Bilateral Strength Asymmetries and Unilateral Strength Imbalance: Predicting Ankle Injury When Considered With Higher Body Mass in US Special Forces

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Context: Ankle injury is one of the most common conditions in athletics and military activities. Strength asymmetry (SA) and imbalance may represent a risk factor for injury, but past investigations have produced ambiguous conclusions. Perhaps one explanation for this ambiguity is the fact that these authors used univariate models to predict injury.

Objective: To evaluate the predictive utility of SA and imbalance calculations for ankle injury in univariate and multivariate prediction models.

Design: Prospective cohort study.

Setting: Laboratory.

Patients or Other Participants: A total of 140 male US Air Force Special Forces.

Main Outcome Measure(s): Baseline testing consisted of body composition, isometric strength, and aerobic and anaerobic capacity. A clinician conducted medical chart reviews 365 days posttesting to document the incidence of ankle injury. Strength asymmetries were calculated based on the equations most prevalent in the literature along with known physiological predictors of injury in the military: age, height, weight, body composition, and aerobic capacity. Simple logistic regression was conducted using each predictor, and backward stepwise logistic regression was conducted with each equation method and the physiological predictors entered initially into the model.

Results: Strength asymmetry or imbalance or both, as a univariate predictor, was not able to predict ankle injury 365 days posttesting. Body mass ($P = .01$) and body mass index ($P = .01$) significantly predicted ankle injury. Strength asymmetry or imbalance or both significantly predicted ankle injury when considered with body mass ($P = .002–.008$).

Conclusions: As a univariate predictor, SA did not predict ankle injury. However, SA contributed significantly to predicting ankle injury in a multivariate model using body mass. Interpreting SA and imbalance in the presence of other physiological variables can help elucidate the risk of ankle injury.

Key Words: symmetry, rehabilitation, military athletes

Key Points

- Strength asymmetry did not predict ankle injury as a univariate predictor.
- Strength asymmetry and body mass predicted ankle injury in a multivariate model.
- Multivariate models may be a more appropriate strategy for predicting injury in active populations.

The ankle joint is a primary sublocation for injury in both athletic and military populations. An epidemiologic study showed that the ankle was the most prevalent sublocation of injury to the lower extremity in Special Forces populations. In addition to their extremely high prevalence, ankle injuries also have a high rate of recurrence and carry an increased risk of chronic ankle instability or the development of osteoarthritis or both. Because of the high prevalence, investigators have attempted to identify risk factors related to ankle injury, such as inadequate proprioception or balance, limb dominance, and range of motion. Strength-related deficits, such as reduced local strength, strength asymmetry (right to left), and strength (unilateral evertor-to-invertor) imbalance have also been suggested as possible risk factors.

As the largest articular joint of the distal lower extremity, and thus the entire kinetic chain when load bearing, the ankle could conceivably be affected by strength asymmetry (SA), especially during bilateral movement. For example, differences in side-to-side force production may influence gait and joint kinematics when a person moves and reacts to environmental stimuli, potentially increasing the injury risk. However, researchers in only a few prospective studies have investigated SA imbalance and the subsequent development of ankle injuries, with ambiguous results. Baumhauer et al reported an elevated eversion-to-inversion strength ratio in college-aged athletes who sustained an ankle injury later in the season. The injured group also presented with a different plantar flexion-to-dorsiflexion strength ratio in the injured ankle compared...
Authors such as Bittencourt et al. have called for a comprehensive approach that recognizes the interdependence and enhancement of injury risk. Contributing to these equivocal results is the inadequacy of univariate predictor models in predicting ankle injuries in college-aged athletes. Perhaps the relationship between plantar flexion-to-dorsiflexion and eversion-to-inversion strength ratios and the prediction of ankle injuries in athletic populations using asymmetries as a representation of the body as a whole. One group to date has adopted this approach to evaluate the increased risk of ankle injury in athletic populations using asymmetries as a predictor. Fousekis et al. reported a predictive model of ankle injury in professional soccer athletes that included increased body mass and asymmetric ankle flexion strength >15%. However, one might expect asymmetry in soccer players to be common due to the unique sport-specific demands placed on the plant leg compared with the dominant kicking leg. Thus, because soccer often involves repetitive motor patterns, investigating the role of SAs and imbalances in another population may elicit more information as to the importance of strength deficits in the incidence of injury. Furthermore, adequate strength of the invertors and evertors surrounding the ankle plays a crucial role in the dynamic stability of the joint, which was not investigated in the aforementioned article. Analyzing the asymmetries and imbalances of these dynamic stabilizers as a covariate, rather than a univariate predictor, may increase the predictive utility and better inform clinical decision making. Therefore, the purpose of our study was to compare the utility of univariate predictive models with that of multivariate predictive models for ankle injury using anthropometric, physiological, and strength characteristics.

