



Relationship Between Ground Reaction Force Characteristics and Bone Mineral Density of the Hip and Spine in Male Runners

MICHELE LEBLANC‡, ALLISON BURDULLIS*, MARCUS MCKINNON*, and STEVEN HAWKINS‡

Department of Exercise Science, California Lutheran University, Thousand Oaks, CA, USA

*Denotes undergraduate student author, ‡Denotes professional author

ABSTRACT

International Journal of Exercise Science 15(1): 655-666, 2022. The purpose of this study was to determine the relationship between running ground reaction force (GRF) characteristics and hip and lumbar spine bone mineral density (BMD) values in male runners. Individuals who ran at least 48.3 km per week and were injury-free were recruited. Kistler force plates collected running vertical and anteroposterior GRF data. A Hologic Discovery W bone densitometer measured lumbar spine and five regional hip BMD values. Only runners who consistently used a rear foot strike pattern were included ($n = 32$). Pearson correlation coefficients were calculated between BMD values and various GRF values and step-wise multiple regression was run to predict BMD values from the various GRF values. The vertical impact force was significantly correlated with the lumbar spine and four of the five hip BMD values ($r > 0.374$, $p < 0.035$). Both the peak early loading rate (ELR) and average ELR were significantly correlated with the lumbar spine and Ward's triangle BMD ($r > 0.430$, $p < 0.014$), while the average active loading rate was correlated only with the Ward's triangle BMD ($r = 0.438$, $p = 0.012$). Multiple regression revealed the peak impact force was the predictor for every hip region BMD other than the trochanter and the average ELR as a predictor for the lumbar spine BMD. The peak braking force was negatively correlated with the Ward's triangle BMD ($r = -0.414$, $p = 0.019$). It appears that the large forces and loading rates associated with rear foot striking may be advantageous and predictive for BMD at the hip and spine.

KEY WORDS: Ward's triangle, impact force, active force, loading rate

INTRODUCTION

Osteoporosis and low bone mineral density are frequently thought to be a challenge primarily for females, but these conditions are prevalent and of concern for both males and females. It was reported that in 2010, approximately 39.5% of men over 50 years old in the United States were diagnosed with osteoporosis or low bone mineral density of the femoral neck or lumbar spine (46).

Bone tissue is altered by external forces that are created primarily by muscle contractions and ground or joint reaction forces. Bone loading during young adulthood has been reported to be

a good predictor for bone mineral density (BMD) at the lumbar spine and total hip later in life (42). Peak bone mass is typically established in the hip and lumbar spine by age 20 for males (3, 22). Previous studies have found that while running involves repetitive impact and muscle forces, the magnitude and primarily compressive nature of these forces are not necessarily effective in stimulating increases in BMD in the hip and lumbar spine when compared to activities that include larger anteroposterior and/or mediolateral forces. There have been numerous studies which have investigated hip and/or lumbar spine BMD values for male runners. Many of these studies have reported equivalent or lower BMD values for male runners when compared to non-runners or participants of other impact sports activities (2, 5, 14, 15, 16, 19, 29, 39). Research has determined that 33-40% of young adult male runners have low BMD of the lumbar spine (16, 25, 36). Studies have investigated relationships between male runner BMD and various factors including lean body mass, BMI, weekly mileage, calcium intake, and bone turnover markers (4, 24, 36, 42, 44). However, these investigations have not considered the role of forces in BMD and it is possible that the size or rate of the vertical or anteroposterior ground reaction forces experienced by the runners are associated with the likelihood of having low BMD in the hip and/or spine. The possibility of this relationship has not been investigated in male or female runners. Many of the relational studies with female runners has focused on the relationship between ground reaction forces and bone stress injuries. Due to the marked difference in hormonal influences on bone density, it is important to view findings for females separate from those involving male runners.

Ground reaction force characteristics differ based on the foot strike pattern of the runner. Researchers have reported values between 75% and 94% of long-distance runners use a rear foot strike pattern (10, 12, 21, 28, 32). Rear foot strike patterns are characterized by an initial impact force while mid-foot or forefoot striking patterns do not experience this early impact force (9, 34). Runners who use the rear foot strike pattern also exhibit higher loading rates than those runners who use other foot strike patterns (1, 41, 47). Previous researchers have affixed an accelerometer to their participants' hip and determined that activities that create a slope of the acceleration curve of at least 1000 were able to generate BMD in the hip (3). It is possible that the early impact force that rear foot strikers experience may meet this threshold and be a valuable stimulus for bone and aid in preventing low bone density for runners. The purpose of this study was to investigate the relationship between the hip and spine bone mineral density values and ground reaction force characteristics for male runners who use a rear foot striking pattern.

