THE RELATIONSHIP BETWEEN BONE QUALITY AND MUSCLE PERFORMANCE IN CROSS COUNTRY AND TRACK AND FIELD ATHLETES

By

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Abstract: **Introduction**: Cross-Country and Track and field (XC+T&F) athletes exhibit high levels of lower body bone injuries compared to other collegiate athletes, as well as lower levels of areal bone mineral density (aBMD). Lower aBMD has been associated with increased frequency and severity of bone injuries. The best none pharmaceutical way of increasing aBMD and reducing these injury risks are through physical training. Both strength and power movements have both been shown to elicit these increased bone mineral density adaptations, but which one of these are a better stimulus? Our study looks to fill this gap of knowledge by looking evaluating both power and strength muscle output and characterizes and their ability to predict total body and site-specific bone mineral density values. **Methods**: Thirty-three XC+T&F athletes provided informed consent followed by an injury and activity questionnaire. Dual-energy X-ray absorptiometry was used to access body composition and aBMD, prior to this, athletes conducted a urine analysis for hydration status and height and weight measurements. Unilateral dynamic knee extension and flexion of both legs were measures by a Biodex 3. Athletes completed three repetitions at 60, 120 and 180°/sec; these speeds are clinically associated with strength, mixed, and power, respectively. Independent *t*-tests were used to assess initial differences between XC+T&F sex baseline characteristics. Pearson's correlation coefficients were calculated to inform independent variables suitability for regression modeling. Forced linear regression modeling evaluated if strength only or power only models accounted for the greatest amount of variance in total body and 4 site-specific aBMD area, as well as three hip structural analysis measures. **Results**: Both strength and power regression models were able to account for variance within ranges of 21.0-59.4% ± 9.6% (all $p \leq 0.005$), but power was able to not only predict the greatest number of variables with significance, but it also had the greatest magnitude of variance that could be accounted for. Power models provided an additional 9.2-25% ± 7.9% increase for accounting for variance over strength models. **Conclusion**: Power training may be a better modality for training over strength, for both athletes and clinical populations that are pursuing greater aBMD adaptations.

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CHAPTER I

INTRODUCTION

Over 100 years ago, Roux and Wolff proposed that bone architecture is determined by mathematical laws; later Pauwels, Thompson, Turner, Frost, Hert, Rubin, McLeod, and others continued to further characterize how bone is a dynamic tissue capable of adapting to loads [1-3]. Turner described three basic rules that a load or stimulus must meet or exceed in order to elicit an anabolic skeletal response (130). First, the load should be a dynamic movement instead of static. Second, short durations of loading are sufficient to induce changes. Lastly, bone cells adapt to the stimuli over time, thus requiring a progression or the introduction of a new stimuli. These stimuli can be described as either internal or external mechanical load. Internal loading consists of the force put on the bone from muscle contraction [4] such as during locomotion. Conversely, an external load is considered any loading vector associated with the gravitational load of the movement and is often described as the magnitude of vertical ground reaction forces (vGRF). Physical activity and exercise both encompass internal and external loading profiles that have osteogenic potential but as to whether strength- or power-based movements are more beneficial to bone is still under investigation.

Athletes who compete in the sports of cross-county and/or track and field (XC+T&F) exhibit muscular characteristics within the designations of endurance, strength, and power [5].

Furthermore, collegiate NCAA Division I athletes have high training demands for competition which may elicit muscular overuse, asymmetries, and imbalances [6]. While training demands of these athletes can be considered to be osteogenic based on the rules described above, increased training frequency [7], lack of quality sleep [8], and reduced energy intake [9] can have a deleterious effect on bone health, leading to increased risk of injury such as stress fractures [10, 11]. Furthermore, since chronically increased training frequency has a negative impact on recovery for athletes, rest between competitive seasons may be necessary to allow athletes to recover and regulate damaged musculoskeletal systems [12, 13]. However, those who compete in multiple consecutive seasons (i.e., transition from one season to the next with minimal recovery time) may incur musculoskeletal taxation due to drastically reduced rest, further increasing the risk of injury [7, 14]. Collegiate XC+T&F athletes may be at the highest risk of musculoskeletal injury due to the ability to compete in four distinct seasons throughout the year (XC, indoor, outdoor, and professional) that allow for very little recovery time between seasons. This musculoskeletal taxation can also impact future circumstances such as the frequency of injuries, severity of injury, and alteration of gait [6, 14, 15]. This can negatively impact XC+T&F athletes by leading to missed training and competitions and impaired performance due to changes in gait.

Research on this athlete cohort and their elevated injury risk may provide an insight on the effectiveness of current injury prevention strategies. Kerr et al., 2016, conducted an epidemiological study investigating 25 men's and 22 women's cross-country programs, providing 47 and 43 seasons of data, respectively. They observed a 5% injury rate in the XC+T&F athletes, with women's cross-country having injury rates at 1.25 times higher than their male counterparts. Males and females were observed to have 53.3% and 57.6% of incidents classified as either muscle or bone overuse injuries, respectively [16]. Reinking et al., 2015, observed a 10% prevalence rate of lower extremity overuse bone injuries within a smaller cohort of 64 female and 20 male collegiate track and field athletes [17]. Furthermore, they were able to identify that

athletes with a calcaneal areal bone mineral density (aBMD) below the mean of the study were 2.1 (95% CI = 1.09-3.35) times more likely to have reported an overuse bone injury [17]. The prevalence of injury within these previous studies is apparent, but they do not evaluate associative factors such as muscular strength or power training within the athlete groups. To further evaluate the association between muscular strength and injury risk, Clark et al., 2011, observed within a cohort of 1500 active adolescents (age 14 ± 1.5 yrs). They found a positive association between forearm fractures and low hand grip strength assessment ($p=0.005$). Additionally, Bennell et al., 1997, performed a 12-month longitudinal study comparing bone mass and bone turnover in track and field athletes. Power athletes in track and field (throwers, sprinters, jumpers) exhibited greater aBMD measures than their endurance (mid and long distance) athlete counterparts at regional and site-specific areas of the upper and lower body (all $p \leq 0.05$). Furthermore, Bennell et al., 1999, further concluded that the prevalence of stress fracture injuries and the difference in injury rate between power and endurance track and field athletes, are the lower levels of aBMD and muscle weakness exhibited by the endurance athletes [10, 18]. For instance, in military cohorts those who remain bone injury free have larger muscle cross-sectional area, greater muscle strength, and greater muscle power than their previously injured counterparts [19]. This evidence supports the idea of muscular strength and power being a protective mechanism to bone health metrics. It is pertinent that we gain a better understanding of the influence muscle strength and power have on bone mass to potentially help protect these athletes from future skeletal injuries [16].

Mechanical loading of the skeletal muscle via strength and power training promote beneficial effects on bone mass [20]. Furthermore, these training modes have been shown to improve areal bone mineral density (aBMD) at fracture-prone sites such as the hip and lumbar spine, primarily in postmenopausal women [20-22]. This has been frequently evaluated within the aging populations, as well as younger more active populations. For instance, Lester et al, 2009,

observed 56 women (20.3 ± 1.8 years) who were assigned either a control group or one of three exercise groups (aerobic, resistance, or combined aerobic and resistance) over an eight-week training intervention. The exercise groups all had increases in aBMD measures, as well as circulatory biomarkers of bone remodeling compared to the control group ($p < 0.05$) [23]. Additionally, power athletes, such as sprinters and throwers (shotput, discus, and hammer), see a positive adaptation to total body bone mineral content (BMC), aBMD, and Z-scores [24] due to the nature of their training but contrary evidence suggests these relationships are altered in aerobic athletes [25]. Such as a study published by Hirsch et al., 2016, who investigated total body BMC, composition, and muscle characteristics in 60 (31 male, 29 female) NCAA Division I track and field athletes after one year. Athletes were stratified into 6 event designation groups, sprints, mid distance, multi-event, jumps, pole vault/javelin, and throws. They found the mid-distance designation had significantly less lean mass, trunk fat, muscle density and bone mineral content than the other five groups (all $p \leq 0.05$) [5]. It was also concluded that all values for body and bone composition were still within healthy clinical ranges. Unfortunately, they did not assess site-specific bone adaptions or muscle strength/power correlations with the measured variables. To my knowledge, the only direct comparisons between power and strength training was conducted by Stengel et al., 2005. This study assigned 53 postmenopausal women to a strength training ($n = 28$) or power training group ($n = 25$) over 12 months. Both groups conducted the same weightlifting movements, but at differing speeds, 2 times per week at a gym and 1 time per week at home. The strength group conducted movements with machines at a 3 second concentric phase and a 3 second eccentric phase while the power group conducted concentric movements fast/explosive and 2 second eccentric phase movements [26, 27]. The authors concluded that the power training group was able to maintain aBDM to a greater extent than the strength training group (ref). Although these data are important, they do not inform us as to the relationship between muscle strength and power in a young XC+ T&F athlete cohort that is yet to reach peak bone mass (late second or early third decade of life for women and early to mid-third decade of

life for men). Additionally, XC+T&F athletes compete in a sport that has one of the highest risks of stress fractures reported compared to other sports like gymnastics, basketball, rugby and American football [28]. Thus, this indicates a potential gap in research knowledge between strength and power training and their effects of bone mineral density in order to mitigate bone injuries that needs further exploration.

