Abdominal Circumference Is Superior to Body Mass Index in Estimating Musculoskeletal Injury Risk

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ABSTRACT

NYE, N. S., D. H. CARNAHAN, J. C. JACKSON, C. J. COVEY, L. A. ZARZABAL, S. Y. CHAO, A. D. BOCKHORST, and P. F. CRAWFORD. Abdominal Circumference Is Superior to Body Mass Index in Estimating Musculoskeletal Injury Risk. *Med. Sci. Sports Exerc.*, Vol. 46, No. 10, pp. 1951–1959, 2014. **Purpose**: The purpose of this study was to compare body mass index (BMI) and abdominal circumference (AC) in discriminating individual musculoskeletal injury risk within a large population. We also sought to determine whether age or sex modulates the interaction between body habitus and injury risk. **Methods**: We conducted a retrospective cohort study involving 67,904 US Air Force personnel from 2005 to 2011. Subjects were stratified by age, sex, BMI, adjusted BMI, and AC. New musculoskeletal injuries were recorded relative to body habitus and time elapsed from the start of study. **Results**: Cox proportional hazards regression revealed increased HR for musculoskeletal injury in those with high-risk AC (males, >39 inches; females, >36 inches) compared with HR in those with low-risk AC (males, ≤35 inches; females, ≤32 inches) in all age categories (18–24 yr: HR = 1.567, 95% confidence interval (CI) = 1.327–1.849; 25–34 yr: HR = 2.089, 95% CI = 1.968–2.218; ≥35 yr: HR = 1.785, 95% CI = 1.651–1.929). HR for obese (BMI, ≥30 $kg{\cdot}m^{-2}$) compared with that for normal individuals (BMI, <25 $kg{\cdot}m^{-2}$) were less elevated. Kaplan–Meier curves showed a dose–response relation in all age groups but most prominently in 25- to 34-yr-old participants. Time to injury was consistently lowest in 18- to 24-yr-old participants. Score chi-square values, indicating comparative strength of each model for injury risk estimation in our cohort, were higher for AC than those for BMI or adjusted BMI within all age groups. **Conclusions**: AC is a better predictor of musculoskeletal injury risk than BMI in a large military population. Although absolute injury risk is greatest in 18- to 24-yr-old participants, the effect of obesity on injury risk is greatest in 25- to 34-yr-old participants. There is a dose–response relation between obesity and musculoskeletal injury risk, an effect seen with both BMI and AC. **Key Words:** OBESITY, CENTRAL OBESITY, MILITARY, INJURY, INJURY PREVENTION

Considered separately, obesity (15,32) and musculoskeletal injuries (16,31) each present substantial public health challenges. Multiple studies demonstrate that these two widely prevalent conditions are associated (21,37,40), particularly with regard to specific injuries including low back pain (14,34), foot and heel pain (9), sprains and strains (17), overuse injuries (2), and knee osteoarthritis (OA) (5). However, the vast majority of the literature regarding obesity and musculoskeletal injury risk has focused on a single measure of obesity, namely body mass index (BMI). Very few studies have considered the effect of other measures of obesity, such as abdominal circumference (AC), body fat percentage, or waist-to-hip ratio, on musculoskeletal injury risk. To the authors' knowledge, only six published studies have evaluated musculoskeletal injury risk as related to alternative measures of obesity, yet none of these compared the relative strengths and weaknesses of different measures in discriminating injury risk beyond simple side-by-side comparison of HR/odds ratios or relative risks (RR). Taanila et al. (36) studied various injury risk factors among 944 young male Finnish Defence Force conscripts over 6 months and found that both high BMI (≥30 $kg{\cdot}m^{-2}$) and AC (>40.2 inches) were associated with an approximately 1.8-fold risk for musculoskeletal disorders. In a civilian study on Finnish young adults (*n* = 2575; age, 24–39 yr;

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12 months of data), Shiri et al. (35) found that increased waist circumference was more strongly associated with low back pain than BMI but this was significant only for females. In two methodologically similar hypothesis-generating studies in 1993 (21,23), Jones et al. (21) found no association between elevated body fat percentage and injury risk in groups (n = 303 and n = 391, respectively) of army conscripts in basic training over 8–12 wk. Only one of these studies found a significantly increased injury risk in subjects with elevated BMI. Lohmander et al. (27) found that elevated BMI (RR, 8.1) was associated with greater risk for knee OA than waist circumference (RR, 6.7) or waist-to-hip ratio (RR, 2.2). Finally, Wang et al. (39) showed that both BMI $\geq$30 kg·m^{-2} and elevated waist circumference were associated with increased risk for total knee arthroplasty (a surrogate marker for symptomatic end-stage OA). The existing literature evaluating injury risk with respect to alternative measures of obesity is limited in number of studies, breadth of populations, and length of follow-up and does not permit conclusions as to which measure best discriminates injury risk.