METHODS
Participants
Baseline testing was completed by US Air Force Special Forces (Special Tactics Operators; n = 140). All operators volunteered and provided written informed consent to participate in the study after an investigator explained the purpose, details, and procedures. All participants were male, and they were allowed to end testing procedures at any time. Operators were excluded from the study if they were not cleared for full duty or had sustained a recent musculoskeletal injury or traumatic brain injury (within 3 months), or if they had a neurologic, balance, metabolic, cardiovascular, or pulmonary disorder. Human participant testing approval was obtained through the University of Pittsburgh Institutional Review Board and the 711th Air Force Human Performance Wing Research Compliance Office.

Study Design
This was a prospective cohort study to analyze the risk of ankle injury over a 1-year period after baseline testing of anthropometric, physiological, and strength variables. Participants completed baseline testing and were monitored for injuries over the subsequent 1-year period. Primary outcome measures from baseline testing were isometric ankle eversion and inversion strength, as well as SA and imbalance. Secondary outcome measures were age, height, body mass, body mass index (BMI), body fat percentage, fat-free mass, and aerobic and anaerobic capacity. We chose these anthropometric and physiological variables due to their prevalence in the military injury-prediction literature. Strategies were applied; specific descriptions of the calculations can be found elsewhere (Table 1). Briefly, the label assigned to each equation was based on the strategy used to analyze SA: RL if the equation used the right and left legs, DND if the equation used the dominant and nondominant legs, and WS if the equation compared the weaker leg with the stronger leg. Injury risk was assessed using univariate models and then reassessed using multivariate models.

Procedures
Body Fat Percentage and Body Mass Index. Body composition was measured using an air-plethysmography chamber (BOD POD Body Composition System; COSMED, Rome, Italy). The machine is prepared using a 2-point calibration process to accommodate environmental changes. Participants wore spandex shorts and a swim cap and were instructed to sit still and breathe normally. Two tests were completed; if the variance was greater than 3 mL of the participant’s volume between the first and second

Table 1. Strength Asymmetry Calculations Index

| Limb | Equation | Reference Symmetry Value | Citation |
|------|----------|--------------------------|----------|
| RL-I | $\text{R-L}/\text{Greatest of either} \times 100$ (%) | 0 | Menzel et al. |
| RL-II | $\text{R-L}$ | 1.0 | Joseph et al. |
| RL-III | $\text{R-L}$ | 0 | Gioftsidou et al. |
| DND-I | $\text{D-ND}$ | 0 | Daneshjoo et al. |
| DND-II | $\text{ND/D} \times 100$ (%) | 100 | Ostenberg et al. |
| DND-III | $\text{D-ND/ND} \times 100$ (%) | 0 | Thomas et al. |
| DND-IV | Absolute value (D-ND)/D (%) | 0 | Eagle et al. |
| WS-I | $\text{W/S} \times 100$ (%) | 100 | Ostenberg et al. |

Abbreviations: D, dominant; L, left; ND, nondominant; R, right; S, stronger, W, weaker.
tests, a third was run before the results were averaged for data analysis. Body fat percentage (%), body mass (kg), fat-free mass (FFM; kg) and height (cm) are outcomes of this test. Body mass index (kg/m²) was calculated as body mass divided by the square of body height.