METHODS

Participants

Forty male runners, aged 18-25 years, were recruited from the local community through advertisements at running stores and clubs. Eligibility for participation in the study required runners to run at least 48.3 km per week (approximately 30 miles/week) for at least a year. Any runner who had a history of orthopedic injury to the lower limbs or back was excluded from the study. Each runner read and signed a consent form that was approved by the university's Institutional Review Board. Once consent was submitted, the participants filled out a survey

that focused on their health and eating and running history to further confirm eligibility for the study. If a participant had any limitations to exercise or metabolic or chronic diseases known to influence bone (e.g. diabetes, hypo- or hyper-thyroidism, hypo- or hyper-gonadism), they were excluded from participating in the study. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (37). Once eligibility was confirmed, mass and height were measured using a balance scale and stadiometer.

Protocol

Each runner ran for at least five minutes at a self-selected pace in the laboratory as a warm up. Participants ran approximately seven meters prior to having one of their feet land on one of two Kistler 9281CA force plates (Amherst, NY) which were embedded in the lab floor. Runners were instructed to run at a typical training pace to obtain typical forces that they experience in each foot strike during their weekly mileage. Trials continued until three successful trials were collected for each foot. A successful trial was one that had the foot fully in contact with the force plate and did not involve any observable stride length or frequency adjustments. The force plates collected three-dimensional ground reaction force data at 1200 Hz. Bioware 5.4.3.0 was used to obtain ground reaction force characteristics from each trial.

Prior to any bone density data being collected, the quality control process was performed for the Hologic Discovery W densitometer (Waltham MA) by first scanning a phantom spine with known density and confirming that the system was accurate. Measurements were maintained within the manufacturer's precision standards of < 1.0% for the spine and < 1.5% for the total hip. All participants wore clothing with no plastic or metal parts (no buttons or zippers). Their anteroposterior lumbar spine (L1-L4) and right hip region were scanned with the same operator analyzing the scans. Bone mineral density values were recorded for the lumbar spine, femoral neck, trochanter region, intertrochanteric region, total hip, and Ward's triangle. Ward's triangle is a region identified by the software that is 1cm² and has lowest BMD in the femoral neck region (48).

Hip bone mineral density was collected for each participant's right hip. Thus, only the running trials with the right foot landing on a force plate were used for analysis. Foot strike patterns were determined for each of the three trials for each participant using the vertical ground reaction force graphs. A runner was classified as a rear foot striker if all three trials exhibited a rear foot strike pattern with a clear vertical impact force prior to the active vertical force. Only participants that were classified as a rear foot striker were used for further analysis.

Bioware 5.4.3 software (Kistler, Amherst, NY) was used to obtain vertical and anteroposterior ground reaction force variables and their corresponding timing for each of three trials for all participants (see Figure 1). In the vertical direction, the peak impact force (F_{z1}), the time to F_{z1} , the peak and average loading rates during the early impact phase (average ELR and peak ELR, respectively), the peak active force (F_{z2}), the time to F_{z2} and the average active loading rate were all determined. In the anteroposterior directions, the maximum braking and propulsive forces and the time from the start of each phase to these maximum values were determined. All force

values were normalized for body weight. Each performer's average from their three trials was used for analysis.