Many different measures of obesity have been used in the literature (6). The World Health Organization (41) primarily uses BMI at the population level on the basis of availability and uniform applicability to both sexes. However, the use of BMI in medical practice has been challenged in recent years, with many studies showing that measures of abdominal obesity are most strongly correlated with disease risk (including cardiovascular disease, diabetes mellitus, metabolic syndrome, and many others) (13,18,20,26) and even mortality (19). In response to these findings, the US Air Force (USAF) began to assess individuals' health risk on the basis of AC as part of routine fitness testing (1). At this time, the USAF is the only military service that measures the AC of every individual during their required physical fitness test. Members are classified as low risk, moderate risk, or high risk using cutoffs consistent with recommendations in the literature (3). Other services use AC as a secondary measure in those not meeting BMI criteria for retention. Whether increased AC is more strongly associated with musculoskeletal injury risk than BMI has not been clearly demonstrated in the literature.

Although significant work has been accomplished on the epidemiology and prevention of injuries in the military, there is yet a shortage of long-term data regarding the relation between obesity and musculoskeletal injuries. Most military studies have included short follow-up periods and/or have focused on young, mostly male recruits (12,21,23–25). A 2009 review (29) highlighted the need for data regarding the implications of obesity on long-term health and physical performance in military personnel. Since that time, very few longer-term injury studies in military personnel have been published. Jones et al. (22) published an important epidemiologic study in 2010 evaluating acute traumatic and overuse injuries from 2000 to 2006. However, it did not specifically evaluate the role of obesity, and the overuse injury data in this study was mostly cross-sectional for a single year (2006). Note that only recently has a standardized format for reporting overuse injuries been introduced (16).

The main purpose of this study was to compare AC and BMI for estimating musculoskeletal injury risk in a large diverse population. Our primary hypothesis was that AC would show a stronger association with injuries than BMI in all groups within our cohort and would serve as a superior predictor of injury risk. We also sought to determine whether age or sex modulates the interaction between body habitus and injury risk, hypothesizing on the basis of anecdotal experience that older individuals and females may be more prone to injury. A final objective was to provide data regarding the relation between obesity and musculoskeletal injury in the active duty USAF at large over a long-term period, with the overarching goal of informing interventions for injury prevention. The literature in this area is limited but thus far has failed to show an effect on musculoskeletal injury rates (neither increasing nor decreasing) with lifestyle interventions in obese individuals (10,11). However, an improved understanding of musculoskeletal injury risk factors may enable weight loss interventions to be better directed and more successful for injury prevention. Dramatic weight loss in the morbidly obese, as seen with bariatric surgery, has been quite successful at reducing obesity-associated musculoskeletal pain and physical disability (28,30).

METHODS

We conducted a retrospective cohort study evaluating time to first musculoskeletal injury among all active duty USAF members from January 2005 through December 2011. Inclusion criteria required that the individual be continuously on active duty status and have performed at least one physical fitness test every year during the study period. All individuals with a musculoskeletal injury during the 12 months before the study period were excluded. In addition, those with conditions known to be associated with weight change (pregnancy, eating disorders, thyroid disorders, etc.) and other specific conditions that may be associated with increased risk for musculoskeletal injury (nicotine dependence, inflammatory bowel disease, cancer, etc.) were also excluded. (see Table, Supplemental Digital Content 1, http://links.lww.com/MSS/A384, for a full list of excluded conditions).

During routine fitness testing, biometric data including height, weight, and AC for each service member are measured by trained USAF individuals (physical training leaders) using standardized techniques and recorded in a database (1). The BMI is calculated as weight (kg)/height (m^2). AC is obtained using specific guidance, as outlined in the *Air Force Instruction 36-2905* (1). This regulation directs physical training leaders to measure AC with a flexible tape measure as the horizontal circumference from the superior aspect of the right iliac crest, with the tape measure directly on the skin. The measurement is repeated three times, and the average is documented. This allows a standardized reproducible procedure for all USAF personnel. We used three primary data sources for our study: 1) the biometric data were abstracted from the USAF Fitness Management System, 2) diagnostic codes for musculoskeletal and other medical conditions were obtained from the Military Health System Medical Mart, and 3) data for restrictions on occupational and/or physical duties due to illness/injury were collected from the Predeployment Individual Medical Readiness (PIMR) database. Institutional review board approval was secured before the acquisition of these data from the Wilford Hall Medical Center institutional review board in San Antonio, TX.