**Aerobic Capacity.** Aerobic capacity (\(\dot{V}O_2\text{max}\)) was measured during an incremental-ramp protocol. Data were captured using a Parvo Medics (Sandy, UT) metabolic cart and a heart-rate monitor (Polar USA, Lake Success, NY) worn by the participant around the chest at the level of the xiphoid process. The incremental-ramp protocol started with a 5-minute warm-up at a comfortable, self-selected pace. An initial 3-minute workload at 0% grade was self-selected by the participant based on his typical training pace. The incline was increased by 2.0% every 3 minutes while the speed remained constant. The participant was instructed to continue running until exhaustion, at which point the test was self-terminated. Aerobic performance was normalized to body weight (mL/kg/min). Data were verified by ensuring that a plateau in \(\dot{V}O_2\) was achieved with increasing intensity, respiratory exchange ratio was greater than 1.1, and heart rate was within 95% of the age-predicted heart rate maximum (220−age). The Borg Rating of Perceived Exertion (6–20) was used to verify volitional fatigue during the protocol.24

**Anaerobic Capacity.** Anaerobic capacity was obtained using a Veloxteron cycling ergometer (RacerMate, Inc, Seattle, WA). The Velotron is an electronically braked ergometer that is controlled by a Windows-based software application. The ergometer was calibrated before use to normalize the wattage output to the factory measurement. After a warm-up stage, the participant was asked to achieve and maintain 100 rotations per minute. He was then instructed to pedal “as hard and fast as possible” during the 5 seconds preceding the initiation of resistance and to attempt to maintain that pace for the remaining 30 seconds of the test. The resistance was set at 9% of body weight. Anaerobic capacity was recorded as the average watts normalized to body weight produced during the 30 seconds of the test.

**Isometric Strength.** Peak force for eversion and inversion was obtained using a handheld dynamometer (HHD; Lafayette Instruments Co, Lafayette, IN). Participants were instructed to sit on the table in a long-sitting position with the foot and ankle just off the edge. The HHD was placed just distal to the head of the first metatarsal on the medial border for inversion and distal to the head of the fifth metatarsal on the lateral border for eversion; the lower leg was stabilized. The participant was instructed to hold the foot as long as possible in the starting position, at half of the available range of motion. A trial contained a ramped force by the researcher until motion occurred at the participant’s ankle. Two warm-up trials were conducted at 50% and 2 warm-up trials at 100% of perceived maximal effort. The test consisted of 3 trials at 100% maximal effort, with a 1-minute rest between trials, and was conducted 1 minute after finishing the warm-up. These methods demonstrated good test-retest reliability before the study began (intraclass correlation coefficient [ICC] > 0.8; unpublished data). Test values were averaged and normalized to body mass (N/kg).

**Medical Chart Reviews.** A certified athletic trainer underwent training on the use of the Armed Forces Health Longitudinal Technology Application to conduct a medical chart review of injuries. *Unintentional musculoskeletal injuries* were defined as injuries to the musculoskeletal system (bones, ligaments, muscles, tendons, etc) and were reviewed over a prospective, 1-year period after laboratory testing; the primary anatomic injury location, sublocation, and injury type were noted. *Ankle injury* was defined as any injury that occurred at the talocrural, subtalar, or inferior tibiofibular joint, as well as any injury to the musculature that crossed the ankle joint. Additionally, the operator had to have sought medical care from a clinician, with lost activity time of at least 24 hours. Only the first incidence of an injury sustained during the follow-up was considered. Medical chart reviews were conducted during 2014 and 2015. The reviewer was blinded to the specific research question and was instructed to document all musculoskeletal injuries in the medical chart over the 1-year period after baseline testing.