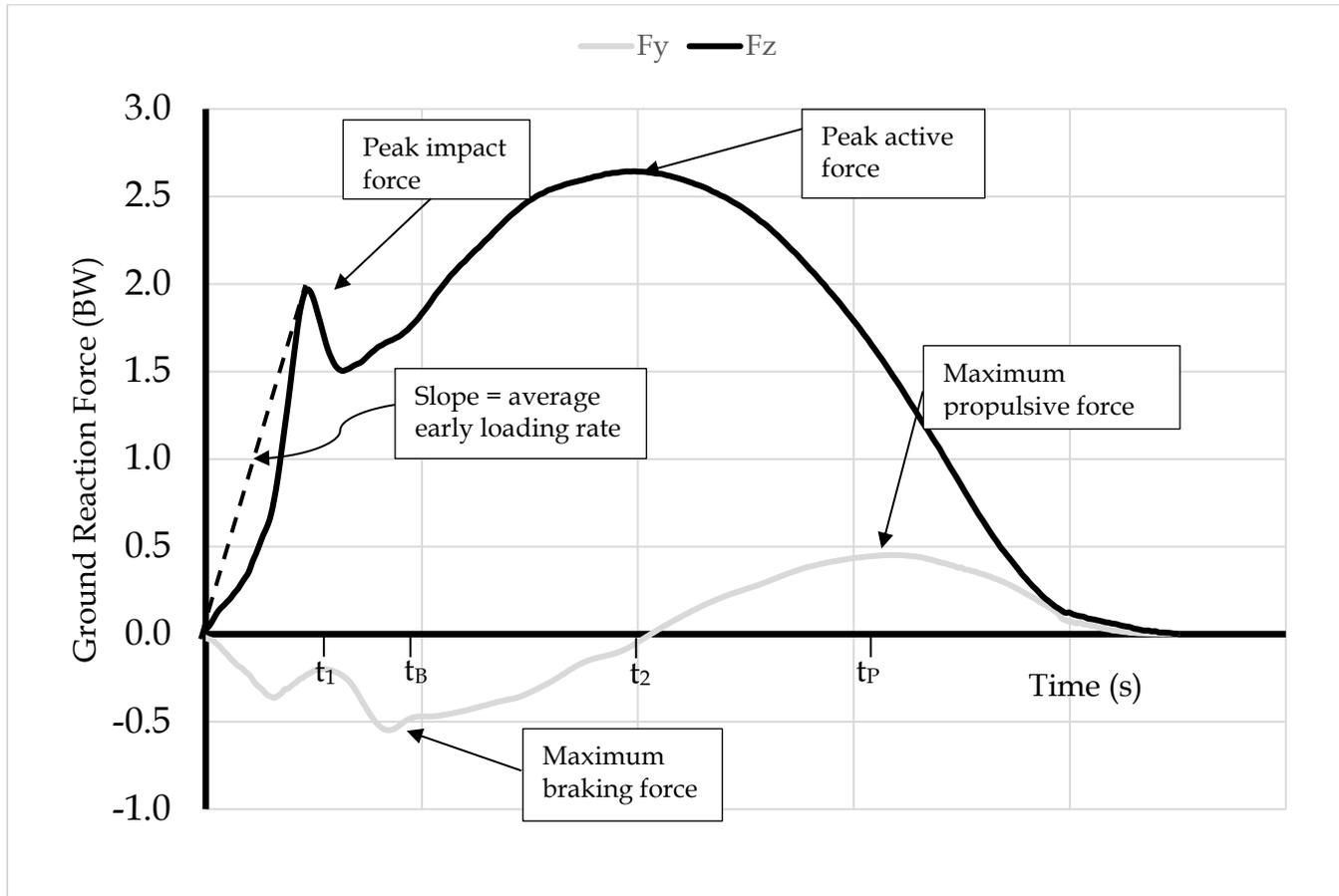


Figure 1. Vertical (F_z) and anteroposterior (F_y) ground reaction force variables. Vertical force characteristics include the peak impact force (F_{z1}) and the peak active force (F_{z2}). The time from first contact until these peak forces are shown with t_1 and t_2 , respectively. The early loading phase is from first contact to F_{z1} with the average loading rate being obtained by the slope of the line joining the first vertical force to F_{z1} (see the dotted line). The maximum braking force and maximum propulsive forces are shown with their time occurrences (t_B and t_P , respectively). It should be noted that the numerical value of t_P was from the start of the propulsive phase until the time of maximum propulsive force.

Statistical Analysis

The statistical analysis was completed using SPSS v.25 (Armonk, NY: IBM Corporation). Mean and standard deviation values were computed for the subject characteristics, the GRF, and BMD values. Pearson correlation coefficients were calculated between each BMD value and the subject characteristics, other BMD values, and vertical and horizontal force characteristics. A stepwise multiple regression was run for each BMD value with all force values entered as predictors. Significance was determined with $p \leq 0.05$.

RESULTS

Thirty two of the forty runners exhibited vertical ground reaction forces that indicated a consistent rear foot strike pattern. Mean age of participants was 21.2 ± 3.0 years and their self-reported weekly running mileage was 81.3 ± 24.5 km (50.5 ± 15.2 miles). Their height, mass, and corresponding body mass index (BMI) were 1.766 ± 0.061 m, 66.3 ± 6.9 kg, and 21.3 ± 1.9 kg/m² respectively. Body mass had a significant relationship with the femoral neck BMD ($r = 0.458$; $p = 0.008$) and the intertrochanteric region ($r = 0.354$; $p = 0.047$). No other subject characteristic had a relationship with any BMD value.

