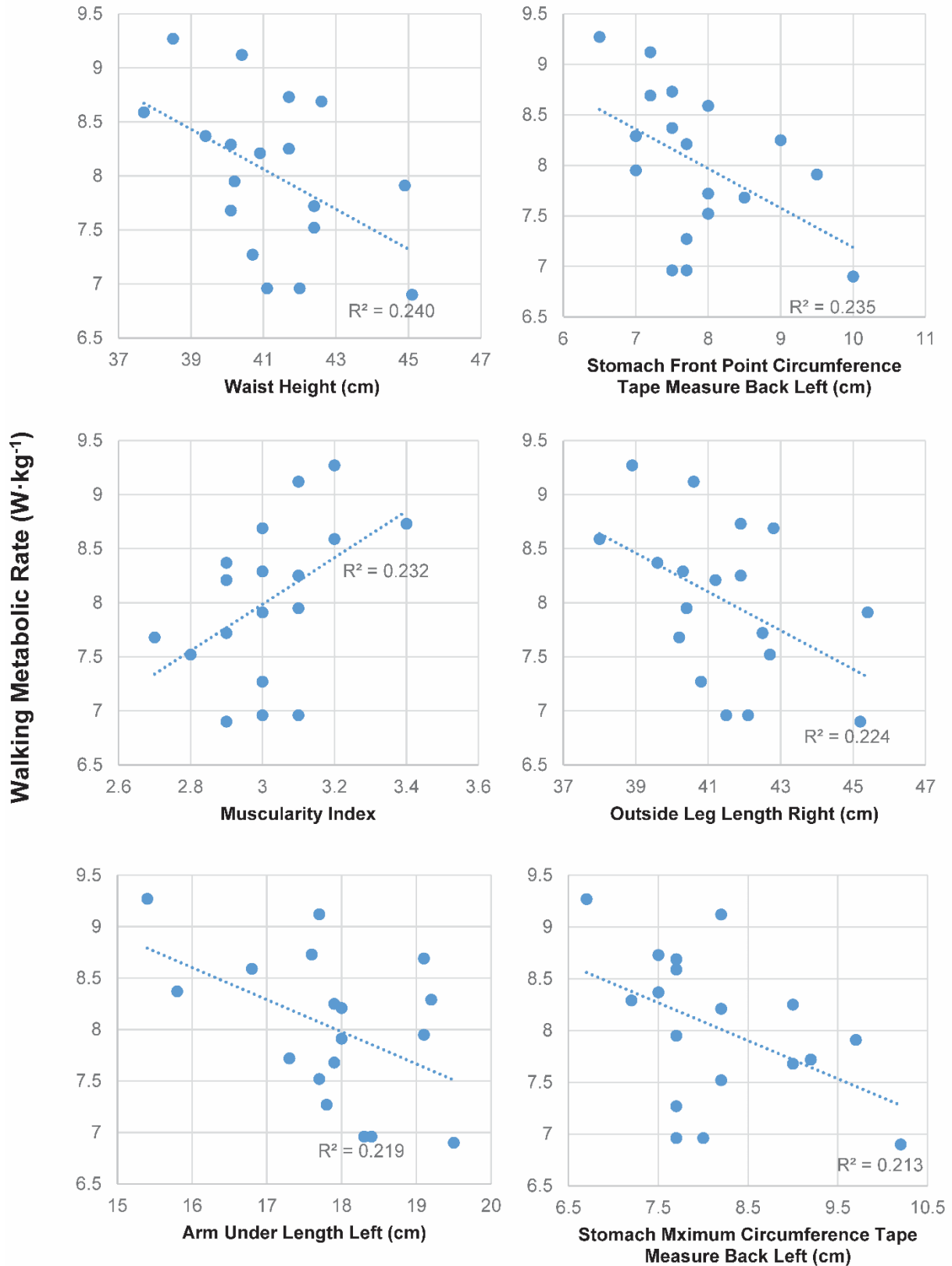


Figure 4 (continued). Walking metabolic rate across top ten ranked body measurements with highest association with walking metabolic rate ($W \cdot kg^{-1}$).



DISCUSSION

This study identified a small group of 3D scanner-derived body measurements ideal for use as inputs in prediction equations to assess walking metabolic rate. Of 243 measurements provided by the Size Stream SS20, 45 measurements had a moderate correlation with walking metabolic rate. Five of the top ten ranked measurements found were midsection body heights and three were partial waist circumferences. The Muscularity Index, which was the seventh ranked measurement, incorporates waist circumference in its denominator. Ultimately, our analysis revealed 9 of the top 10 measurements pertained to the midsection or waist. This study proposes that these midsection height and waist circumference measurements from the 3D scanner are predictors of metabolic rate that should be investigated further by a more extensive study.