Purpose

To determine if muscle strength or power more strongly predicted total and site-specific aBMD in NCAA Division I XC+T&F athletes over time.

Research Questions

Our aim was to elucidate which muscle performance metric (strength or power) would be more predictive of total and site-specific aBMD using regression models of change.

Hypotheses

We hypothesized that muscle power would be a stronger predictor of total and site-specific aBMD.

Sub Questions

Our aim was to quantify the influence of tertiary factors that may modulate the statistical relationship between muscle strength or power and aBMD. These factors included sleep and training and injury status.

Sub Hypotheses

We hypothesized training frequency would be positively correlated with muscle performance and bone density, while higher injury prevalence would be negatively correlated to muscle performance and bone health.

Significance of the Study

Longitudinally assessing musculoskeletal adaptations in XC+T&F populations throughout the course of a competitive year would provide critical insight whether strength or power are better correlated with markers of bone health and reduced injury prevalence. This will assist both coaches and athletes with maintain bone injury free participation at a collegiate NCAA Division I and professional level. The tremendous monitoring responsibilities placed upon a coaching, performance, and sports medicine staff may a not allow for scoping diagnostic evaluation pertaining to muscle and bone health. Creation of predictive risk and injury models encompassing musculoskeletal health and performance, dietary and sleep habits, and other factors may streamline individual athlete health and performance analysis. These findings have the potential to benefit sports medicine, athletic, and performance specialists in developing a comprehensive athlete care and development program to mitigate historical pitfalls which have impacted acute and long-term performance and health outcomes in this population.

Assumptions

Athletes' musculoskeletal health and performance metrics would fluctuate throughout the course of the competitive year with expected reductions in muscular strength and power and increased aBMD during off-season phases and inverse effects during peak training phases. Additionally, athletes that have a clinically good score for sleep will have greater bone mineral measurements.

Delimitations

All participants were able to participate in-person at Oklahoma State University. Sample size is 33 NCAA Division I athletes.

Limitations

There are three main limitations of this study: generalizability, subject attrition, and vitamin D status. The findings from this study may not be generalizable to athletes who compete outside of NCAA Division I, at other institutions, or in other sports, as based on competitive level and a variety of training factors which could influence conclusions. Second, NCAA athletes' time availability is highly stringent which could have impacted participation. Our research team aimed to mitigate this potential issue by maintaining consistent communication with athletes, coaches, and sports medicine staff. Lastly, some athletes had serum Vitamin D concentrations measured at the beginning of the study but not throughout. Because level of Vitamin D fluctuates, it may be a confounding factor for musculoskeletal health that our team cannot account for.

CHAPTER II

REVIEW OF LITERATURE

Strong and stable bones are quickly coming to the forefront of sports science and clinical research. This requires a balance in metabolic bone activity between bone forming cells and bone resorbing cells, these being osteoblasts and osteoclasts, respectively. When either of these two metabolic actions are in an imbalance, disruptions in the bone remodeling process may occur. For instance, osteoporosis is a progressive disease characterized by low aBMD due to high rates of bone resorption from osteoclast activity and suppressed osteoblast activity [29]. Older adults and those with bone metabolism diseases are not the only populations that suffer from abnormal bone remodeling processes and injuries. Many young athletic populations can experience exercise-induced mechanical stress injuries, which occur when the loading profile criteria exceeds the bone's integrity and trauma occurs [30, 31]. Cross-country and track and field athletes (XC+T&F) are at particular risk of bone related injuries due to the nature of the sport, with literature reporting up to a 21% incidence rate in 17-26 mixed sex cohort of state and national level athletes. [32]. In order to better understand the relationship between muscle and bone health in track athletes we first must discuss the principles of skeletal metabolism, muscle morphology and function, and key factors which influence specific injury risks such energy availability, hormonal imbalances, and rest profiles.

Bone Physiology and Mechanotransduction

Skeletal homeostasis is a dynamic process that involves a wide variety of cell types and signaling pathways. The genetic blueprint for bone is contained within the bone cells. There is also an epigenetic component of skeletal design that is directed by the chemical milieu of the cell's internal environment and the mechanical forces exerted on the bones. Together, these forces shape the bone until it can meet the structural requirements applied to it [1]. There are primarily three cell types that work in unison to engineer bone's microstructure: osteocytes, osteoclasts and osteoblasts. The way that these cells interact determines the spatial orientation and extent of mineralized matrix forming either cortical or trabecular bone. Highly integrated signaling pathways regulate how these bone cells function throughout developmental, maintenance, and disease stages. Each cell type has its own specific function to the overall engineering of bone. For instance, osteoclasts are specialized, multinucleated cells that are primarily responsible for bone resorption. Osteoclasts secrete hydrochloric acid and proteases effectively dissolving the bone mineral [33]. This is important for the remodeling process since it strips away older, possibly damaged bone and recycles the calcium into the system for purposes of calcium signaling or new bone formation. Mesenchymal stem cells differentiate into osteoblasts that are responsible for re-mineralizing old bone matrix or creating new bone. When osteoblasts or osteoclasts out work the other cell type pathological conditions such as osteoporosis or Paget's disease may occur. Osteocytes are previous osteoblasts that became entrapped within the bone and have undergone a functional shift. The purpose of osteocytes is to signal osteoblasts or osteoclasts to increase their activity based on the magnitude and volume of bone loading from either internal or external stimuli (such as exercise). This is relevant to the remodeling process of the bone, since they can signal when a part of the bone needs to undergo reformation which commonly represents an adaptation to a load in active populations.

As previously mentioned bone responds to stimuli if it meets Turner's three rules; the stimuli being a dynamic movement, can be of a short duration, and is progressive over time. [34]. However, Frost described how osteocytes have specific minimum and maximum thresholds that must be exceeded for either osteoblasts to build or osteoclasts to resorb bone, this is called the Mechanostat Theory [1]. Another aspect of the stimulus to consider is the frequency, magnitude, duration, and rest. How the stimuli are transmitted to the skeleton can be altered and in turn dictates the cellular response. Muscle strength and power meet and exceed the required threshold differently, strength puts a large gravitational stress on the bone while power creates a large fluid shear stress inside of the bone. Furthermore, based on one's training program the loading from these movements have differing frequency, magnitude, duration, and rest profiles. These factors influence how much new bone is laid down in response to strength or power movements.

Muscle Strength and Power

Muscle strength is defined as the maximum amount of force one can generate, whereas power is a derivative of work with respect to time and is often explosive in nature. Both of these have physiological relevance to the remodeling of bone, since both cause an accumulation of microdamage in the bone [35-37]. The application of stress is most notable during force production at the ends of the long bones. For instance, even during normal locomotion over 2 kg of force generated by the muscles is required to move each kg of body weight [38]. In certain regions of the body, bone loading is increased by an internal muscular force as a result of contraction; however, this contraction also decreases the bone loading observed in other regions of the bone [39, 40]. Depending on the anatomical locations of the points of insertion and origin, paired with pennation angle, a muscle can provide compression, tension or bending strains to a bone. Additionally, if an external load is applied to the bone from vertical ground reaction forces, the compensatory muscle contraction can reduce the compression, shear, torsional, or bending forces applied to the long bones. Individuals, who vary in muscle strength, are able to produce

and redistribute different magnitudes of load [41]. These results suggest the same exercise, being performed by two people of unequal muscular strength, may result in unequal osteogenic effects. An example of this would be a drop or depth jump, were the individuals jump off of an 18-inch box and reactively moves ground contact into an immediate jump onto another box of similar or greater heights; the higher muscular power individual will be able to produce more of a dynamic stress on the bone, causing a greater positive osteogenic metabolic response.