Definitions. For the purposes of this study, we used the World Health Organization definitions of obesity and overweight based on BMI (normal, $<25\ \text{kg·m}^{-2}$; overweight, ≥ 25 but $<30\ \text{kg·m}^{-2}$; obese, $\geq 30\ \text{kg·m}^{-2}$) and USAF categorizations of AC (low risk (males, ≤35 inches; females, ≤32 inches), moderate risk (males, >35 but ≤39 inches; females, >32 but ≤36 inches), and high risk (males, >39 inches; females, >36 inches)). In light of the known preponderance (7) of overweight compared with normal subjects in the military and given the controversy about misclassification (8) of highly muscular individuals, we included an additional categorization termed "adjusted BMI" (aBMI). This measure (8) gives a more lenient definition of normal as BMI $<27.8\ \text{kg·m}^{-2}$ for males and $<27.3\ \text{kg·m}^{-2}$ for females. Accordingly, in aBMI, overweight is defined as BMI ≥ 27.8 but $<30\ \text{kg·m}^{-2}$ for males and ≥ 27.3 but $<30\ \text{kg·m}^{-2}$ for females. We hypothesized that this approach would reduce misclassification by allowing some number of muscular but physically fit (low adiposity) individuals to be classified as normal. To account for subjects' multiple fitness measurements during the study period, which may vary with time, we used the average of all documented measurements up until their incident injury (or end of study for those never injured) for each measure of interest. An underweight group was not included because of very low prevalence of BMI $<18.5\ \text{kg·m}^{-2}$ in the study population (7).

Musculoskeletal injury was defined as any damage to the musculoskeletal system resulting from acute or chronic overexposure to mechanical energy. This definition was adapted from the broader injury definition used by the Department of Defense Military Injury Prevention Priorities Working Group (33).

Outcome measures. The main outcome measure was any new diagnosis of a musculoskeletal injury in the medical record, whether intentional or unintentional. As stated previously, these injuries were correlated to a subject's BMI and AC (specifically, the average of all BMI and AC measurements taken from the subject before injury). Medical records from deployed or remote installations were not included because of different injury risks. A relatively small number of individuals had a new documented duty restriction for a musculoskeletal injury in the PIMR database but no specific diagnosis of such in their electronic medical records. In these instances, it is likely that these injuries were simply coded under an administrative or nonspecific *International Classification of Diseases, Ninth Revision,* code in the electronic medical record (or medical documentation was simply omitted by the provider or lost because of technical reasons) yet were coded more specifically in PIMR. To gain a more complete and accurate data set, these injuries were also counted as an outcome of interest. Using our definition of musculoskeletal injury, we created a list of *International Classification of Diseases, Ninth Revision, Clinical Modification,* diagnosis codes on the basis of previous literature (16,22,33). All musculoskeletal codes from the widely used Barell injury matrix (4) were combined with all codes from the injury-related musculoskeletal conditions matrix (16). Because OA is often the result of chronic repetitive joint trauma or overloading (and therefore meets our definition of musculoskeletal injury), we also added a series of OA codes to create a unified musculoskeletal injury matrix (see Table, Supplemental Digital Content 2, http://links.lww.com/MSS/A385, for the complete list of codes in matrix format). Although OA is typically not included among injury classification schemes in the published literature (4,16), we feel that doing so comes closer to true recognition of the acute, subacute, and chronic effects of excessive mechanical energy on the musculoskeletal system.

Statistical analysis. Subjects were stratified by age (18–24, 25–34, and ≥35 yr, determined at the start of study period). Subjects within each age group were categorized by BMI (normal, overweight, or obese), aBMI (normal, overweight, or obese), and AC (low risk, moderate risk, or high risk), as described previously. Unadjusted injury rates were calculated by dividing numerator (number of subjects in each body habitus category with at least one versus zero diagnosis of musculoskeletal injury during study period) by denominator (total subjects within each weight classification category). Kaplan–Meier curves were created for each age group on the basis of the three body habitus classifications (BMI, aBMI, and AC) and the calculated time to first musculoskeletal injury or end of the study period. Cox proportional hazard regression analysis was used to estimate the risk for musculoskeletal injury within each age and sex group, adjusting for BMI, aBMI, and AC. In a secondary analysis, the aBMI system was modified to make subgroup sizes more comparable with AC group sizes in an effort to remove any possible bias from the subgroup definitions and more fully assess the null hypothesis (cutoff for obese was raised to $\geq 32.3\ \text{kg·m}^{-2}$ for females and $\geq 32.8\ \text{kg·m}^{-2}$ for males, and obese group was renamed "over obese"). Cox proportional hazard regression was then repeated for the newly defined groups. Finally, the models were compared (AC, BMI, and aBMI, including higher cutoffs for "over obese" in aBMI model) for best fit to the data by using a best subset selection method. This method (score chi-square) finds the model with the highest likelihood score statistic for all possible model sizes and all possible combinations of predictor variables. Data were analyzed using the SAS and SPSS softwares. A P value < 0.05 was considered significant.

RESULTS

Population. Table 1 presents subject demographics. As shown, 67,904 individuals met the criteria for inclusion in

TABLE 1. Demographics.