The leading measure, Outside Leg Length Left, had a $R^2 = 0.277$. Our findings compare with others suggesting accurate measurements of leg length to include ASIS to medial malleolus (8, 10, 11, 14), ASIS to lateral malleolus (15), and umbilicus to medial malleolus (11, 15). Although the Size Stream SS20 does not make these exact same measurements, close analogs are Outside Leg Length Left and Outside Leg Length Right, which were shown to account for 27.7% and 22.4% of the metabolic rate variance. Waist Height is also a close analog, which accounted for 24.0% of the metabolic rate variance. Arm Under Length Left, which accounted for 21.9% of metabolic rate variance, was not expected as an upper body measurement to have one of the highest predictive values of metabolic rate. In previous work leg length and arm span were shown to be successful predictors of body height across sexes and ethnicities (23-25), which may explain the higher correlation for Arm Under Length Left than most other body measurements provided by the Size Stream.

Anthropometric measures have been shown to accurately predict individual variability in walking economy to include sex-based differences in walking metabolic rate (5), differences across individuals walking at high speeds (6) and were found to be essential variables to consider, along with step rate in order to predict metabolic cost (7). As 3D scanners and other modern tools capable of collecting anthropometric measurements become available with good reliability and accuracy across measures, such technologies will significantly increase the volume and efficiency of data collection over manual methods. However, additional research is needed to determine whether a combination of 3D scanner-derived body measurements is optimal for integration into prediction equations for accurate and reliable measures of metabolic rate.

The current study focused on 3D measures from a small cohort of eighteen individuals of similar sex, race/ethnicity, size (**Figure 1**), fitness levels and occupational backgrounds. Future studies should include a larger sample population with greater diversity across all demographic variables and military occupations to provide a more

representative data set for use in the military. A larger group of volunteers across sexes could enable one or more body measurements to emerge as ideal for individualized metabolic rate estimations.

Inclusion of a greater sample of women in future work has the potential to explore sex differences between the 3D-derived body measurements and walking metabolic rate. Previous studies have shown basic walking differences between men and women (26). At “common speeds”, males have a longer stride length on average than females, but lower stride frequency (5). Yet, at higher speeds, females tend to rely more on stride length and males tended to rely more on stride frequency. This difference in running economy between sexes indicates that women, due to their innate shorter stature, and thus shorter stride lengths in combination with shorter ground contact time, will typically have a higher metabolic cost than men at common speeds (5). Additionally, it is of interest to explore sex differences that may be revealed through 3D scanner-derived body measurements as compared to metabolic cost. With more women entering the military each year (26), it is important that the data included in future studies best represents the current military population. This may play an important role as we begin to understand how a sex-integrated force trains and works efficiently as a unit.

This is the first study to examine 3D scanner-derived body measurements from the Size Stream SS20 in relation to walking metabolic rate. Our preliminary results show a number of midsection and waist-related 3D scanner-derived body measurements that better predict individual differences in walking metabolic rate, and allude to further research on larger military populations to develop more comprehensive use of such measures in military accepted prediction equations. Future studies should consider investigating relationships between body measurements and walking metabolic rates in circumstances shown to alter metabolic demands such as various walking speeds (3), incline/decline, slopes (27), different types of terrain (28, 29), and military load carriage (30). As 3D total body scanning technology continues to evolve, it has the potential to become a useful tool for body composition and anthropometric measurements, especially as these measurements can aid in predicting values such as metabolic cost.

CONCLUSION

This investigation provides quantitative evidence that 3D scanner-derived midsection heights and stomach circumferences have the strongest relationships with walking metabolic rate out of the available Size Stream measurements. To achieve optimal performance, predicting the performance potential and physiological response of individual Soldiers by using metabolic cost derived from 3D scanner-derived body measurements can be beneficial. Further research is needed to better represent large military populations and reveal the full potential of using 3D body scanners to measure anthropometrics to assist in predicting individual difference in energy expenditure.

REFERENCES

1. Potter AW, Santee WR, Clements CM, Brooks KA, Hoyt RW. Comparative analysis of metabolic cost equations: A review. *Journal of Sport and Human Performance*. 2013;1(3):34-42.
2. Knapik J, Reynolds K. Load carriage in military operations. A review of historical, physiological, biomechanical and medical aspects Borden Institute, Walter Reed Army Medical Center, Washington, DC. 1997.
3. Looney DP, Potter AW, Pryor JL, Bremner PE, Chalmers CR, McClung HL, et al. Metabolic costs of standing and walking in healthy military-age adults: a meta-regression. *Med Sci Sports Exerc*. 2019;51(2):346-51.
4. Kuo AD, Donelan JM. Dynamic principles of gait and their clinical implications. *Phys Ther*. 2010;90(2):157-74.
5. Chapman RF, Laymon AS, Wilhite DP, McKenzie JM, Tanner DA, Stager JM. Ground contact time as an indicator of metabolic cost in elite distance runners. *Med Sci Sports Exerc*. 2012;44(5):917-25.
6. Vaughan CL, O'Malley MJ. Froude and the contribution of naval architecture to our understanding of bipedal locomotion. *Gait Posture*. 2005;21(3):350-62.
7. Zarrugh MY, Radcliffe CW. Predicting metabolic cost of level walking. *Eur J Appl Physiol Occup Physiol*. 1978;38(3):215-23.
8. Farahmand B, Ebrahimi Takamjani E, Yazdi HR, Saeedi H, Kamali M, Bagherzadeh Cham M. A systematic review on the validity and reliability of tape measurement method in leg length discrepancy. *Med J Islam Repub Iran*. 2019;33:46.
9. Gurney B. Leg length discrepancy. *Gait Posture*. 2002;15(2):195-206.
10. Khamis S, Carmeli E. A new concept for measuring leg length discrepancy. *J Orthop*. 2017;14(2):276-80.
11. Sabharwal S, Kumar A. Methods for assessing leg length discrepancy. *Clin Orthop Relat Res*. 2008;466(12):2910-22.
12. Waite S, Grigorian A, Alexander RG, Macknik SL, Carrasco M, Heeger DJ, et al. Analysis of perceptual expertise in radiology—Current knowledge and a new perspective. *Frontiers in human neuroscience*. 2019;13:213.
13. Friedl KE. Mathematical modeling of anthropometrically based body fat for military health and performance applications. *Body Composition: Health and Performance in Exercise and Sport*. 2017:285-305.