Additionally, both plyometric high-impact exercises and traditional strength training promote beneficial effects on bone mass [20]. In young adults, both training modes have been reported to increase aBMD at the hip and lumbar spine [20-22], which are sites prone to osteoporotic fractures. Beneficial changes in circulating levels of bone formation markers (e.g., type 1 collagen amino-terminal propeptide [P1NP]) and bone resorption markers (e.g., type 1 collagen C breakdown products [CTX]) have also been reported [42, 43]. Gurbuz et al., 2016 took 32 healthy males and divided them into an exercise and control group, the exercise group then completed 10 weeks of jogging and explosive power movement exercises three times per week. Results demonstrated the exercise group improved femoral neck and total aBMD scores while controls did not [44]. These results are not anything new for the field of bone research, where we start to see new information is with Yingling et al., 2021, 147 participants (81 females and 66 males) completed a hand grip strength measurement, a vertical peak power jump for muscular output measures, and a peripheral Quantitative Computed Tomography (pQCT) to measure site-specific bone mineral content variables and geometric bone strength. They demonstrated vertical peak power predicted bone strength parameters to a greater extent than hand grip strength of the radius [45]. Interestingly peak power, a lower limb measurement explained the most variance in the bone strength of the upper limb. This further supports the creation of a predictive model for strength or power and their ability to predict high to moderate levels of variance for bone health metrics.

REDs, Hormonal Imbalances, Diet and Sleep

Although the primary outcome measures of this thesis revolve around bone and muscle it is important to understand the tertiary factors associated with bone health. Other arms of the study not included in this thesis are measuring aspects of REDs, hormonal factors, and sleep thus these are briefly included in this review.

The female Athlete Triad [46] and updated Relative energy deficiency in sport (RED-S) [47] describes a multifactorial syndrome (Figure 1) which commonly presents with overtraining, and/or disordered eating behaviors resulting in weight loss and reduced performance [46-49]. Weight-loss due to REDs can result in a significant amount of bone loss [50, 51] which is often not recovered with weight regain [52]. Additionally, reduced muscle protein synthesis [53, 54] and hormonal imbalances [41, 55] increase the risk of bone injury. Lastly, those suffering from REDs also have decreased glycogen stores and an impaired ability to store carbohydrates further impairing performance [56].

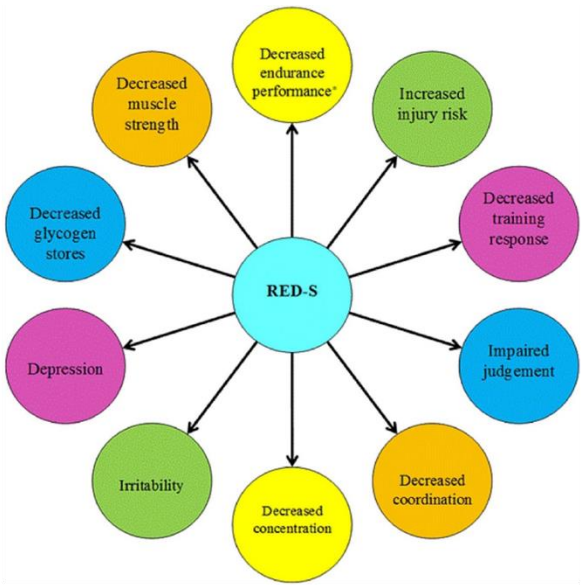

Figure 1. Potential Performance Effects of Relative Energy Deficiency in Sport (*Aerobic and anaerobic performance). Adapted from Mountjoy 52. Mountjoy, M., et al., *The IOC consensus statement: beyond the Female Athlete Triad—Relative Energy Deficiency in Sport (RED-S).* 2014. **48**(7): p. 491-497.

Altered sex hormone levels can have a deleterious effect on bone health and muscle performance in athlete cohorts. In females, amenorrhea is defined as persistent anovulation with no identifiable organic cause [57]. This has been observed occurring in a wide range of studies, ranging from 21% in English runners to 61% in gymnasts [58, 59]. This often

stems from low energy availability and high exercise-related caloric expenditure causing an inhibition of the hypothalamus-pituitary-ovarian axis leading to estrogen deficiency [60, 61], further exacerbating other REDs symptoms, such as decreased training response, glycogen storages, and muscle strength. In males, low testosterone levels are associated with low aBMD [62] and can be attributed, in part, to low energy availability and its relationship with other stress related hormones like catecholamines and cortisol [63], all of which can be catabolic to both bone and muscle.

Recovery from strenuous exercise requires a healthy diet and quality sleep, both of which are strongly related to bone and muscle health and athlete's performance. It is well established that adequate protein, vitamin D, and calcium are extremely important and integrative components of health [64]. For instance, 99% of the body's calcium is stored within the skeleton [65] and it is the most tightly regulated ion in the body as it serves a vital role in muscle contraction, transmission of nerve impulses, regulation of hormonal secretion, and cardiac activities [66-68]. Additionally, it is well known that sleep is in important factor for numerous biological processes and systems in the body [69], as well as mitigation of metabolic, cardiovascular, endocrine and neurological disorders. [70-72]. Sleep circadian disruption has been reported to increase the risk of injury for individuals that work night shift [73] and environmental hazards [74] such as driving, as well as bone turnover markers. For instance, Qvist et al., 2002, found that bone resorption increased over 140% in 100 postmenopausal who participated in a sleep disturbance protocol. Protein plays a key role in bone health due to its effects on acid production and renal acid excretion and its stimulating effects on the liver and its release of bone insulin-like growth factor 1 (IGF-I), which is turn increases osteoblast proliferation and activity, resulting in more bone being absorbed rather than rebuilt into new bone [75, 76]. These effects create a multifaceted problem for both athletes and clinical populations

that express symptoms of RED-s and/or lack sleep and diet quality, as well as a potential loss in training modality (strength or power) which may mitigate levels of bone loss.

Summary

Bone and muscle health are vital to athletic performance but their growth, maintenance, and response to training is multifactorial. Prioritizing a predictive model to determine whether strength or power will more strongly predict high bone mineral density could serve as valuable knowledge in the mitigation of bone related injuries. Additional areas of importance for athletes' musculoskeletal health include maintaining proper hormonal levels, getting adequate sleep, and monitoring dietary quality to maximize performance gains from training protocols. This body of literature could provide a better framework and understanding of strength and power adaptations in bone not only in athlete populations, but could carry over to the professional and clinical realms.

CHAPTER III

METHODOLOGY

Participants

This study was proposed to all of the OSU XC+T&F athletes in search for their participation, with a total of 33 athletes participated in the study. Participants were informed of the risks and benefits before providing voluntary written consent prior to testing. All procedures were approved by the Institutional Review Board at Oklahoma State University (IRB #22-113-STW).

Inclusion Criteria for XC+T&F

1. Participants were aged between 18-26 years old.
2. Participants were members of the Oklahoma State University XC+T&F teams.
3. Participants weighed less than 500 lbs.
4. Participants were willing to provide a urine sample

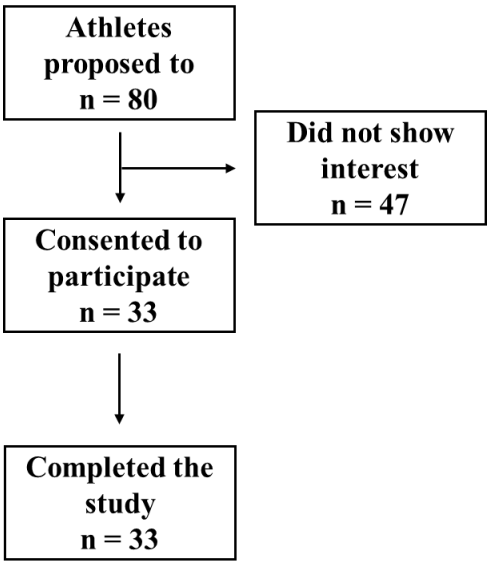

Figure 2. Recruitment flow chart

For hydration testing and pregnancy status (if applicable).

Exclusion Criteria for XC+T&F

1. Participants were not pregnant or planning on becoming pregnant.

2. Participants were not receiving any type of radiation treatment.

Research Design

This study was a prospective cohort design encompassing three testing phases (Figure 2). This allowed for a comprehensive assessment of general health, training and injury status, current and past menstrual cycle characteristics, body composition, bone health, muscle performance, active range of motion, diet, and sleep quality. Below are details of each of the specific testing procedures.