Vertical and anteroposterior ground reaction force data are given in Table 1. Table 2 provides the BMD values for the lumbar spine and five hip locations. The BMD values were all significantly correlated to each other ($r > 0.459$; $p < 0.008$).

Table 1. Characteristics of the vertical ground reaction force on the runners' right foot during the stance phase.

Variable	Mean \pm standard deviation
Peak impact vertical force (F_{z1})	2.33 ± 0.62 BW
Time to F_{z1} (t_1)	15.7 ± 6.0 ms
Peak early loading rate	497.2 ± 210.8 BW/s
Average early loading rate	167.3 ± 74.5 BW/s
Peak active force (F_{z2})	2.65 ± 0.19 BW
Time to F_{z2} (t_2)	92.6 ± 15.5 ms
Active loading rate	29.5 ± 5.8 BW/s
Peak braking force	-0.54 ± 0.16 BW
Time to peak braking force	36.4 ± 12.9 ms
Peak propulsive force	0.40 ± 0.05 BW
Time to peak propulsive force	51.7 ± 6.6 ms

BW = body weight

Table 2. Bone mineral density (mean \pm standard deviation) for the lumbar spine (L1-L4) and hip joint regions.

Region	Mean \pm standard deviation bone mineral density (g/cm ²)
Total Lumbar Spine	0.972 ± 0.097
Femoral neck	0.952 ± 0.118
Trochanter region	0.759 ± 0.078
Intertrochanteric region	1.204 ± 0.119
Total hip	1.030 ± 0.095
Ward's triangle	0.801 ± 0.118

Table 3 provides the Pearson correlation coefficients between the BMD values and the vertical and anteroposterior GRF measures. The normalized impact force, F_{z1} , was significantly correlated with the lumbar spine and four of the five hip BMD values. The time from initial contact to F_{z1} was significantly correlated to the lumbar spine BMD only and had a negative relationship. Both the normalized peak early loading rate (ELR) and normalized average ELR

were significantly correlated with the lumbar spine BMD and Ward’s triangle. The normalized active peak vertical ground reaction force, Fz_2 , was not significantly correlated with any of the bone mineral density measurements. The time to Fz_2 had a significant negative relationship with Ward’s triangle BMD values while the active force loading rate was positively correlated with the Ward’s triangle BMD values.

Table 3. Pearson correlation coefficients between vertical and anteroposterior ground reaction variables and the spine and hip bonemineral density values. The p-value for any significant relationship is provided in parentheses.

	Total Lumbar BMD	Femoral Neck BMD	Trochanter Region BMD	Inter-trochanteric Region BMD	Total Hip BMD	Ward's Triangle BMD
Peak impact force (Fz_1)	0.400 (0.023)	0.450 (0.010)	0.288	0.374 (0.035)	0.401 (0.023)	0.610 (<0.001)
Time to peak impact force (t_1)	-0.447 (0.010)	0.116	0.175	0.189	0.200	-0.031
Peak early loading rate	0.588 (<0.001)	0.273	0.153	0.206	0.221	0.515 (0.003)
Average early loading rate	0.662 (<0.001)	0.269	0.192	0.233	0.241	0.430 (0.014)
Peak active force (Fz_2)	0.346	0.054	0.138	0.017	0.055	0.132
Time to peak active force (t_2)	-0.023	-0.346	-0.232	-0.185	-0.273	-0.466 (0.007)
Active loading rate	0.290	0.291	0.238	0.151	0.230	0.438 (0.012)
Peak braking force	0.033	-0.291	-0.038	-0.053	-0.078	-0.414 (0.019)
Time to peak braking force	-0.204	-0.164	0.113	-0.050	-0.009	-0.436 (0.013)
Peak propulsive force	0.175	0.196	0.113	0.087	0.155	0.179
Time to peak propulsive force	-0.198	-0.372 (0.036)	-0.230	-0.239	-0.275	-0.437 (0.012)

Table 4 provides the results of step-wise multiple regression analyses to predict each BMD value by considering each of the eleven force characteristics in Table 3 as predictors. The spine BMD had only the average ELR identified as a predictor with the other ten force values eliminated. The femoral neck, intertrochanteric region, the total hip, and Ward’s triangle all had the normalized Fz_1 identified as a predictor with the other ten force values eliminated. The analysis to predict the trochanter region resulted in no force value being identified as a predictor.

