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# Comprehensive biomechanical characterization of feet in USMA cadets: Comparison across race, gender, arch flexibility, and foot types

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ABSTRACT

Lower extremity musculoskeletal injuries are common, complex, and costly problems. Literature supports associations between static foot structure and dynamic foot function, as well as between overuse injury and demographic characteristics. Previous studies failed to provide a comprehensive biomechanical foot characteristics of at-risk military personnel. In this study, foot structure, function, and arch height flexibility (AHF) were objectively measured in 1090 incoming cadets (16.3% female, mean age of 18.5 years and BMI of 24.5 kg/m$^2$) of the United States Military Academy at the start of their training. A Generalized Linear Model with an identity link function was used to examine the effects of race, gender, foot types, and AHF while accounting for potential dependence in bilateral data. Planus and flexible feet independently demonstrated over-pronation, as measured by reduced Center of Pressure Excursion Index (CPEI). When comparing across race, Black participants showed a significantly lower arch height index (AHI), a larger malleolar valgus index (MVI), and a higher prevalence of pes planus (91.7% versus 73.3% overall). However, Asian participants with flexible arches, rather than Black with low arch, displayed over-pronation in gait. Females showed no significant difference in standing AHI and MVI but demonstrated a significantly greater AHF and a reduced CPEI than male participants. This was the first large scale investigation that comprehensively characterized biomechanical foot in a cohort of young at-risk individuals with lower limb musculoskeletal injuries. Long-term goal is to examine the relationship between these biomechanical features and injuries, ultimately to develop effective preventive measures.

## 1. Introduction

Musculoskeletal (MSK) lower extremity disorders are common and costly problems [1]. More than two-thirds of unintentional injuries in the US annually are in the MSK system with total direct costs of $176.1 billion between 2009 and 2011 [1]. In military personnel, between 15% to 35% of men and 38% to 67% of women sustain at least one injury during Basic Combat Training, with 77% located in the pelvis and lower extremity [2]. MSK injuries are also the leading reason for medical care during active tour of duty. More than 75% of non-battle medical evacuations from Iraq or Afghanistan were for MSK conditions [3]. About 10% of active duty soldiers are non-deployable due to temporary or permanent MSK pathologies. Lower extremity pain and pes planus represented approximately 11% of all discharges [4]. Incidence of osteoarthritis is significantly higher in service personnel, compared to age-matched general population [5]. These acute and chronic conditions associated with MSK injuries can pose life-long challenges in maintenance of a healthy lifestyle and well-being. As stated by Teyhen et al., "Correctly identifying people with foot types susceptible to severe lower extremity MSK injuries could help inform clinical decision making, reduce recurrent injuries and injury-related costs" [6].

While ankle injuries are most prevalent, lower limb stress fractures can impede readiness of combat unit as the affected individuals are not able to engage in weight-bearing activities for 6–8 weeks. A study of 3025 US Marine Recruits during 12-week basic training showed a 2.45 relative risk of stress fractures or stress reactions in White recruits [7].

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Another study, which included all US service members from 2009 to 2012, similarly showed higher unadjusted incidence rate for lower extremity stress fractures in White (6.08 per 1000 person-years), compared to African-American (5.21) and subjects of other race categories (4.41) [8]. A prospective study of 449 Navy Sea, Air, and Land (SEAL) trainees reported that the risk for developing stress fractures in either low or high arch was twice that of normal arch feet [9].

A number of investigations focused on cadets of United States Military Academy (USMA) – an ideal setting for a number of reasons, including high prevalence of overuse injuries, standardized rigorous training, and enclosed health care system with integrated injury tracking and treatment. Cosman et al. reported at least one stress fracture (58% metatarsal and 29% tibial) in 5.7% of male and 19% of female USMA cadets primarily during the first 3 months, which encompasses basic training [10]. In males, the risk of stress fracture was higher for those who exercised less than 7 h per week during the prior year, with smaller tibial cortical area, lower bone density, and smaller femoral neck diameter. In females, the risk of stress fracture was higher for those who had a shorter time since menarche and smaller femoral neck diameter. These factors accounted for less than 10% of model variance; the authors suggested considering biomechanical factors such as foot type, leg length discrepancy, or external hip rotation. Levy et al. showed a correlation between severity of flatfoot and the incidences of lower extremity injuries at USMA cadets. However, female cadets experienced a higher incidence of lower extremity injuries than males in the absence of severe flatfoot [11].

Studies suggest potential importance of arch flexibility to foot function and MSK injuries. Three-dimensional motion analysis of the navicular displacement in the pediatric feet showed uncoupling of the navicular motion, which suggest impaired midfoot function in flatfoot [12]. Subjects with medial tibial stress syndrome demonstrated increased navicular drop in quiet standing and increased arch deformation in gait than healthy control [13]. Subjects with patellofemoral pain displayed a more medially oriented plantar loading during drop jump, and those who experienced an immediate decrease in peak plantar pressure with the use custom foot orthoses were more likely to report improvements after 12 weeks of use [14,15]. While females demonstrated greater arch motion or flexibility than males [16,17], significance of arch flexibility on foot function and lower limb MSK injuries remained largely unknown.