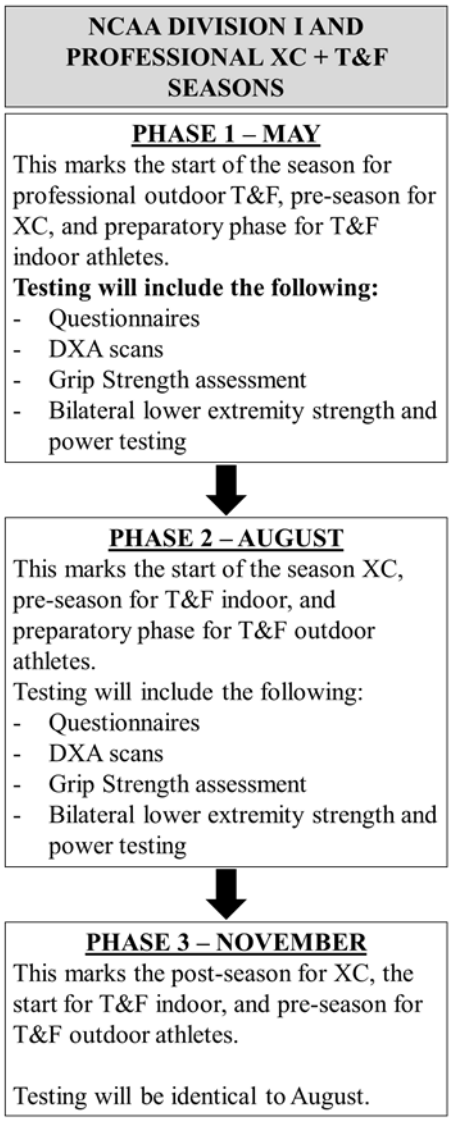

Figure 3. A detailed testing timeline for the proposed study

Questionnaires

1. Informed Consent was used to ensure the participant had a complete understanding of the study procedures including potential risks and benefits before providing voluntary consent for enrollment.

2. Training and Injury Questionnaires [77] were used to describe auxiliary forms of exercise in which the participant was engaging in and any musculoskeletal injuries they had previously sustained.

3. Bone-Specific Physical Activity Questionnaire (BPAQ) used to quantify bone loading activities that participants were engaged in across their lifespan. [78]

4. Pittsburg Sleep Quality Index (PSQI) was used to evaluate assess sleep quality and disturbances over a 1-month time interval, resulting in an overall sleep score. Scores of ≤ 5 is classified as a good sleeper and ≥ 6 is classified as a poor sleeper, clinically.

Anthropometrics

Height (cm) and weight (kg) were collected via Health o meter Professional 500KL-BT scale and stadiometer (Health o meter Professional., McCook, IL, USA). These measures were used to calculate BMI (kg/m2).

Urine Analysis

All participants provided a urine sample. Urine specific gravity, a measure of hydration status, was measured using a digital refractometer (MISCO #PA201, Solon, OH); samples needed be within 1.004-1.028 urine specific gravity (SG) to be considered within normal hydration ranges. If participants were dehydrated, they were given water and retested after 30 minutes. If participants were over-hydrated, they were asked to reschedule the visit. Urine samples from female participants were also used to test for pregnancy status using a pregnancy strip (Pregmate, Fort Lauderdale, FL). The strip was dipped into the urine for 15 seconds and then left to rest for four minutes, after which time the strip was read.

Dual-energy X-ray Absorptiometry

A Hologic Horizon A model DXA (Apex Software V 5.6.1.2 rev 009, Hologic Inc., Marlborough, MA, USA) was used to measure bone and body composition. Total body scans were used to measure bone mineral content (BMC; g), fat mass (FM; g), and bone-free lean body mass (BFLBM; g). From this total body aBMD g/cm2, body fat percent (BF%), and lean mass to fat mass ratios (LM:FM) were calculated. Additionally, BMC and aBMD were calculated from lumbar spine (L1-L4) and dual proximal femoral (total hip, femoral neck, greater trochanter) scans. Tissue asymmetries were evaluated through automatic segmental processing and specific region of interests using custom analyses methods [77, 79]. The in vivo coefficients of variation for DXA variables ranges from 0.5 to 1.0% in in the Oklahoma State University Musculoskeletal Adaptations to Aging and eXercise (MAAX) Lab [80].

Hip Structural Analysis

The Hip Structural Analysis (HSA) program measures geometric properties for a given cross-sectional of the femur. This is done by structural analysis of three specific areas on the proximal femur. The specific areas consist of the narrow neck, intertrochanteric, and femoral shaft. The narrow neck (NN) is measured as the diameter of the narrowest part of the femoral neck, and is more commonly known as the ward's triangle measurement. The NN measured profile is made up of 60% cortical bone and 40% trabecular bone. The Intertrochanteric (IT) is located at the bisect of the neck-shaft angle (close to the distal part of the greater trochanter). The IT measured profile is made up of 70% cortical bone and 30% trabecular bone. Lastly, the femoral shaft (FS) is measured at 2 centimeters below the lesser trochanter, and is commonly known as the surgical neck area. Each of these three regions will have both left and right femoral measures, and six different structural measures. The structural measures consist of 1) cross sectional area (cm2) (CSA), which is the amount of cortical bone on the surface, that excludes

trabecular and tissue spaces; 2) Cross sectional moment of inertia (cm4) (CSMI), an index of structural rigidity that reflects distribution of mass about the center of the structure element; 3) Subperiosteal width (cm) (SPW), the outer diameter of the bone; 4) Endocortical diameter (cm) (ECW), the inside diameter of the cortex; 5) Section modulus (cm3) (SM), an indicator of bending strength for maximum bending stress; and 6) buckling ratio (BR), an estimate of cortical stability in buckling.

Muscle Strength and Power Testing

Alternating unilateral grip strength was assessed through alternating three-second maximal effort repetitions using a Jamar (G.E. Miller Inc., Yonkers, NY, USA) handgrip dynamometer [81]. The handgrip test was conducted with the participant standing with a firm grip on the dynamometer handle, the elbow bent to 90° with the elbow and upper are arm not resting on the side of the torso. Three alternating repetitions were conducted with each hand, with 30 seconds of rest given between bilateral assessments. Unilateral lower extremity strength and power assessments of both the left and right legs were conducted using a Biodex Isokinetic Dynamometers (Biodex Medical Systems, NY, USA). Three repetitions of knee joint concentric extension and flexion were conducted at 60/120/180 °/sec with a 90 second rest period between speeds. This encompasses a wide spectrum of torques that are associated with muscular strength at 60 °/sec and muscular power at 180◦/sec [82, 83]. From this, a dynamic quadricep to hamstring ratio (Q:H) was calculated. The Q:H ratio is a validated metric used to determine lower extremity musculoskeletal injury risk, especially in this cohort [84]. The unilateral nature of testing allowed for determination of muscular asymmetries which has also been a reliable measurement for acute and chronic injury risk [6].

Statistical Analyses

All statistical procedures were performed using IBM SPSS (v26, Armonk, New York). The significance of all statistical analyses was set at $p \leq 0.05$, and normality was tested using the Shapiro-Wilks test. Independent t-tests were used to assess initial differences between XC+T&F sex baseline characteristics. Cohen's effect size (d) was calculated and interpreted as small (d=0.2), moderate (d=0.5), and large (d=0.8). Pearson's correlation coefficients were calculated to inform independent variables suitability for regression modeling, such as number of injuries, mileage per week, weight training days per week as well as BPAQ and sleep questionnaire responses. Pearson (r2) strength was interpreted as: small (0.1-0.3), moderate (0.3-0.5), and strong (0.5-1.0) [85]. The previously mentioned independent variables were analyzed for their use in a regression model. Forced linear regression modeling evaluated if strength only or power only models accounted for the greatest amount of variance in site-specific aBMD (lumbar spine, greater trochanter, femoral neck, femoral shaft and total body), as well as the three HSA (narrow neck, intertrochanter, and femoral shaft section moduli) measures. Following this analysis, hierarchical linear block regression was used to identify if the number of injuries would provide statistical and predictive strength to the strength and power regression models of total body and site-specific aBMD.

CHAPTER IV

FINDINGS

The purpose of this study was to determine whether strength or power metrics would be a stronger predictor of bone density in collegiate track and field and cross-country athletes. A secondary purpose was to quantify the influence of tertiary factors that may modulate the statistical relationship between muscle strength or power and aBMD. These factors included sleep quality, total mileage per week, and number of injuries.

Participant Characteristics

A total of 33 athletes (female n=25; male n=8) were enrolled in the study. All 33 athletes signed a consent form prior to completing the screening documentation and completing the study in full. Baseline athlete participant characteristics are found in Table 1. Males were significantly taller and heavier than females and reported a greater number of total injuries (both $p \leq 0.005$). Males and females were equivalent for age, BMI, the number of events they reported competing in, their sleep quality, and BPAQ scores (all $p \geq 0.064$).

Table 1. Table 1. Baseline comparisons of participant characteristics, data are shown as mean ± standard deviation.