**Statistical Analysis.**

We calculated descriptive statistics (means and standard deviations as appropriate) for all variables. Imbalance equations were calculated as the eversion value divided by the inversion value for each limb before applying the asymmetry methods described previously. Before the regression analysis, we converted all test outcomes to Z-scores for direct comparison of the predictors with the risk of ankle injury. Simple logistic regression analyses were used to evaluate the associations between all predictor variables (ie, all primary and secondary outcomes) at baseline and the occurrence of ankle injury. Backward stepwise logistic regression was used to evaluate the association between the baseline values of 1 SA equation and all secondary outcome predictor variables and the incidence of ankle injury. In addition to the SA calculation, each model initially included body fat percentage, BMI, body mass, fat-free mass, height, aerobic capacity, anaerobic capacity, and age as predictors. An all-possible-regressions approach was used after backward stepwise regression was conducted in order to generate the most efficient model possible. We calculated descriptive statistics, Shapiro-Wilk normality tests, and independent-samples t tests using SPSS (version 24; IBM Corp, Armonk, NY) and Stata/IC (version 15; StataCorp LP, College Station, TX) for the simple logistic regression and backward stepwise regression analyses.

**Regression Model Diagnostics.** Normality of the final models was confirmed with graphic assessments using kernel density plots and histograms. Only those predictors with \(P < .2\) were included in the final backward stepwise model. Collinearity was evaluated with correlations and variance inflation factor calculations. We defined collinearity as a correlation of \(r > 0.8\) and variance inflation factor \(>10\). Statistical significance was set a priori at \(\alpha = .05\), two sided.

### RESULTS

**Group Differences.**

Participant demographics are shown in Table 2. Fourteen ST operators sustained ankle injuries during the 1-year follow-up period, but 21 total ankle injuries were incurred...
Nondominant Limb strength capacity (Table 2). The injured group demonstrated heavier percentage, fat-free mass, aerobic capacity, or anaerobic capacity between the injured and uninjured groups in age, height, body fat percentage, and fat-free mass. No differences were observed between the follow-up period, while 1 operator reported 3 injuries to the Achilles tendinitis and closed fibular fracture. Six operators reported bilateral injuries during the follow-up period, while 1 operator reported 3 injuries to the same side. No differences were observed between the injured and uninjured groups in age, height, body fat percentage, fat-free mass, aerobic capacity, or anaerobic capacity (Table 2). The injured group demonstrated heavier body mass and larger BMI (Table 2).

### Univariate Regression Analyses

Simple logistic regression results for the physiological characteristics as well as mean eversion, inversion, and intralimb ratios normalized to body weight are provided in Table 3. Eversion, inversion, and intralimb ratios as predictors of ankle injury are given in Table 4, with the results separated by SA calculation strategy. Body fat percentage, age, height, fat-free mass, and aerobic and anaerobic capacity did not predict ankle injury during the follow-up period in this population (Table 3). However, body mass (odds ratio [OR] = 2.25, 95% confidence interval [CI] = 1.21, 4.19; \( P = .011 \)) and BMI (OR = 2.24, 95% CI = 1.23, 4.08; \( P = .008 \)) each significantly predicted ankle injury (Table 3). Left inversion strength and nondenominant inversion strength alone significantly predicted ankle injury (Table 3). Using simple logistic regression, we found that none of the SA equations significantly predicted ankle injury in this population (Table 4).