Table 4. Results of Step-wise Multiple Correlation Analysis to predict each BMD value using the different force, loading rates and time values.

Region	Predictor	R ²	F	Significance
Total Lumbar Spine	Average ELR	0.438	23.353	< 0.001
Femoral neck	Fz ₁	0.203	7.633	0.010
Trochanter region	NA	-	-	-
Intertrochanteric region	Fz ₁	0.140	4.873	0.035
Total hip	Fz ₁	0.161	5.750	0.023
Ward's triangle	Fz ₁	0.372	17.803	< 0.001

DISCUSSION

The aim of this paper was to investigate the relationship between the hip and spine bone mineral density values and ground reaction force characteristics for male runners who use a rear foot striking pattern. Except for the trochanter region, all the BMD values were positively correlated to the peak impact force size. Additionally, the peak impact force size was identified as the predictor in the multiple regression for all the BMD values other than the trochanter region and the spine. These two findings suggest that the impact force exhibited by rear foot strikers may be advantageous for hip and spine BMD. There has been speculation that these larger vertical ground reaction forces and greater loading rates, which may help develop greater bone density, may also increase injury risk, but most of these findings involve female runners (27, 45, 49). Also, any finding regarding previously injured versus non-injured subjects does not infer a causal relationship between high loading rates and injury. It is possible that the injured runners' mechanics have been altered due to the injury, as opposed to causing the injury. It should be noted that the runners in this study were selected specifically to be injury-free for the past 12 months and had not experienced any lower extremity surgeries.

The peak and average early loading rates in the current study were also positively correlated to the lumbar spine and Ward's triangle BMD. Additionally, in the multiple regression analysis, the average early loading rate was identified as the predictor for the lumbar spine BMD. The active loading rate and the time to Fz₂ only correlated with the Ward's triangle BMD value. The Ward's triangle BMD has been identified as a sensitive predictor for osteoporosis, especially in males (48) and is a region in the femoral neck that illustrates initial bone loss (8). This suggests an important relationship between this early loading rate and osteoporosis risk. Both Ward's triangle and the lumbar spine are composed of a good amount of trabecular bone tissue which has a greater turnover rate than cortical bone (38). Jämsä et al. (26) studied an exercise intervention program over a year and reported that the greatest increase in BMD was at Ward's triangle. There were also increases at the femoral neck and trochanter, but they were smaller. The lumbar spine was not investigated. Heikkinen et al. (23) investigated the slope of the acceleration graph from accelerometers attached to women during exercise training that included a variety of activities that created different acceleration slope values (slow step to drop jumps). They concluded that physical activity that induced a slope of at least 1000 was associated with increased in BMD at the femoral neck, Ward's triangle and the trochanter, but not the

lumbar spine in premenopausal women. While it is difficult to compare the actual values computed for the peak and average ELR to the identified acceleration slope value, it is likely that a larger loading rate is beneficial. Reenalta et al. (40) used IMUs to investigate tibial and sacral accelerations during a run at lactate threshold on a track. They reported that the tibial accelerations increased over the run but the sacral accelerations didn't change. This finding illustrates how accelerations (and their associated forces) differ within regions of the lower extremity. This may explain why the current study determined more relationships between force values and the lumbar spine and Ward's triangle as opposed to the trochanter and intertrochanteric regions.

While similar sized peak braking and propulsive forces have been reported in other studies involving runners, no previous research has been completed on the relationships between these forces and BMD at the hip and spine. The peak braking force and the time to this peak were significantly related only to the Ward's triangle with the lumbar spine and four other hip regions having very low correlation coefficient values. The negative relationship indicates that the larger the braking force size, the greater the BMD. While the peak braking force is relatively small when compared to the peak vertical forces analyzed, it appears that it creates a force in a different direction that is helpful for BMD in the Ward's triangle.

The normalized impact force size, Fz_1 , was found to be 2.33 ± 0.62 BW in the current study. Other studies have reported values ranging from 1.5 BW – 2.8 BW (9, 11, 13, 30, 31, 34) with most studies reporting values less than 2.0 BW. Differences between reported values are likely associated with the GRF values being filtered which would likely decrease any peak or extreme values. The current study did not filter the GRF values for this very reason. The largest value (2.8 BW) reported from the other studies mentioned also was obtained from unfiltered data (13). Additionally, not all these studies included runners using only a rear foot striking pattern which results in larger impact forces.