	Female (n=25)	Male (n=8)	p	*d*
Age (years)	20.8 ± 1.6	21.5 ± 1.5	0.326	0.40
Height (cm)	167.2 ± 5.4	179.2 ± 7.4	<0.000*	1.54
Body Mass (kg)	61.5 ± 13.2	81.81 ± 24.3	0.005*	1.11
BMI (kg/m^2)	21.8 ± 3.6	25.2 ± 6.1	0.064	0.75
BPAQ- Total	62.4 ± 50.4	56.1 ± 45.5	0.752	0.13
PSQI	4.9 ± 2.7	5.1 ± 2.9	0.826	0.09
# of Events	3.6 ± 1.6	3.5 ± 1.9	0.906	0.05
# of Injuries	4.8 ± 2.6	2.4 ± 2.6	0.005*	1.10

BMI: Body Mass Index; BPAQ: Bone Physical Activity Questionnaire; PSQI: Pittsburg Sleep-Quality Index; * denotes $p \leq 0.050$.

Pearson's Correlation Matrix

Pearson's bivariate correlations were run for 224 variables to inform the suitability for regression modeling. In total, 33 variables did not violate collinearity and were considered for regression modeling, as discussed below. Table 2 includes the correlation of bone variables with number of injuries and 60/120/180°/sec dominant leg extension values.

Table 2. Pearson's correlations (r^2) for total body, lumbar spine, and hip DXA variables with total number of injuries and each of the three speeds.

# of Significant Correlations	**14**	**26**	**26**	**27**
Variables	**# of injuries**	**Ext60**	**Ext120**	**Ext180**
Total Body BMC (g)	.451*	.589**	.642**	.758**
aBMD (g/cm^2)	.415*	.688*	.747*	.753*
Z-Score	.170	.286	.333	.366*
Lumbar Spine 1-4 BMC (g)	.282	.531**	.585**	.672**
aBMD (g/cm^2)	.218	.569*	.607*	.649*
Z-Score	.166	.403*	.478**	.545**
Mean Femoral Neck BMC	.448**	.589**	.634**	.744**
aBMD (g/cm^2)	.373*	.606**	.651**	.669**
Z-Score	.164	.399*	.437*	.405*
Mean Greater Trochanter BMC	.257	.498**	.536**	.631**
aBMD (g/cm^2)	.181	.439*	.506**	.573**
Z-Score	-.101	.166	.226	0.239
Mean Femoral Shaft BMC	.485**	.632**	.661**	.770**
aBMD (g/cm^2)	.201	.479**	.542**	.578**
Z-Score	.018	.224	.260	.218
Mean Total Hip BMC	.450**	.625**	.659**	.770**
aBMD (g/cm^2)	.267	.535**	.599**	.650**
Z-Score	-.011	.269	.328	.328
Narrow Neck CSA (cm^2)	.444**	.594**	.630**	.732**
CSMI (cm^4)	.408*	.421*	.447**	.631**
Section Modulus (cm^3)	.434*	.488**	.517**	.682**
Cortical Thickness (cm)	.302	.582**	.609**	.594**
Intertrochanter CSA (cm^2)	.383*	.618**	.650**	.734**
CSMI (cm^4)	.365*	.612**	.633**	.755**
Section Modulus (cm^3)	.384*	.626**	.655**	.766**
Cortical Thickness (cm)	.311	.540**	.582**	.622**
Femoral Shaft CSA (cm^2)	.375*	.632**	.670**	.776**
CSMI (cm^4)	.346*	.538**	.551**	.678**
Section Modulus (cm^3)	.338	.534**	.542**	.668**
Cortical Thickness (cm)	.204	.425*	.492**	.544**

Abbreviation: BMC: Bone Mineral Content; BMD: bone Mineral Density; Z: Z-score; SPW: Subperiosteal Width; ECW: Endosteal Width; CSA: Cross Sectional Area; CSMI: Cross Sectional Moment of Inertia; SM: Section Modulus: CT: Cortical Thickness; BR: Buckling Ratio; * or ** denotes a p value <0.05 or <0.01, respectively.

The 33 bone variables used in the correlations above were not consistently or strongly correlated with tertiary variables of interest such as PSQI (sleep), BPAQ (bone-loading), years of competing, and total number of events participants are currently competing in (correlation and regression data not shown).

Regression Models

Based on significant correlations from above, regression models were created for eight key bone measures of total body, lumbar spine, mean total hip, mean femoral neck, and mean greater trochanter bone densities (aBMD) and HSA measures of mean narrow neck, mean intertrochanter, and femoral shaft section modulus. Dominant leg extension and flexion values were used for as the predictor/independent variables at 60 and 180°/sec, or strength and power, respectively.

Tables 3-10 depicts the percentage of variance a muscle power only, strength only, or combination of power and strength regression models can predict for Total Body, Lumbar Spine 1-4, Total Hip, Femoral Neck, and Greater Trochanter aBMD's and narrow neck, intertrochanter, and femoral shaft section modulus. Power only models predicted the highest amount of variance for all sites with R2 values ranging from 0.347 to 0.594.

Table 3. Total body aBMD regression models using power only, combination, and strength only.

Model	Predictors	Predictor Statistics			Model Statistics	
		UStd β	C SE	*p*	R^2	*p*
Power Only	Flex180°/sec	-0.003	0.001	0.087	0.448	<0.001
	Ext180°/sec	0.002	0.001	0.001		
Combination	Flex120°/sec	-0.003	0.002	0.185	0.313	0.001
	Ext120°/sec	0.002	0.001	0.019		
Strength Only	Flex60°/sec	-0.002	0.002	0.340	0.236	0.007
	Ext60°/sec	0.001	0.001	0.054		

Flex/Ext: Flexion/Extension; UStd: Unstandardized; C SE: Coefficient Standard Error

Table 4 Lumbar spine 1-4 aBMD regression models using power only, combination, and strength only.

Model	Predictors	Predictor Statistics			Model Statistics	
		UStd β	C SE	p	R^2	*p*
Power Only	Flex180°/sec	-0.003	0.001	0.087	0.482	<0.001
	Ext180°/sec	0.002	0.001	0.001		
Combination	Flex120°/sec	-0.003	0.002	0.185	0.356	0.001
	Ext120°/sec	0.002	0.001	0.019		
Strength Only	Flex60°/sec	-0.002	0.002	0.340	0.284	0.007
	Ext60°/sec	0.001	0.001	0.054		

Flex/Ext: Flexion/Extension; UStd: Unstandardized; C SE: Coefficient Standard Error

Table 5. Mean Total Hip aBMD regression models using power only, combination, and strength only.

Model	Predictors	Predictor Statistics			Model Statistics	
		UStd β	C SE	p	R^2	*p*
Power Only	Flex180°/sec	-0.002	0.002	0.393	0.437	<0.001
	Ext180°/sec	0.003	0.001	0.008		
Combination	Flex120°/sec	-0.001	0.002	0.713	0.362	0.001
	Ext120°/sec	0.002	0.001	0.115		
Strength Only	Flex60°/sec	-0.001	0.002	0.559	0.293	0.005
	Ext60°/sec	0.001	0.001	0.109		

Flex/Ext: Flexion/Extension; UStd: Unstandardized; C SE: Coefficient Standard Error

Table 6. Mean Femoral Neck aBMD regression models using power only, combination, and strength only.

Model	Predictors	Predictor Statistics			Model Statistics	
		UStd β	C SE	p	R^2	*p*
Power Only	Flex180°/sec	-0.002	0.002	0.236	0.473	<0.001
	Ext180°/sec	0.003	0.001	0.003		
Combination	Flex120°/sec	-0.002	0.002	0.489	0.433	<0.001
	Ext120°/sec	0.002	0.001	0.042		
Strength Only	Flex60°/sec	-0.002	0.002	0.420	0.381	<0.001
	Ext60°/sec	0.002	0.001	0.039		

Flex/Ext: Flexion/Extension; UStd: Unstandardized; C SE: Coefficient Standard Error

Table 7. Mean Greater Trochanter aBMD regression models using power only, combination, and strength only.

Model	Predictors	Predictor Statistics			Model Statistics	
		UStd β	C SE	p	R^2	*p*
Power Only	Flex180°/sec	-0.002	0.002	0.335	0.347	0.002
	Ext180°/sec	0.002	0.001	0.017		
Combination	Flex120°/sec	-0.002	0.002	0.420	0.272	0.009
	Ext120°/sec	0.002	0.001	0.085		
Strength Only	Flex60°/sec	-0.001	0.002	0.414	0.210	0.029
	Ext60°/sec	0.001	0.001	0.108		

Flex/Ext: Flexion/Extension; UStd: Unstandardized; C SE: Coefficient Standard Error

Table 8. Narrow Neck Section Modulus regression models using power only, combination, and strength only.