### Multivariate Analyses

Results of the backward stepwise logistic regression models for ankle injury are presented in Table 5. The BMI violated collinearity assumptions, as it correlated highly with body mass, and was removed from the model (\( r > 0.8 \)). Five total models were generated: 1 for each SA equation strategy in addition to the physiological predictors (eg, age, height, BMI, body fat, body mass, aerobic capacity, anaerobic capacity). Right versus left limbs (RL-II), dominant versus nondenominant limbs (DND-II), and weaker versus stronger limbs (WS-I) significantly predicted ankle injury, but the models were severely collinear. Post hoc model diagnostics revealed that for these equations, the only significant predictor was body mass; including the asymmetry equations violated the collinearity assumptions. Each of the remaining 5 models significantly predicted ankle injury (\( P < .05 \)). At least 1 ratio (ie, evertor, invertor, or intralimb) was included as a predictor in the final model based on each equation. The RL-I model was the strongest predictor of ankle injury (\( P = .002 \)), including the evertor ratio (coefficient = 0.124, 95% CI = 0.021, 0.228; \( P = .019 \)), body mass (coefficient = 0.104; 95% CI = 0.025, 0.182; \( P = .010 \)), and intralimb ratio (coefficient = −0.058; 95% CI = −0.128, 0.011; \( P = .10 \)). Each predictor equation also included body mass in the final model.

### DISCUSSION

Our results demonstrated that the SA and imbalance equations were not able to predict ankle injury up to 1 year.
after baseline testing. Body mass ($P = 0.01$) and BMI ($P = 0.01$) were able to significantly predict ankle injury in this population, consistent with previous findings.$^1$ However, when incorporated into backward stepwise logistic analyses, a combination of SA or imbalance (or both) and body mass significantly predicted ankle injury, with the exception of the DND-IV and WS-I equations, which only included body mass in the final model (Table 5). The strongest predictive model included the evertor ratio, body mass, and intralimb ratio ($P = 0.003$). These findings indicate that interpreting SA and imbalance in the presence of other physiological variables can help to elucidate the risk of ankle injury.

Body mass (OR = 2.25) and left- or nondominant-sided inversion strength (OR = approximately 0.5) were the only univariate predictors of ankle injury in this population (Table 3). These results are unsurprising, as many investigators have noted increased body mass as a risk factor for injury in military populations.$^{2,5}$ as well as the importance of inversion strength in ankle injury studies.$^{3,8}$ It has been theorized$^{10}$ that neuromuscular control of the ankle invertors is paramount to stabilize the lateral displacement of the lower leg during movement. Ryan$^{26}$ reported inversion strength deficits in those with acute lateral ankle sprain and chronic ankle instability. The author postulated that reflexive inhibition of the inversion motion may occur after lateral ankle sprain and contribute to chronic ankle instability. Regardless of injury status, operators in the present study exhibited intralimb ratios of 1.2–1.4, indicating stronger evertors than invertors. Incorporating eccentric strengthening exercises and dynamic stabilization could improve evertor strength and ankle injury outcomes in this population.

In a seminal study, Baumhauer et al$^8$ noted a higher incidence of inversion ankle sprains in college-aged

| Table 3. Simple Logistic Regression for Physiological Characteristics and Individual-Limb Strength Performance |
| Variable | $P$ Value | Odds Ratio | 95% Confidence Interval |
| --- | --- | --- | --- |
| Physiological characteristic | | | |
| Age | .41 | 1.24 | 0.76, 2.02 |
| Height, cm | .44 | 1.04 | 0.94, 1.15 |
| Body mass, kg | .01 | 2.25 | 1.21, 4.19 |
| Body fat, % | .22 | 1.41 | 0.82, 2.44 |
| Fat-free mass, kg | .09 | 1.60 | 0.92, 2.80 |
| Body mass index, kg/m² | .01 | 2.24 | 1.23, 4.08 |
| Aerobic capacity, mL/kg/min | .25 | 0.72 | 0.40, 1.28 |
| Anaerobic capacity, W/kg | .16 | 0.56 | 0.25, 1.26 |

| Limb strength | | | |
| Right | | | |
| Eversion | .94 | 0.98 | 0.56, 1.70 |
| Inversion | .14 | 0.63 | 0.33, 1.20 |
| Eversion: inversion ratio | .34 | 1.30 | 0.76, 2.22 |
| Left | | | |
| Eversion | .19 | 0.69 | 0.39, 1.22 |
| Inversion | .04 | 0.50 | 0.25, 1.01 |
| Eversion: inversion ratio | .68 | 1.12 | 0.65, 1.94 |