Variable	Total
n	67,904
Age	
Mean (SD)	32.61 (6.14)
Minimum, maximum	19, 60
Gender, *n* (%)	
Female	6398 (9.4)
Male	61,506 (90.6)
Age, *n* (%)	
18–24 yr	5395 (7.9)
25–34 yr	38,499 (56.7)
≥35 yr	24,010 (35.4)
AC, *n* (%)	
Low risk	47,191 (69.5)
Moderate risk	18,874 (27.8)
High risk	1839 (2.7)
BMI, *n* (%)	
Normal	25,158 (37.1)
Overweight	35,118 (51.7)
Obese	7628 (11.2)
aBMI, *n* (%)	
Normal	48,209 (71.0)
Overweight	12,067 (17.8)
Obese	7628 (11.2)

Descriptor variables for the cohort are reported as quantities and percentages.

the study, 7.9% of which were 18–24 yr old, 56.7% were 25–34 yr old, and 35.4% were ≥35 yr old at study start. The vast majority (90.6%) of subjects were male (note that in 2010, the entire USAF active duty force consisted of 81.0% male personnel) (38). Whereas 11.2% were obese by average BMI, 51.7% met the definition of overweight using traditional thresholds (BMI ≥ 25 but $<30\ \text{kg}\cdot\text{m}^{-2}$), as compared with that in the more lenient aBMI threshold (≥ 27.3 but $<30\ \text{kg}\cdot\text{m}^{-2}$ for females and ≥ 27.8 but $<30\ \text{kg}\cdot\text{m}^{-2}$ for males) where only 17.8% were classified as overweight. Using the USAF criteria for AC risk groups, we found that the majority of subjects were classified as low risk (69.5%) (i.e., AC, ≤35 inches (males) or ≤32 inches (females)). The population was noted to include 27.8% with moderate-risk AC and 2.7% with high-risk AC. We also noted the expected trend of a decreasing proportion of low-risk AC as age increased. Of the low-risk AC individuals, 44.2% and 1.7% were classified as overweight and obese, respectively, by traditional BMI criteria. Furthermore, of all subjects with BMI $\geq 30\ \text{kg}\cdot\text{m}^{-2}$, 9.9% had low-risk AC and 66.7% had moderate-risk AC.

Musculoskeletal injury. Unadjusted injury rates by age, gender, and body habitus were calculated, representing the proportion of individuals in each stratum who had an incident musculoskeletal injury (Table 2). There was an overall injury rate of 67.6% over the study period. Among obese individuals, the injury rate was 74.3% compared with 68.1% for overweight and 64.8% for normal subjects, based on traditional BMI. Very similar results were found using the original aBMI categories (74.3%, 70.9%, and 65.7%, respectively). Using AC, however, there was a wider range of injury rates, as follows: high risk (88.5%), moderate risk (72.0%), and low risk (64.9%). Injury rates among the normal BMI, normal aBMI, and low-risk AC groups were similar (64.8%, 65.7%, and 64.9%, respectively) despite differences in the size of each group.

Kaplan–Meier curves for each age group based on AC (Fig. 1), BMI (Fig. 2), and aBMI (see Figure, Supplemental Digital Content 3, http://links.lww.com/MSS/A386, for the aBMI Kaplan–Meier curve, which is quite similar to Fig. 2) were created. These curves show, over time, the decreasing probability of remaining free from injury within each subgroup. A dose–response relation is evident in all three models, in that injury-free survival decreases more rapidly with each successive increase in BMI, aBMI, or AC category. In addition, these figures highlight the relatively rapid onset and high penetrance of injuries within the youngest group (18–24 yr) compared with those within the older groups, with nearly 100% of these individuals incurring an injury by approximately 60 months from study start. Finally, visual inspection of the Kaplan–Meier curves shows that in all three age groups, differences in injury-free time between low-risk, moderate-risk, and high-risk AC are more pronounced than those between normal, overweight, and obese groups seen in the BMI and aBMI curves.

Cox proportional hazard regression analysis of AC categories showed significantly increased HR for musculoskeletal injury in high-risk AC compared with that for low-risk AC in both sexes and all age groups (Table 3). Notably, for males and females combined, those with high-risk AC were at approximately 1.5- to twofold risk of injury compared with that in their low-risk counterparts over the study period, depending on their age group. When broken down by gender, similar analysis showed higher HR values for injury in females than those in males, except in the 18- to 24-yr-old group where the sample size for high-risk AC females was very small and HR was not statistically significant. Musculoskeletal injury HR values for moderate-risk AC compared with those for low-risk AC were also significantly increased in all except the youngest age group. Using BMI and aBMI, HR showed significant risk increases for obese compared

TABLE 2. Unadjusted injury rates were calculated for each body habitus category and reported as quantities and percentages (within each row).