Model	Predictors	Predictor Statistics			Model Statistics	
		UStd β	C SE	p	R^2	*p*
Power Only	Flex180°/sec	-0.008	0.006	0.173	0.498	<0.001
	Ext180°/sec	0.009	0.003	0.001		
Combination	Flex120°/sec	-0.009	0.008	0.290	0.294	0.005
	Ext120°/sec	0.007	0.004	0.048		
Strength Only	Flex60°/sec	-0.006	0.007	0.372	0.258	0.011
	Ext60°/sec	0.005	0.003	0.070		

Flex/Ext: Flexion/Extension; UStd: Unstandardized; C SE: Coefficient Standard Error

Table 9. Intertrochanter Section Modulus regression models using power only, combination, and strength only.

Model	Predictors	Predictor Statistics			Model Statistics	
		UStd β	C SE	p	R^2	*p*
Power Only	Flex180°/sec	-0.014	0.019	0.481	0.594	<0.001
	Ext180°/sec	0.03	0.009	0.001		
Combination	Flex120°/sec	-0.014	0.026	0.593	0.435	<0.001
	Ext120°/sec	0.023	0.011	0.056		
Strength Only	Flex60°/sec	0.003	0.022	0.887	0.392	0.001
	Ext60°/sec	0.012	0.009	0.199		

Flex/Ext: Flexion/Extension; UStd: Unstandardized; C SE: Coefficient Standard Error

Table 10. Femoral Shaft Section Modulus regression models using power only, combination, and strength only.

Model	Predictors	Predictor Statistics			Model Statistics	
		UStd β	C SE	p	R^2	*p*
Power Only	Flex180°/sec	-0.011	0.008	0.174	0.480	<0.001
	Ext180°/sec	0.012	0.003	0.002		
Combination	Flex120°/sec	-0.009	0.010	0.405	0.311	0.004
	Ext120°/sec	0.009	0.004	0.066		
Strength Only	Flex60°/sec	0.002	0.009	0.827	0.286	0.006
	Ext60°/sec	0.003	0.004	0.359		

Flex/Ext: Flexion/Extension; UStd: Unstandardized; C SE: Coefficient Standard Error

Discussion

Bone and muscle injuries are the leading cause of athletes missing practices, and events such as regional or national level competitions [86, 87]. McCormack et al., 2019, concluded that the training and dietary strategies are not sufficient to stop these athletes from developing overuse injuries at higher rates than active control; even though the athletes scored greater for dietary quality and exhibited higher aBMD measurements than their non-running active control counterparts [88]. The purpose of this study was to investigate the relationship of strength and power and their ability to predict whole body and site-specific aBMD and hip bone geometry values in collegiate D1 athletes. Both strength only and power only, as well as the combination of strength and power, were able to account for variance within the range of 21.0-59.4% ± 9.6%. Power only was able to not only predict the greatest number of variables with significance, but it also had the greatest magnitude of variance that could be accounted for. Power models provided an additional 9.2-25% ± 7.9% increase for accounting for variance. Most questionnaire data failed to meet correlation strength and therefore were not used in any regression modeling.

Athlete Health

Athlete health has become a large concern for collegiate athletic clubs around the world. Many athletes are now selecting their school based on the prospect of continuing on with a professional career after college, this is creating an environment of competition in recruiting just by the resources and steps clubs/coaches take to protect their players. Many of these health metrics are areas in which colleges are making vast improvements, examples include the introduction of team specific nutritionists, strength and conditioning staff, and physicians, especially with women's sports [89]. This emphasis on athlete health can be seen in this cohort of athletes, with their overall diet quality or healthy eating index score of 69, 11 points higher than the national average of 58 [90]. Another important factor with the athletes in the current study is their sleep quality. Dietch et al., 2016, found on two different college campuses the average PSQI sleep score was a 6.39 [91], while the athletes in this study are at a 4.94 sleep score. The athletes are not only 1.4 points lower, but they also categorized as clinically good sleep quality score [92]. Due to the lack of statistical correlation strength with aBMD measures these values were not able to be used in regression modeling.

When analyzing bone health for both athletic and clinical populations, normative values are typically used, in this case the z-score. This is a statistical measurement that describes the individuals (athlete) bone relationship to the mean of the group (population). This score can have a wide range of values, but individuals whom fall within ± 2 standard deviation of the mean are deemed to have clinically safe values [93]. Key areas of the body that were evaluated for this and their average z-scores were: total body (0.66 ± 1.0), lumbar 1-4 (0.34 ± 1.4), formal neck (0.32 ± 0.31), greater trochanter (0.76 ± .91) and total hip (0.2 ± 0.17). All total body and site-specific measures have positive and healthy values associated with them for the overall cohort. With no values less than -1.0 z-score the athletes overall bone health when compare to the population is good [94]. Some members of the team were approaching a clinically bad measure, this could

provide valuable information that leads to the development of training protocols that lead to better bone health.

Strength and power training

Both power and strength training are known for increasing an individual's aBMD values due to the internal and external mechanical loading on the system [95]. Hurt et al., 1971, demonstrated that these movements need to be of a dynamic nature instead of static, this led into a plethora of research coming from Ducher and Turner that confirmed strength training increases aBMD measures [14]. Liang et al., 2012 took this a step further with comparing a high-intensity plyometric group, a moderate leg strength exercise group (working loads at 65-70% 1 repetition maximum) and a control group. Their findings were that both the experimental groups had significant strength increases (both $p < 0.05$), while the high-intensity plyometric group saw an increase in aBMD of the lower body ($p=0.05$).

This provides some information on how current training strategies for some populations could benefit from conducting power movements in order to produce specific adaptations in bone mineral density. A caveat to this is, athletes and coaches may not have the time to do so due to the recovery demands of their sport. For example, XC athletes commonly compete in 3-4 different seasons (indoor, outdoor, XC, and professional) and may not have time to implement in-season power training due potential interference with race performance, or off-season power training as that time is used for much needed recovery. In this study, both strength and power measures had positive correlations with whole body and site-specific aBMD. Furthermore, power had greater regression values for whole body and site-specific aBMD. With power additional accounting of variance over strength models, these ranging from a R2 of 0.09-0.25 or 9 – 25% of increased variance assumed (all $p\leq0.002$, and the greatest difference being total body aBMD with a difference of 0.22 or 22% of a variance difference ($p<0.001$)). This provides a clear indication

that power output may be better associated with predicting aBMD values than strength only output.

Greater differences may be observed in different populations due to the nature of the cohort of athletes that participated in the study. The athletes all came from a wide range of track and field and cross-country event designations (sprinters, distance, and throwers), with majority of the athletes being classified as distance runners (n=21), followed sprinters (n=10) and throwers (n=2), which may not accurately represent the athletic populations of track and field and cross country as a whole.

Hip Structural Analysis

Structural analysis and more importantly structural integrity have been at the forefront of many coaches, players and, training strategies in reference to the hip and femoral neck area of these running athletes. Infantino et al., 2021, observed that athletes through one year of collegiate distance training (>100 km/week) had decreased HSA measurements compared to their non-athlete controls (expended less than 500 kcal per/day above basil metabolic rates) counterparts who were matched for height, BMI and age [96]. This is a critical loss for the athletes for both their collegiate career and professional careers, but also to their longitudinal bone health due to decreased bone mineral density values have been associated with greater injury, fracture risk and severity [97]. In other athletic populations Hind et al., 2012, examined swimmers, gymnasts, runners, and non-athlete controls who did not take part in any regular structured exercise or sport. Athletes group had significantly higher HSA measurements (all $p \leq 0.05$) across all variables (NN, IT, and FN) when compared to non-athlete controls [98]. This provided a large variety of loading profiles across the three sports and concluded, similar to DXA whole body and regional measures for aBMD, that loading of the skeleton would improve geometric derived bone measurements.

In this study, we analyzed HSA measurements to use as a site-specific area for regression modeling. The main area we observed was the section modulus, a measure of maximum bending strength of the bone. This measurement is critical when accounting for the gravitational forces applied during vertical athletic movement to the lower body, and specifically the femur itself. These values did share a similar trend with the DXA regional measurements, as both groups aBMD and SM measures were better predicted by the power only group. This provides insight that power may be a better predictor bone density, and is able to better predict the structural integrity of the bone.