| Dominant | | | |
| Eversion | .89 | 0.96 | 0.55, 1.68 |
| Inversion | .15 | 0.65 | 0.35, 1.21 |
| Eversion: inversion ratio | .37 | 1.28 | 0.75, 2.17 |

| Nondominant | | | |
| Eversion | .20 | 0.69 | 0.40, 1.22 |
| Inversion | .03 | 0.48 | 0.23, 1.00 |
| Eversion: inversion ratio | .64 | 1.14 | 0.66, 1.98 |

| Abbreviations: D, dominant; L, left; ND, nondominant; R, right; S, stronger; W, weaker. |

| Table 4. Simple Logistic Regression Outcomes in Evertor, Invertor, and Intralimb Ratios Categorized by Strength Asymmetry Equation |
| Strength Asymmetry Equation | Variable | $P$ Value | Odds Ratio | 95% Confidence Interval |
| --- | --- | --- | --- | --- |
| RL-I | Evertor ratio | .06 | 1.71 | 0.96, 3.06 |
| Invertor | .32 | 1.34 | 0.74, 2.42 |
| Intralimb | .54 | 1.19 | 0.69, 2.03 |
| RL-II | Evertor ratio | .06 | 1.68 | 0.97, 2.92 |
| Invertor | .39 | 1.28 | 0.73, 2.25 |
| Intralimb | .58 | 1.16 | 0.69, 1.96 |
| RL-III | Evertor | .07 | 1.74 | 0.95, 3.22 |
| Invertor | .43 | 1.26 | 0.71, 2.24 |
| Intralimb | .49 | 1.21 | 0.63, 2.34 |
| DND-I | Evertor | .17 | 1.44 | 0.87, 2.39 |
| Invertor | .28 | 1.38 | 0.76, 2.48 |
| Intralimb | .62 | 1.15 | 0.67, 1.99 |
| DND-II | Evertor | .12 | 0.63 | 0.35, 1.13 |
| Invertor | .19 | 0.66 | 0.35, 1.26 |
| Intralimb | .56 | 0.85 | 0.49, 1.48 |
| DND-III | Evertor | .12 | 1.03 | 0.99, 1.07 |
| Invertor | .19 | 0.96 | 0.91, 1.02 |
| Intralimb | .56 | 0.99 | 0.97, 1.02 |
| DND-IV | Evertor | .19 | 0.64 | 0.31, 1.33 |
| Invertor | .21 | 0.66 | 0.32, 1.33 |
| Intralimb | .17 | 0.63 | 0.31, 1.29 |
| WS-I | Evertor | .27 | 1.41 | 0.75, 2.66 |
| Invertor | .27 | 1.41 | 0.75, 2.68 |
| Intralimb | .23 | 1.44 | 0.77, 2.67 |

| Abbreviations: D, dominant; L, left; ND, nondominant; R, right; S, stronger; W, weaker. |