	Musculoskeletal Injury Status, *n* (row %)	
Variable	No	Yes
Gender		
Female	1801 (28.2)	4597 (71.8)
Male	20,228 (32.9)	41,278 (67.1)
Total	22,029 (32.4)	45,875 (67.6)
AC		
Low risk	16,453 (35.1)	30,648 (64.9)
Moderate risk	5274 (27.9)	13,600 (72.1)
High risk	212 (11.5)	1627 (88.5)
Total	22,029 (32.4)	45,875 (67.6)
BMI		
Normal	8859 (35.2)	16,299 (64.8)
Overweight	11,210 (31.9)	23,908 (68.1)
Obese	1960 (25.7)	5668 (74.3)
Total	22,029 (32.4)	45,875 (67.6)
aBMI		
Normal	16,556 (34.3)	31,653 (65.7)
Overweight	3513 (29.1)	8554 (70.9)
Obese	1960 (25.7)	5668 (74.3)
Total	22,029 (32.4)	45,875 (67.6)

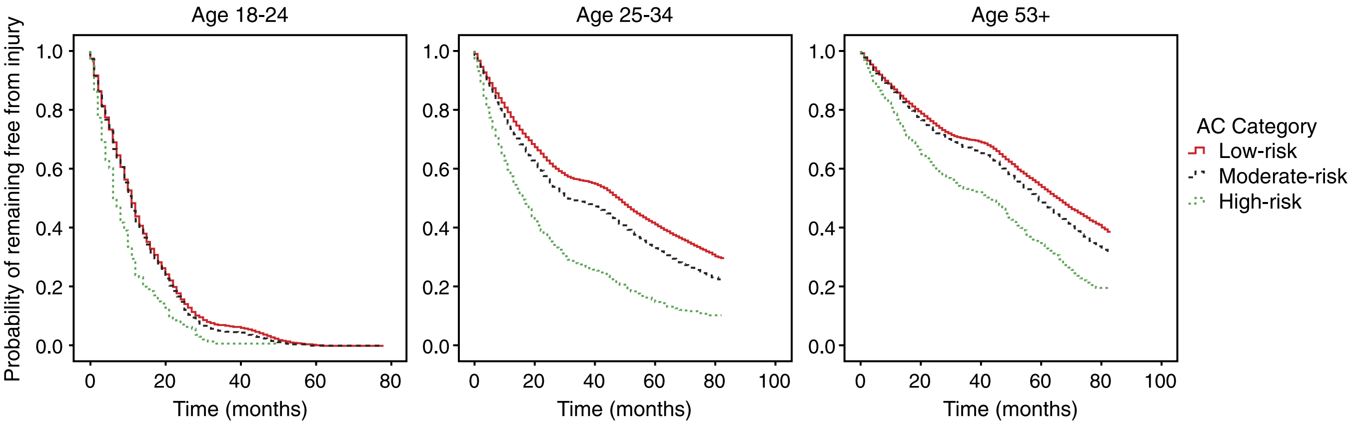

FIGURE 1—Kaplan–Meier curves: musculoskeletal injury-free survival by AC and age.

with those for normal groups across all ages; however, HR values were consistently smaller than those seen with AC. Initial Cox results for BMI and aBMI were very similar despite vast differences sometimes seen in how the cohort was divided into respective subgroups (e.g., 14,454 subjects age 25–34 yr with normal BMI vs 27,383 subjects of same age with normal aBMI). After modifying the aBMI groups to create the over-obese group (BMI ≥32.8 $\text{kg}\cdot\text{m}^{-2}$ for males, and BMI ≥32.3 $\text{kg}\cdot\text{m}^{-2}$ for females), HR values were higher than those of obese groups (Table 3, bottom rows). Regardless of the body habitus classification used, HR values were higher for 25- to 34-yr-old participants than those for the older and younger age groups. Finally, results of best subset selection analysis (Table 4) showed greater chi-square scores for AC than those for BMI or aBMI in all age groups (note that this analysis for aBMI was performed using over-obese rather than obese groups because of group sizes being more comparable with AC and to favor the null hypothesis that BMI and AC are equivalent as discriminators for injury).

DISCUSSION

Comparing AC, BMI, and aBMI. These findings provide several important and novel insights regarding the relation between obesity and musculoskeletal injury. Most importantly, this study is the first to directly demonstrate that AC is a better discriminator of risk for musculoskeletal injury than BMI. This conclusion is supported by multiple observations. Foremost, statistical comparison of the AC, BMI, and aBMI models using chi-square scores from the best subset analysis showed superior performance of AC as a predictor of musculoskeletal injury risk for all age groups separately and for the overall cohort. This result is consistent with the observation that HR values were consistently higher for AC subgroup comparisons for all ages and genders than those for the BMI or aBMI subgroups (with rare exception). Second, differences in injury-free survival (Figs. 1 and 2) were greatest and most consistent among the AC subcategories.