Physical performance and questionnaires

Collegiate athletes continuously stress their bodies throughout multiple competitive seasons, with very little time to recover between seasons [6]. Many athletes within this study were responding with weekly mileage of 60+ miles per week, along with resistance training two or three times per week. Unfortunately, we were not able to gather a full training load (inside and outside of practice) for each of the athletes. This left out physical activity data in very critical areas, such as practice duration, intensity, and work load of the athlete. This may have caused the weak correlations from the limited physical activity questionnaire data that we had collected. Injury questionnaire responses did not significantly contribute to any of the regression models. This may be due to the wholistic approach taken towards the study, since we did not look into the specific areas of each injury and the associated aBMD associated, but instead examine injury as a value related to total number of injuries obtained.

Limitations

The findings from this study may not be generalizable to athletes who compete outside of NCAA Division I or at other institutions, as based on competitive level and a variety of training factors which could influence conclusions. Second, NCAA athletes' time availability is highly

stringent which could have impacted participation. Our research team aimed to mitigate this potential issue by maintaining consistent communication with athletes, coaches, and sports medicine staff. Lastly, some athletes had serum Vitamin D concentrations measured at the beginning of the study but not throughout. Because level of Vitamin D fluctuates, it may be a confounding factor for musculoskeletal health that our team cannot account for.. Athlete participation was also a limiting factor due to not only their training schedule, but also their academic responsibilities. This resulted in a skewed sample of female to male athletes (25 females to 8 males).

CHAPTER V

CONCLUSION

The purpose of this study was to determine if strength or power was a better predictor of whole body and site-specific aBMD. Power did show a greater number of predictive values as well as higher R2 values, resulting in power being the strongest predictor of aBMD, both site-specific and total body. The secondary purpose was to evaluate tertiary factors into this regression. All factors failed to either meet consistent correlation strength or failed to bring significance to the regression models.

Research Question

Which muscle performance metric (strength or power) would be more predictive of total and site-specific aBMD using regression models of change? These data suggest that power created the strongest regression models to predict aBMD variables. Additionally, the overall correlation matrix gave us an insight to the overall strength of each of the models, where power was the greatest correlation factor.

Sub question

What is the influence of tertiary factors that may modulate the statistical relationship between muscle strength or power and aBMD? These factors included sleep quality and number of injuries. Tertiary factors did not influence the statistical relationship between the model types. This was due to many of the factors failing either a sufficient strength correlation test or failing due to collinearity. The single variable that was used in regression (running miles per week) held no meaningful changes to the regression models.

Recommendations for future research

Using a normative group for controls could be used in a better identification of regression models towards measurements of better bone health. This would be done by evaluating the regression models from normative values with the values of athletic populations. Currently, these data are a subset of a larger project where age (±2 years), sex, and weight (±2.5 kg) controls were collected. Additionally, this study was also done over three different time periods, May, August, and November, and could result in some levels of differing questionnaire responses. Both controls and additional groups of athletes will be further investigated for their contribution to further regression models, including a non-athlete regression model to observe any differences between these two groups. Gaining a greater number of questionnaires responses as well as a comprehensive physical load profile for the athlete's practice would drive the questionnaire data in a possible positive direction. A more accurate training load would allow us to create more accurate data sets which would reflect the studied population more accurately. We currently did not account of individual training styles, only for days per week and intensity.

Research needs to explore a wider variety of ages and ethnicities. The current study included 22 athletes identifying as White, 6 as African American, 4 as Hispanic and 1 as Asian; all of the athletes in this study ranged in age from 19-24 years of age, providing a fairly narrow

age range and limiting the applicability of the research to older populations. Therefore, the results are very limited to generalization claims. Additionally, the sex demographic of the study was largely female with 25 females compared to 8 males; therefore it would not be appropriate to apply these results to teams that have an even distribution of athlete sexes.

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APPENDICES

Oklahoma State University Institutional Review Board

Date:	04/22/2022
Application Number:	IRB-22-113
Proposal Title:	A Longitudinal Assessment of Track and Field Athletes' Health and Performance
Principal Investigator:	Bree Baker
Co-Investigator(s):	Jill Joyce, Taylor Dinyer
Faculty Adviser:	
Project Coordinator:	
Research Assistant(s):	Allen Redinger, Olivia Anderson, Shawn Allen
Processed as:	Full Board

Status Recommended by Reviewer(s): Approved
Approval Date: 04/22/2022
Expiration Date: 04/21/2023

The IRB application referenced above has been approved. It is the judgment of the reviewers that the rights and welfare of individuals who may be asked to participate in this study will be respected, and that the research will be conducted in a manner consistent with the IRB requirements as outlined in section 45 CFR 46.

The final versions of any recruitment, consent and assent documents bearing the IRB approval stamp are available for download from IRBManager. These are the versions that must be used during the study.

As Principal Investigator, it is your responsibility to do the following:

1. Conduct this study exactly as it has been approved. Any modifications to the research protocol must be approved by the IRB. Protocol modifications requiring approval may include changes to the title, PI, adviser, other research personnel, funding status or sponsor, subject population composition or size, recruitment, inclusion/exclusion criteria, research site, research procedures and consent/assent process or forms.
2. Submit a request for continuation if the study extends beyond the approval period. This continuation must receive IRB review and approval before the research can continue.
3. Report any unanticipated and/or adverse events to the IRB Office promptly.
4. Notify the IRB office when your research project is complete or when you are no longer affiliated with Oklahoma State University.

Please note that approved protocols are subject to monitoring by the IRB and that the IRB office has the authority to inspect research records associated with this protocol at any time. If you have questions about the IRB procedures or need any assistance from the Board, please contact the IRB Office at 223 Scott Hall (phone: 405-744-3377, irb@okstate.edu).

Sincerely,
Oklahoma State University IRB

SCHOOL OF KINESIOLOGY, APPLIED HEALTH, AND RECREATION

CONSENT FORM

A Longitudinal Assessment of Track and Field Athletes' Health and Performance

Background Information: You are invited to be in a research study of how bone and muscle change across a full track and field (T&F) and/or cross country (XC) season. You were selected as a possible participant because you're between the ages of 18-26 years. We ask that you read this form and ask any questions you may have before agreeing to be in the study. Your participation is entirely voluntary.

This study is being conducted by Drs. Baker, Dinyer-McNeely, and Joyce from the Kinesiology and Nutrition Departments in conjunction with the Oklahoma State University T&F + XC program.

Procedures: If you agree to be in this study, we would ask you to do the following things:

1. First you will meet with a member of our research team to ensure that you are eligible for participation and fully understand the informed consent (this document) prior to signing. Next we will complete a series of questionnaires to help us learn more about your nutrition and training status. This process will be completed for each visit and will take 15 minutes each time.
2. Next, we will measure your height and weight and have you provide a small urine sample, which is used to ensure proper hydration and a non-pregnant reading in females. If you would like a same-sex researcher to complete this process we can accommodate that request. This process will be completed for each visit and will take 10 minutes each time.
3. Next, we will complete a series of DXA scans to determine your bone mineral density of your total body, lumbar spine, and each hip during each visit. A DXA is a type of x-ray used to measure bone strength. You will lie flat on a table and a machine will take pictures of different areas of your body. DXA is a radiation procedure and is for research purposes only. There are risks associated with DXA which will be addressed below. These scans will be completed for each visit and will take 15 minutes each time.
4. Lastly, you will complete a lower body strength and power assessment using a Biodex strength testing machine. During these tests, you will be seated in a position similar to sitting in a chair and the tested leg will have a cushioned pad comfortably strapped around your leg. Electromyography (EMG) sensors will be placed on the skin of your thigh muscles to monitor muscle function as you push and pull against the machine. This process will be completed for each visit and will take 20 minutes each time.

Participation in the study involves the following time commitment: one hour per visit or four hours total.

Risks and Benefits of being in the Study:

The study involves the following foreseeable risks: ***Use of Radiation.*** *In this study, you will be exposed to a small amount of radiation called "ionizing radiation," which is like x-rays. Studies have shown that getting a lot of radiation at one time or getting many small doses over time may cause cancer. The risk of getting cancer from the small radiation dose in this study is very small. You will get less than 13 mrem (a "mrem" is how we measure radiation dose) of radiation per visit, which is equivalent to spending about 4 1/2 hours outside from background radiation. If you complete all phases of testing over the four visits you will be exposed to just over 50 mrem which is the equivalent to about 18 hours outside. Background radiation or most common x-rays have not been found to harm most healthy adults. At doses much higher than you will receive, radiation is known to increase the risk of developing cancer after many years. At the doses you will receive, it is unlikely that you will see any effects at all.*

Tell us now if you have been in other research studies where you had ionizing radiation or have been exposed to radiation in other ways, like on your job or in radiation therapy. If you are pregnant or nursing, you cannot be in this research study because the radiation may harm your baby. If after participation in this study, you are scheduled for any procedures such as dental x-rays or radiation therapy be sure to discuss your participation in this study with your medical provider.