A number of large-scale studies have been conducted to assess the efficacy of shoe or foot orthoses on MSK injuries with inconsistent findings. Selection of running shoes based on visual inspection of plantar shape in 722 Marine Corps in basic training had little influence even after considering other injury risk factors [18]. Cochrane review of 16 trials concluded that the use of cushioning shoe insert probably reduced lower limb MSK injuries [19]. Authors also concluded that there is insufficient evidence to determine the best insert design and recommended consideration of comfort and tolerance.

There is a significant gap in literature. Specifically, no investigation to date provided comprehensive measures of foot biomechanics in a young active cohort. A comprehensive foot assessment is needed as a baseline description of study cohort to elucidate relationship between foot structure, function, and flexibility; to eventually identify risk factors associated with lower limb MSK injuries, and to develop effective interventions. The purpose of this study was to employ a comprehensive set of foot measurements (1) to describe biomechanical characteristics of feet using a large cohort of healthy young participants at risk for lower limb MSK injuries and (2) to compare differences in foot structure, function, and flexibility across race and gender.

## 2. Participants and methods

### 2.1. Participants

The study protocol was approved by the Institutional Review Board of the United States Military Academy (USMA). Of the 1173 incoming cadets at the USMA, 1124 (95.8%) subjects volunteered to participate in the study and provided informed consent. Data were collected within 3 days of the 6-week basic training in the summer of 2013, while study participants were fitted for their boots. To accommodate their rigorous training schedule, some participants were instructed to bypass measurement stations, resulting in varying sample sizes for different parameters.

## 3. Methods

Overall foot geometry and arch flexibility were assessed using the Arch Height Index Measurement System (JakTool LLC, Cranbury) [20]. This device provides a quick and reliable means to measure foot length, truncated foot length (distance from heel to the first metatarsophalangeal joint), and arch height in sitting and standing positions. Arch Height Index (AHI) is a ratio of the dorsal arch height measured at half the foot length in sitting, normalized by the truncated foot length. AHI was calculated for sitting and standing postures. Each foot was categorized as planus, rectus, or cavus foot type based on previously published standing AHI criteria [21]. Arch drop is the change in arch height from sitting to standing. Foot elongation (ΔFL) is the change in foot length from sitting to standing. Arch height flexibility (AHF, mm/kn) is defined as the arch drop, normalized to change in load, estimated to be 40% of the body weight [21]. AHF was stratified into 3 categories: largest quintile as flexible, middle 3 quintiles as referent, and smallest quintile as stiff.

Twelve stations were set up to measure AHI of each participant, with two testers at each station. Rater measured the foot dimensions while the recorder entered the data into a customized Filemaker Pro app running on an iPad. The two-person team allowed for efficient data acquisition (about 90 s per participant) and a means to check for accuracy of data entry. Resulting foot dimensions were also used to facilitate boot fitting. Podiatric medical students were trained to measure AHI. To ensure consistency of measurements, 12 randomly selected teams of trained students measured AHI on 12 volunteers twice in non-consecutive order and yielded an intra-rater reliability (ICC (2,1)) of 0.88 and an inter-rater reliability (ICC (3, 1)) of 0.84 [22,23].

Standing hindfoot alignment was assessed using the Malleolar Valgus Index (MVI). Instead of using a computer flatbed scanner as originally described [24], one station was set up with a Plexiglas platform, a mirror, and a digital camera to expedite data collection. While a subject stood comfortably in his/her base and angle of stance, the sole of each foot was photographed using a mirror position at 45°. The camera (Nikon D5200 with a 35 mm lens) was physically fixed relative to the mirror to minimize potential parallax. A 5.08 $cm^2$ area calibration square was photographed simultaneously with the foot, to provide a conversion factor needed to calculate the MVI. Custom developed software was used to compute MVI (%) – larger MVI is associated with greater hindfoot valgus or pronatory foot posture. Consistency of photo-based MVI was compared to the original scanner-based MVI (non-published). Two independent measurements of 14 healthy participants (28 feet) by 2 raters using both methods showed no significant difference between two methods ($p = 0.587$, mean difference = 0.24%). Intra-rater reliability (ICC 2,k) was 0.941 and inter-rater reliability (ICC 3,k) was 0.917 [22,23].

Each participant's dynamic plantar pressure distribution was captured with a second-step barefoot protocol at comfortable walking speed using emed-X (novel gmbH, Munich) with a resolution of 4 sensors per $cm^2$ and sampling rate of 100 Hz. Five stations were set up to collect dynamic plantar pressures on both feet, 5 trials per foot. Peak pressure (PP, $N/cm^2$) and the Center of Pressure Excursion Index (CPEI, %) were calculated as the mean of 5 trials per foot using novel scientific software (version 24) [25].