A relative assessment of how the cohort was distributed among AC, BMI, and aBMI subgroups is important to compare their risk discriminating ability. As noted above, despite vast differences in group sizes, the normal BMI (n = 25,158) and low-risk AC (n = 47,191) groups had similar unadjusted injury rates (64.79% vs 64.94%, respectively). To take this one step further, one notes that the normal aBMI and low-risk AC groups were similarly sized (n = 48,209 vs 47,191, respectively) and had similar unadjusted injury rates (65.7% vs 64.9%, respectively). However, there remained a

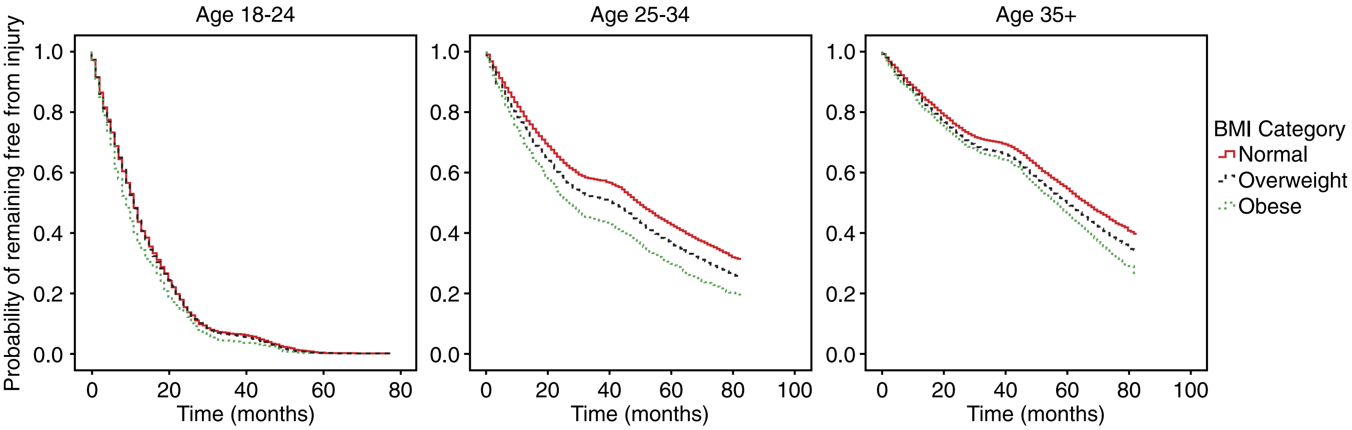

FIGURE 2—Kaplan–Meier curves: musculoskeletal injury-free survival by BMI and age.

TABLE 3. Cox proportional hazards regression representing injury risk for each of the body habitus category, as broken down by age and sex.

Body Habitus Classification		Age Group (yr)	HR—Males (95% CI, *P*) (n_{test}, n_{ref})	HR—Females (95% CI, *P*) (n_{test}, n_{ref})
AC	Moderate vs low risk	18–24	1.069 (0.994–1.150, 0.071) (905, 3707)	1.033 (0.829–1.288, 0.770) (96, 521)
		25–34	1.241 (1.207–1.276, <0.001) (10,054, 23,466)	1.327 (1.199–1.470, <0.001) (565, 2946)
		≥35	1.198 (1.156–1.243, <0.001) (8360, 12,232)	1.322 (1.165–1.500, <0.001) (423, 1734)
	High vs low risk	18–24	1.579 (1.335–1.868, <0.001) (143, 3707)	1.452 (0.460–4.524, 0.520) (3, 521)
		25–34	2.098 (1.974–2.229, <0.001) (1275, 23,466)	2.758 (1.982–3.838, <0.001) (38, 2946)
		≥35	1.836 (1.697–1.988, <0.001) (889, 12,232)	2.575 (1.490–4.451, 0.001) (15, 1734)
BMI	Overweight vs normal	18–24	1.025 (0.965–1.089, 0.470) (2040, 2246)	0.977 (0.810–1.177, 0.804) (148, 453)
		25–34	1.202 (1.168–1.236, <0.001) (18,544, 12,088)	1.229 (1.130–1.337, <0.001) (1066, 2366)
		≥35	1.195 (1.148–1.244, <0.001) (12,594, 6612)	1.218 (1.092–1.359, <0.001) (726, 1393)
	Obese vs normal	18–24	1.177 (1.066–1.298, 0.001) (484, 2246)	1.204 (0.798–1.817, 0.376) (24, 453)
		25–34	1.455 (1.396–1.515, <0.001) (4299, 12,088)	1.858 (1.542–2.239, <0.001) (136, 2366)
		≥35	1.383 (1.305–1.465, <0.001) (2599, 6612)	1.233 (0.941–1.615, 0.129) (86, 1393)
aBMI	Overweight vs normal	18–24	1.013 (0.932–1.100, 0.763) (671, 3615)	1.076 (0.801–1.446, 0.627) (48, 553)
		25–34	1.214 (1.175–1.254, <0.001) (6416, 24,216)	1.256 (1.111–1.419, <0.001) (365, 3067)
		≥35	1.206 (1.155–1.260, <0.001) (4328, 14,878)	1.168 (0.994–1.373, 0.059) (239, 1880)
	Obese vs normal	18–24	1.165 (1.059–1.281, 0.002) (484, 3615)	1.218 (0.809–1.835, 0.345) (48, 553)
		25–34	1.355 (1.305–1.407, <0.001) (4299, 24,216)	1.785 (1.484–2.147, <0.001) (136, 3067)
		≥35	1.283 (1.218–1.352, <0.001) (2599, 14,878)	1.172 (0.896–1.532, 0.246) (86, 1880)
	Over obese vs normal	18–24	1.479 (1.232–1.774, <0.001) (121, 3615)	1.551 (0.734–3.274, 0.250) (7, 553)
		25–34	1.640 (1.527–1.761, <0.001) (981, 24,216)	2.897 (2.073–4.049, <0.001) (37, 3067)
		≥35	1.586 (1.421–1.770, <0.001) (467, 14,878)	1.735 (0.982–13.064, 0.058) (16, 1880)