Muscle Testing: As is the case with any test involving maximal physical exertion, there is a chance of musculoskeletal injury or discomfort to the leg during testing. There is a chance you could experience soreness after testing. A standardized warm-up will be administered before each strength testing visit to help avoid injuries. Physical activity causes temporary blood pressure/heart rate elevation due to resistance-training movements, but the likelihood of lightheadedness or fainting is minimal. Additionally, alcohol and drug use have been shown to exacerbate muscle damage and swelling. Therefore, it is advised that you refrain from using these substances throughout the duration of the study.

In case of injury or illness resulting from this study, Dr. Baker will refer you to your primary care physician or OSU Health Services and it will be reported to the IRB immediately. In case of emergency, 911 will be called. Stillwater Medical is 1 mile away and will be the closest location to receive medical care. No funds have been set aside by Oklahoma State University to compensate you in the event of illness or injury.

The study involves the following foreseeable benefits: There are no direct benefits to you except you will be provided with a copy of your DXA scans. These data can help you be more informed of your bone health. We encourage you to share your results with your primary care physician.

Compensation: You will receive no payment for participating in this study.

What Steps Are Being Taken to Reduce Risk of Coronavirus Infection?
The following steps are being taken to address the risk of coronavirus infection:

Screening: Researchers and participants who show potential symptoms of COVID-19 (body temperature over 100.4°F, cough, shortness of breath, etc.) will NOT participate in this study at this time.

Physical distancing: Whenever possible, we will maintain at least 6 feet of distance between persons while conducting the study.

Mask/Covering: Researchers will wear and participants will be advised to shield their mouth and nose with a cloth face cover or mask during the study, even when maintaining at least 6 feet of distance. Masks and tissues will be available to participants cover coughs and sneezes.

Handwashing: Researchers and participants will wash hands before/during the focus group or use a hand sanitizer containing at least 60% alcohol.

Disinfecting materials: We will clean and disinfect surfaces between participants, using an EPA-registered disinfectant or a bleach solution (5 tablespoons of regular bleach per gallon of water) for hard materials and by laundering soft materials. Disinfected materials will be handled using gloves, paper towel, plastic wrap or storage bags to reduce the chance of re-contamination of materials.

Electronics: Alcohol-based wipes or sprays containing at least 70% alcohol will be used to disinfect shared touch screens, mice, keyboards, etc. Surfaces will be dried to avoid pooling of liquids.

Confidentiality:
Coded Data linked with identifying information: The information that you give in the study will be handled confidentially. Your information will be assigned a code number. The list connecting your name to this code will be kept in a locked file. When the study is completed and the data have been analyzed, this list will be destroyed. Your name will not be used in any report.

We will collect your information through data collection sheets and electronic versions of your food recal reports, DXA scans, and Biodex data. The paper data sheets will be stored a locked drawer in a restricted access laboratory. Your electronic data will be stored on a computer, in a restricted access laboratory or office. When the study is completed and the data have been analyzed, the code list linking names to study numbers will be destroyed. This is expected to occur no later than April 1st, 2024. This informed consent form will be kept for 3 years after the study is complete, and then it will be destroyed.

It is unlikely, but possible, that others responsible for research oversight may require us to share the information you give us from the study to ensure that the research was

conducted safely and appropriately. We will only share your information if law or policy requires us to do so.

Data Sharing:

The data we collect in the MAAX Lab as part of this study belongs to you. Additionally, the data the OSU T&F+XC sports medicine staff and coaches is your data. We would like to share small amounts of your data between each group. Please read the below statements carefully and circle the answer (Yes or No) that best fits your data sharing preferences. If you have any questions please don't hesitate to ask us.

(circle one)		I consent to allowing my data generated in the **MAAX lab** to be shared with OSU T&F+XC **sports medicine staff**. I also, understand
Yes	**No**	these data will have my name on it, also known as identified data.
Yes	**No**	I consent to my data generated by the OSU T&F+XC **sports medicine staff** to be shared with the **research team of this study**. I understand these data will have my name on it, but will be deidentified after it is received by Dr. Baker or Dr. Dinyer-McNeely.
Yes	**No**	I consent to my deidentified data generated by this study to be shared in group summary form to OSU T&F+XC coaches. I understand these data **will not** have my name on it.

HIPAA Authorization for Release of Health Information for Research Purposes

The Health Insurance Portability and Accountability Act (HIPAA) allows a hospital or doctor's office to use or release protected health information (PHI) for the purposes of treatment, payment or health care operations. Health care operations activities include such things as audits, quality assurance initiatives, audits from insurance companies, treating physicians, legal advisors, insurers and data storage companies.

This HIPAA authorization gives permission from you to use or release your PHI for research purposes. A HIPAA authorization is in addition to your consent to participate in this research study.

What will be done with your protected health information? Your protected health information (PHI) will be collected and entered in a database along with the information from other people taking part in this study.

Why are you being asked to release it? Your protected health information (PHI) will be used to properly classify you into age and ethnicity norms for bone and performance measures.

What will be released? To complete this research study, we will need to collect and release (disclose) information about you. This information will include your date of birth, sex, ethnicity, and new health information collected for purposes of this study.

Who will use it or share it? The researcher and his/her research study staff and potentially OSU T&F+XC coaching sports medicine staff depending on your data sharing preferences selected above.

Once your protected health information (PHI) has been disclosed, it is possible that anyone who receives that information may re-disclose it. Because some of these individuals who receive your PHI may not be required by law to keep your information confidential, we cannot guarantee that your information will not be released or made available to another party once it leaves Oklahoma State University. Therefore, we share your information only if necessary and we use all reasonable efforts to request that those individuals who receive your information take steps to protect your privacy.

How long will this authorization last? This authorization has no expiration date.

Can you stop your protected health information (PHI) from being used? You can tell us to stop collecting health information that can be traced to you at any time. We will stop, except in very limited cases if needed to comply with law, protect your safety, or make sure the research was done properly. If you have any questions about this please ask.
If you want us to stop, you must tell us in writing. Write or email Dr. Baker at Bree.Baker@OkState.edu

What happens if you do not want us to collect and release your information? If you decide not to authorize release of your protected health information (PHI) as part of this study, your decision will in no way affect your medical care or cause you to lose any benefits to which you are entitled. You cannot participate in this research study if you do not authorize the use or release of your PHI.

When will it be destroyed? We do not know when your de-identified information will no longer be used therefore the information will be kept for an indefinite length of time.

Voluntary Nature of the Study
Your participation in this research is voluntary. There is no penalty for refusal to participate, and you are free to withdraw your consent and participation in this project at any time. The alternative is to not participate. Your decision whether or not to participate in this study will not affect your employment, medical care, grades, etc…

Termination of Participation: This study or your participation may be terminated without regard to your consent by Dr. Bree Baker if equipment fails or if you refuse to complete all aspects of testing. You will be told about new information that may affect your health, welfare, or willingness to stay in the study.

Contacts and Questions
The Institutional Review Board (IRB) for the protection of human research participants at Oklahoma State University has reviewed and approved this study. If you have questions about the research study itself, please contact the Principal Investigator at 405-744-9315

or Bree.Baker@OkState.edu. If you have questions about your rights as a research volunteer or would simply like to speak with someone other than the research team about concerns regarding this study, please contact the IRB at (405) 744-3377 or irb@okstate.edu. All reports or correspondence will be kept confidential.
You will be given a copy of this information to keep for your records.

Statements of Consent

(circle one) **Yes**	**No**	I have read the above information. I have had the opportunity to ask questions and have my questions answered. I consent to participate in the study.
Yes	**No**	I give consent for my data to be used in future research studies
Yes	**No**	I give consent to be contacted for follow-up in this study or future similar studies:

Participant Signature:_____ Date: _____

Signature of Investigator:_____ Date: _____

VITA

Shawn Michael Flanagin Allen

Candidate for the Degree of

Master of Science

Thesis: THE RELATIONSHIP BETWEEN BONE QUALITY AND MUSCLE PERFORMANCE IN CROSS COUNTRY AND TRACK AND FIELD ATHLETES

Major Field: Health and Human Performance

Biographical:

Education:

Completed the requirements for the Master of Science in Health and Human Performance at Oklahoma State University, Stillwater, Oklahoma in May, 2023.

Completed the requirements for the Bachelor of Science in Applied Exercise Science at Oklahoma State University, Stillwater, Oklahoma in 2021.

Experience:

Served 4 years in an active duty role as a team leader and 4 years in the Oklahoma National Guard as a squad leader.
Studied in a Cellular Metabolism Laboratory for three years

Professional Memberships:

American College of Sports Medicine – 2 years
National Strength and Conditioning Association – 2 years