| Table 5. Backward Stepwise Regression Outcomes for Prospective Ankle Injury Based on Strength Asymmetry Equation Strategy |
| Strength Asymmetry Equation | Included Predictors | Odds Ratio | 95% Confidence Interval | $P$ Value |
| --- | --- | --- | --- | --- |
| RL-I | Evertor ratio | 1.13 | 1.02, 1.26 | .003* |
| Body mass | 2.39 | 1.24, 4.60 | |
| Intralimb ratio | 0.94 | 0.88, 1.01 | |
| RL-II | Evertor ratio | 1.17 | 1.03, 1.29 | .003* |
| Body mass | 2.37 | 1.23, 4.58 | |
| Intralimb ratio | 0.96 | 0.86, 1.02 | |
| RL-III | Evertor ratio | 1.30 | 1.01, 1.67 | .004* |
| Body mass | 2.32 | 1.22, 4.40 | |
| Intralimb ratio | 0.38 | 0.00, 4.32 | |
| DND-I | Evertor ratio | 1.10 | 0.98, 1.23 | .005* |
| Body mass | 2.25 | 1.17, 4.34 | |
| Intralimb ratio | 1.15 | 0.95, 1.39 | |
| DND-III | Evertor ratio | 1.11 | 1.01, 1.22 | .006* |
| Body mass | 2.36 | 1.19, 4.67 | |
| Intralimb ratio | 1.05 | 1.00, 1.10 | |
| DND-IV | Body mass | 2.34 | 1.23, 4.44 | .010* |
| Intralimb ratio | 2.25 | 1.21, 4.17 | .007* |

| Abbreviations: D, dominant; L, left; ND, nondominant; R, right; S, stronger; W, weaker. |
| $^*$ Indicates statistical significance at $P \leq 0.05$. |
athletes with elevated strength-imbalance ratios (ie, >1.0, indicating stronger evertors than invertors for the same limb). However, we did not find that a strength imbalance as a univariate predictor significantly predicted ankle injury (Table 3). Yet a strength imbalance was included in several multivariate models (Table 5). This would suggest that a side-to-side difference in evertor-to-invertor symmetry may play a role in the injury risk among this population. For example, if a person had an intralimb ratio of 1.0 for the right leg and 1.4 for the left leg, he or she may be at an increased risk of ankle injury. Importantly, the intralimb ratio did not predict ankle injury on its own, regardless of the equation used; only in the presence of body mass did the intralimb ratio contribute to predicting ankle injury (Table 5).

Large volumes of high-force activities, such as those experienced during athletics or military exercises, combined with internal (ie, heavier body mass) or external loads, could increase the injury risk. In fact, heavier people endured larger joint forces during activity. The addition of external loads is particularly relevant to military personnel, as load carriage is pervasive throughout military activity. It was estimated that Special Forces personnel were required to carry nearly 60 kg during engagements. Specific to the Air Force Special Operations Command population, a task and demand analysis identified a large volume of work-related tasks during full mission profiles with potentially high injury risks. High-risk activities were classified as those expected to have a large impact on the joints, especially in the presence of an external load. These tasks included casualty transports, Humvee tire changes, weapons transports, casualty drags, and vehicle dismounts. The unique demands of military exercise may magnify the intrinsic factors of injury risk, such as abnormal strength imbalances and heavier-than-average body mass. Future researchers should consider how to best quantify asymmetry during dynamic movement.

This study’s major contribution to the literature was the finding that SA or imbalance (or both), combined with body mass, significantly predicted ankle injury in this population, but asymmetry or imbalance alone did not predict ankle injury. The RL-I/RL-II and DND-III equations produced the strongest predictive models, which included body mass, the evertor and intralimb ratio, and the intralimb and invertor ratio, respectively (Table 5). In these models, the predictive value of body mass was raised by considering it in the presence of SA (OR = 2.36–2.39; Table 5), compared with predicting ankle injury using body mass alone (OR = 2.25; Table 3). Further, neither SA nor imbalance significantly predicted ankle injury as a univariate predictor, but the evertor ratio (OR = 1.13–1.17), as well as the intralimb ratio (OR = 1.05) and invertor (OR = 1.11) ratio, significantly contributed to the RL-I/RL-II and DND-III multivariate models in conjunction with body mass. Thus, SA and body mass seemed to interact and enhance the prediction of ankle injury among this population.