14. Neelly K, Wallmann HW, Backus CJ. Validity of measuring leg length with a tape measure compared to a computed tomography scan. *Physiother Theory Pract.* 2013;29(6):487-92.
15. Woerman AL, Binder-Macleod SA. Leg length discrepancy assessment: accuracy and precision in five clinical methods of evaluation*. *J Orthop Sports Phys Ther.* 1984;5(5):230-9.
16. Xia S, Guo S, Li J, Istook C. Comparison of different body measurement techniques: 3D stationary scanner, 3D handheld scanner, and tape measurement. *The Journal of The Textile Institute.* 2019;110(8):1103-13.
17. Pedroli E, Digilio R, Tuena C, Durá Gil J, Cernigliaro F, Riva G, et al. The Use of 3D Body Scanner in Medicine and Psychology: A Narrative Review: 7th International Conference, MindCare 2018, Boston, MA, USA, January 9–10, 2018, Proceedings. 2018. p. 74-83.
18. Tinsley GM, Moore ML, Benavides ML, Dellinger JR, Adamson BT. 3-Dimensional optical scanning for body composition assessment: A 4-component model comparison of four commercially available scanners. *Clin Nutr.* 2020;39(10):3160-7.
19. Gordon CC, Blackwell CL, Bradtmiller B, Parham JL, Barrientos P, Paquette SP, et al. 2012 Anthropometric Survey of US Army Personnel: Methods and Summary Statistics. Natick, MA: U.S. Army Natick Soldier Research, Development, and Engineering Center; 2014.
20. Kipp S, Byrnes WC, Kram R. Calculating metabolic energy expenditure across a wide range of exercise intensities: the equation matters. *Appl Physiol Nutr Metab.* 2018;43(6):639-42.
21. Péronnet F, Massicotte D. Table of nonprotein respiratory quotient: an update. *Can J Sport Sci.* 1991;16(1):23-9.
22. Taylor R. Interpretation of the correlation coefficient: a basic review. *Journal of diagnostic medical sonography.* 1990;6(1):35-9.
23. Mohanty SP, Babu SS, Nair NS. The use of arm span as a predictor of height: A study of South Indian women. *J Orthop Surg (Hong Kong).* 2001;9(1):19-23.
24. Quanjer PH, Capderou A, Mazzioglu MM, Aggarwal AN, Banik SD, Popovic S, et al. All-age relationship between arm span and height in different ethnic groups. *Eur Respir J.* 2014;44(4):905-12.
25. Sarma A, Barman B, Das GC, Saikia H, Momin AD. Correlation between the arm-span and the standing height among males and females of the Khasi tribal population of Meghalaya state of North-Eastern India. *J Family Med Prim Care.* 2020;9(12):6125-9.

26. Bensahel N, Barno D, Kidder K, Saylor K. Battlefields and Boardrooms. Women's Leadership in the Military and the Private Sector Washington, DC: Center for a New American Security. 2015.
27. Looney DP, Santee WR, Hansen EO, Bonventure PJ, Chamlers CR, Potter AW. Estimating energy expenditure during level, uphill, and downhill walking. *Med Sci Sports Exerc.* 2019; 51(9): 1954-1960.
28. Richmond PW, Potter AW, Santee WR. Terrain factors for predicting walking and load carriage energy costs. *J Sport Hum Perf.* 2015; 3(3):1-26.
29. Richmond PW, Potter AW, Looney DP, Santee WR. Terrain coefficients for predicting energy costs of walking over snow. *Appl Ergon.* 2019; 74:48-54.
30. Looney DP, Doughty EM, Figueiredo PS, Vangala SV, Pryor JL, Santee WR, et al. Effects of modern military backpack loads on walking speed and cardiometabolic responses of US Army Soldiers. *Appl Ergon.* 2021; 94.