Data for males and for females were analyzed separately. Individuals with moderate- and high-risk AC were compared with low-risk individuals within the same age group as the reference, whereas overweight and obese individuals were referenced to those with normal BMI within the same age group. In secondary analysis, an 'over-obese' group replaced the obese group within aBMI and was then analyzed in the same manner.

n_{test}, number of subjects in test group of interest (e.g., high-risk AC); n_{ref}, number of subjects in reference group (e.g., low-risk AC).

large difference between the size of our high-risk AC and obese groups (BMI ≥30 kg·m^{-2}). One might ask whether the higher HR values seen with AC were merely due to the more stringent definition of the high-risk subgroup. To address this concern, a secondary analysis was performed with the newly defined aBMI "over-obese" group, with BMI ≥32.8 kg·m^{-2} for males and BMI ≥32.3 kg·m^{-2} for females. The cutoffs for normal and overweight aBMI categories were kept the same. This resulted in much more comparable subgroup sizes between AC (low risk, 47,191 (69.5%); moderate risk, 18,874 (27.8%); high risk, 1839 (2.7%)) and aBMI (normal, 48,209 (71.0%); overweight, 16,417 (24.2%); obese, 1629 (2.4%)) and allowed a more fair comparison between the two measures. Even when this was done, injury HR values for AC subgroups remained higher than those for aBMI subgroups (Table 3), with rare exception (females age 25–34 yr). The differences between HR values were particularly great among 25- to 34-yr-old males (over obese vs normal: HR = 1.640, 95% CI = 1.527–1.761, $P < 0.001$, $n = 981$ (over obese), $n = 24{,}216$ (normal); high-risk AC vs low-risk AC: HR = 2.098, 95% CI = 1.974–2.229, $P < 0.001$, $n = 1275$ (high risk), $n = 23{,}466$ (low risk)). These observations suggest that AC measurement enables superior detection of the individuals at highest risk for musculoskeletal injury while leaving behind a larger cohort of low-risk individuals versus using BMI.

Part of the reason why AC is a better predictor of injury risk may be that it reduces the misclassification of muscular yet lean individuals. Note that 9.9% of individuals with a BMI ≥30 kg·m^{-2} had a low-risk AC. These are likely to represent misclassified muscular individuals, who may potentially have a lower injury risk than that of BMI-matched individuals who have higher adiposity and higher AC. The superior strength of AC in predicting risk for musculoskeletal injury, in addition to other medical conditions and death (13,18–20,26), makes it a powerful measure of individual fitness and health. Decreasing AC to moderate- or low-risk levels should be included among the goals of obesity treatment programs. Also, organizations that measure fitness or track injury risk, including all military services, should consider including AC with routine testing protocols.

Another important finding is that there is a dose–response relation between excess body weight and musculoskeletal injury risk. This is a consistent finding seen on Kaplan–Meier curves among all age groups but is most pronounced in the 25- to 34-yr-old group. This dose–response relation rings true with anecdotal clinical experience, and plausible mechanisms have been studied. These include the repetitive excessive loading of major joints in obese individuals and altered biomechanics caused by space-occupying fat deposits (40). However, obesity may not increase risk for all types of musculoskeletal injuries.

Age, sex, and risk progression over time. This study makes the following additional contributions to obesity

TABLE 4. Score chi-square analysis.

Body Habitus Classification	Age (yr)	Score Chi-Square
AC	18–24	46.208
	25–34	1332.796
	≥35	573.464
BMI	18–24	12.316
	25–34	428.106
	≥35	230.270
aBMI	18–24	22.084
	25–34	436.238
	≥35	239.521

Each of the three body habitus classification schemes was analyzed as an injury risk prediction model using the best subset selection technique. This method uses a branch-and-bound algorithm to find the model with the highest likelihood score (score chi-square), where a higher score indicates that the model in question fits the data better.

and musculoskeletal injury research: details on the progression of musculoskeletal injury risk over several years and the ability to compare injury risk between age groups and sexes. The time to first musculoskeletal injury was significantly decreased in the youngest group (18–24 yr). This group, as a whole showed a steep decline in injury-free survival over the first 2 yr of the study, reaching 100% injury penetrance in those with high-risk AC by 35 months and within the entire age group by 60 months. In light of previous studies showing that sports and physical training are the leading causes of injury in the military (22,33), it is probable that higher participation in sports and physical training among this age group partially accounts for the higher injury rate. Although previous studies (12,21,23) have shown a high rate of musculoskeletal injuries during basic training, this effect does not explain our findings because basic training occurs during the first year of military service and all of our subjects were enrolled in the USAF and were injury free for 12 months before inclusion in the study. Other potential factors could include a more physical nature of job descriptions in younger personnel and prestudy attrition of injury-prone individuals (injury-related medical discharge), leaving a healthier cohort in the older groups. The consistently higher HR values for 25- to 34-yr-old participants (especially females) and greater spread between Kaplan–Meier curves show that the effects of excess body weight seem to matter more in this age group.