Our findings agree with those of Fousekis et al, who used a similar multivariate model to predict ankle injuries among soccer players. Indeed, a number of investigators have recognized the importance of characterizing the multifactorial nature of the musculoskeletal injury risk. For example, Bittencourt et al advocated for applying a complex systems approach to identify injury patterns specific to a given population. This approach requires the identification of predictors, establishing relationships among the predictors, and developing profiles for how these relationships influence the risk of injury. As stated previously, SA or imbalance or both may truly become injurious when intrinsic aspects of a person’s body push the mechanical limits of his or her unbalanced articular, ligamentous, and muscular architecture. One clinical implication of these findings is that, although both body mass and SA can be considered modifiable, performance demands may require larger-than-average body mass for occupational success (eg, American football lineman). Larger-than-average body mass alone predicted ankle injury, but our results suggested that body mass, SA, and imbalance should be considered together to estimate the risk of ankle injury. Because performance demands may dictate that body mass cannot be reduced in certain circumstances, clinicians may wish to focus on improving SA or imbalances or both as a useful alternative for reducing the potential injury risk.

Another important implication of these findings is that often-reported anthropometric and physiological predictors of injury in military populations, such as age, height, body fat percentage, fat-free mass, and aerobic and anaerobic capacity, did not significantly predict ankle injury in this model (Table 3), nor did they contribute to predicting ankle injury in a multivariate model (Table 5). It is important to consider population differences between our work and previous epidemiologic studies of military populations. Although we examined Special Tactics operators, previous researchers characterizing musculoskeletal injury risk typically evaluated basic combat trainees or military recruits. Special Forces operators are required to maintain above-average physical fitness, which might make differentiation of injury risk among operators difficult due to lack of variability in body composition and energy-system performance. Thus, it is important to consider population-specific injury predictors that may be more relevant to the unique demands of each population. Population-specific injury predictors may be more nuanced than originally proposed, and an informative assessment of the potential risks of injury to the musculoskeletal, ligamentous, and tendinous structures may contribute to a broader understanding.

This study had several limitations. A history of ankle injury is a widely reported risk factor for future ankle sprain, but unfortunately, that information was not available for our analysis. Additionally, the use of a break test for ankle strength carries the risk of inadvertently capturing data points from an eccentric contraction if the participant’s ankle moved from the starting position. We were unable to control for this possibility. Another potential limitation is generalizability because all participants were men in the US Special Forces. (At the time of data collection, women were not yet integrated as operators in the US Air Force.) Another limitation was that strength ratios were measured using isometric dynamometry. The primary criticism of isometric testing is its lack of functional applications, yet it does possess significant advantages for research purposes. By controlling velocity, direct comparisons of peak force can be
obtained by isolating individual muscle groups during unilateral testing.\textsuperscript{31} Furthermore, handheld dynamometry is highly reproducible and a valid measure of force output.\textsuperscript{31} Still, it may be more relevant to asymmetry during dynamic tasks, and future investigators addressing the relationship of asymmetry and injury risk should focus on dynamic movements with a strength component to encompass the multifactorial nature of injury risk. Indeed, researchers have assessed asymmetry in more dynamic environments. For example, the symmetry angle method has applicability to functional assessments, such as the single-legged jump, as well as being relatively easy to implement and relevant to human movement.\textsuperscript{32}

CONCLUSIONS

The SA or imbalance or both, when considered as a univariate predictor, were not able to predict ankle injury in this population. However, asymmetry or imbalance or both contributed to significantly predicting ankle injury when body mass was included in multivariate prediction models. These results agree with those of Fousekis et al,\textsuperscript{5} who reported similar findings in soccer athletes. It seems SA may be a relevant predictor when included as a covariate that contributes to injury risk. Future authors should consider the role that muscular strength and SA play in the asymmetry of dynamic movement and how that may relate to the risk of musculoskeletal injury.

ACKNOWLEDGMENTS

This study was funded by Air Force Special Operations Command, \#FA8650-12-2-6271. We thank Meleesa Wohleber, Andrew Simonson, and Deirdre McFate for their contributions to data collection. The opinions expressed in this manuscript are those of the authors and do not necessarily reflect those of the US Air Force or the Department of Defense.

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