The early loading rates (both peak and average) in the current study were larger than most of the values reported by other investigators (20, 30, 31, 33, 34, 48). The larger loading rates in the current paper may be due to the larger Fz_1 value, but also the other investigators used a variety of methodologies to obtain the loading rate which may decrease its value. In particular, not all investigators used the entire time from touchdown to Fz_1 to compute slope. Rather, some studies used 20-80% of this time period (20, 31, 33) or from 200N to 90% (34, 43). Finally, some of the loading rates reported in other studies included subjects who used a foot strike pattern that produced a vertical GRF without a clear impact force and thus computed the loading rate using the slope of the graph for a set time period after touchdown.

The active peak vertical ground reaction force, Fz_2 , had no significant relationship with any of the BMD values. The size determined in this current study (2.65 ± 0.19 BW) matched values reported for other male runners which varied from 2.18 BW – 2.86 BW (9, 11, 20, 30, 31, 43). In particular, the size of Fz_2 in the current study was comparable to that reported by Kowalski and Li (30) for male recreational runners who used a rear foot strike pattern.

It was determined that body mass was associated with femoral neck and intertrochanteric region BMD which was consistent with other findings (25). The analysis in the current study used force values that were normalized for body weight to minimize the effect that just having more body mass would have on BMD. Body mass index (BMI) has been related to BMD in other studies with differing findings, based on the populations. Tenforde et al. (44) reported that adolescent male runners with BMI < 17.5 kg/m² are more likely to have low BMD. Others have identified the cutoff to correspond with the definition of underweight (BMI < 18.5 kg/m²) (18) but those results were not specific to males or to runners. None of the participants in the current study had BMI values below 18.5 kg/m² so it was not surprising that this was not a significant relationship for this group of runners. Hind et al. (25) also reported no relationship between BMI and BMD for their male runners that had a mean BMI = 21.1 kg/m² which matches the values in the current study.

There was no relationship between the runners' weekly mileage and hip or spine BMD values. These results agree with findings from Kemmler et al. (29), but disagree with the results of several other studies. Both Hetland et al. (24) and Hind et al. (25) reported a negative relationship between various hip or lumbar spine BMD values and mileage for male runners with a larger range of weekly mileage. It may be that there is no relationship when a more homogeneous group of runners is considered. MacKelvie et al. (35) compared high volume (64 to 80 km/week) and very high-volume male runners (96 to 112 km/week) and found that while there was no difference in their lumbar spine BMD, the very high-volume runners had lower BMD at several sites within the hip.

A limitation of this study was that while GRF data was collected and determined to have relationships with various BMD values, it is not guaranteed that these forces were transferred to the hip and spine. It would be possible to bridge this gap by calculating joint reaction forces using motion capture data, along with the force plate data. A study by Giarmatzis et al. (17) investigated the hip contact force peaks for running at a range of velocities and reported that the peak hip contact forces ranged from 7.5 – 10.0 BW at velocities slower than the current study's runners. The loading rate related to these joint forces are likely sizeable and influential for the hip BMD. Another limitation of the current study was that nutritional and blood chemistry data was not collected. Studies that have included this analysis in their studies with male runners have concluded that biochemical markers of bone turnover were not predictive of changes in lumbar spine BMD (4). Brahm et al. (6) reported that runners had lower levels of both ICTP and PICP than controls, but that there was no difference in the levels of bone specific alkaline phosphatase (b-ALP) or osteocalcin. The relatively large BMI values for the runners in the current study, along with the lack of self-reported eating disorders, make drastic nutritional deficiencies less likely than those identified in other studies (44).

Future studies should include an analysis of the joint reaction forces and their relationship to hip and spine BMD. Also, a longitudinal study should be conducted to determine if there is consistency in early loading rates and if they continue to be positively associated with BMD

values. Peak loading rates have been found to be similar in younger and older male runners when each group runs at their self-selected pace (7). However, when running at the same pace (faster than the older group would choose), the loading rate was higher for the older runners. The current study focused on male runners to eliminate the need to consider hormonal influences, but as osteoporosis is even more prevalent for females, the relationships investigated in this paper are also important to consider for a female population. Finally, a more complex statistical analysis could be performed to determine if a combination of force characteristics is most related to desirable BMD values.

In conclusion, there appears to be important relationships between the forces experienced during running and the subjects' bone mineral density, especially at the lumbar spine and Ward's triangle. While some literature suggests running as not beneficial to bone density at the hip and spine, rear foot striking runners seem to make impact and braking forces that create loading conditions that are advantageous.

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