Although studies methodologically similar to this one have been carried out, these have been limited in length of follow-up. Cowan et al. (12) followed a group of 18-yr-old male recruits for 90 d, whereas Hu et al. (17) analyzed medical records spanning 3 yr with no preceding washout period. The results of this study also expand upon the previous studies referenced showing a significant risk of musculoskeletal injuries with elevated AC and BMI (27,35,36,39). Specifically, the present study confirms findings of Taanila et al. (36) who showed a 1.8-fold increase in musculoskeletal injury risk in those with elevated BMI or AC. The much longer follow-up (7 yr vs 6 months) and larger sample size (67,904 vs 944) in this study add strength and applicability to this finding. Beyond this, the present study suggests that AC is a better predictor of overall musculoskeletal injury risk. This is consistent with work done by Shiri et al. (35), who found that AC was associated with higher risk of back pain than BMI in young females by evaluating a broader range of injuries and describing effects of age and sex on injury risk. The present cohort was significantly larger and younger than that in the studies of Wang et al. (39) and Lohmander et al. (27), both of whom demonstrated that BMI was associated with greater or equivalent risk of severe knee or hip OA than AC. It should be pointed out that although many musculoskeletal injury reporting systems do not include OA (4,16), we include OA and discuss these studies for completeness (see injury definition in Methods). These findings carry important implications for obesity prevention and treatment strategies. For example, on the basis of these data, weight loss interventions including increased physical activity are less likely to result in injury when used before individuals reach obesity or high-risk AC thresholds. Although our findings suggest that females are at slightly higher risk for injury than males (especially in 25- to 34-yr-old participants), these differences are inconsistent. Prospective studies investigating injury risk with respect to weight loss interventions aimed at lowering BMI and AC are needed.

Our study has several limitations. First, our sample was largely male. While in 2010, the entire USAF active duty force consisted of 81.0% male personnel (38), our 90.6% male cohort is in part explained by some female airmen becoming pregnant at some point during the 7-yr study period. As reported by the 2005 *Health Related Behaviors Survey* (8), of all surveyed active duty USAF women who reported gaining weight during 2005, 24.6% attributed their weight gain to pregnancy or child birth. This helps to appreciate the prevalence of pregnancy among the active duty USAF at any given time. Also, as is inherent with any observational study, there may be confounding conditions that we failed to identify in our exclusion criteria. In addition, subjects with diagnostic codes for OA or other chronic injuries may not have been new diagnoses. Any such diagnostic codes occurring during the present study (2005–2011) were likely new diagnoses, given that any subject with one of these diagnoses during the washout period (2004) was excluded from the study. However, it was impossible to determine with certainty when their initial diagnosis occurred because our data set did not include data before 2004. Further limitations of this study included its retrospective nature and the fact that injury data were correlated to average BMI or AC, which may not reflect the subject's true BMI or AC at the time of injury. The relevance of body habitus measurements from multiple years before injury, as were included in calculating averages, may be questioned. However, it is not known whether actual BMI or AC at the time of injury is the most important risk factor. Perhaps, the amount of time the subject spent in a BMI or AC category or the rate of change of BMI or AC are equally or more important. This issue deserves further investigation.

This study provides a basis for several important conclusions. AC, a measure of central obesity, is a better discriminator of musculoskeletal injury risk than BMI. Although both are significant risk factors, abdominal obesity seems to be a more important risk factor for musculoskeletal injury than generalized excess body weight. Given that this is the first investigation to demonstrate statistical superiority of AC as a predictor of injury risk, additional studies are warranted. Furthermore, both BMI and AC show a dose–response relation with musculoskeletal injury risk. The dose response is most prominent, and HR is consistently greatest in 25- to 34-yr-old persons, suggesting that excess body weight carries greater consequences to this group than those in older or younger groups and especially so in females. The absolute injury risk is greatest (shortest mean time to injury) in those age 18–24 yr regardless of body habitus. These findings suggest that treatment and prevention of obesity, in particular targeting abdominal obesity in the 25- to 34-yr-old age group, may reduce injury rates. However, injury prevention and obesity management are both decidedly complex problems, and prospective studies are needed to determine whether nonsurgical obesity treatment and prevention strategies can be successful at lowering musculoskeletal injury rates. These findings should be incorporated into existing obesity treatment program goals and, in the military, fitness testing protocols and recruitment and retention standards.

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