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Bone Mineral Loss During Pregnancy: Is Tennis Protective?

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Background: Pregnancy may stress calcium economy in women through fetal calcium requirements, and increasing maternal body weight. Bone is stimulated by compression forces. Playing tennis may decrease bone resorption through intermittent mechanical loading. This study tests the thesis that maternal bone mineral changes during pregnancy in women who play tennis are less compromised compared with nontennis playing controls. ***Methods:*** This is a prospective cohort study, a pilot study of 18 healthy pregnant women: 8 tennis players and 10 controls, ages 18 to 39 years. Calcanei bone mineral density (BMD) and ultrasound (Stiffness Index (SI)) measurements, were made at 12 weeks gestation and 2 to 4 weeks postpartum. SI was also measured at 20 to 24, and 33 to 36 weeks gestation. Statistical analysis included analysis of variance and covariance. ***Results:*** Age, height, and weight at study entry were not different between tennis players and controls. At 12 weeks, BMD was higher in tennis players versus controls 0.57 ± 0.02, 0.43 ± 0.03 g/cm^2, ($P = .003$); but not postpartum. SI Z-scores fell significantly during pregnancy in both groups, but were consistently higher in tennis players. ***Conclusions:*** Bone measures dropped overall during pregnancy, but were significantly higher in tennis players versus controls at 12 weeks and through gestation.

Keywords: bone mineral density, dual-energy X-ray absorptiometry, ultrasound, exercise, women

Tennis is a load-bearing sport that involves intermittent sudden torsional strains on limbs and spine.[1–3] An increase in bone mineral content may be expected in the lower limbs. Specifically, the calcaneus, which is mostly trabecular bone, receives ground reaction forces at heel strike from the on court impact caused by sprinting, stopping, and planting motions.

Pregnancy and lactation are characterized by significant alterations in the maternal endocrinologic environment, which may alter bone metabolism and density.[4] Theoretically, during pregnancy bone mineral may increase, due to greater blood estrogen concentrations in the last trimester and increased bone-loading related to weight gain in pregnancy. In a review of 6 prospective studies of bone mineral in pregnancy, there is an inconsistency as to whether there are any bone mineral changes in pregnancy.[4] Some of the inconsistencies in these studies of BMD are attributed to substantial methodological and technical limitations. There is little evidence of bone loss in pregnancy among well-nourished Caucasian women. However, bone turnover markers are increased in pregnancy reflecting substantial bone turnover.[4]

A radiation-free method currently available to measure bone parameters is ultrasound. Calcaneus ultrasound does not provide bone mineral density measurements, but its parameters: speed of sound (SOS, m/s), and broadband ultrasonic attenuation (BUA, dB/MHz), are reflective of bone properties comparable to that of bone density and structure respectively.[5,6] SOS is representative of bone density, a measurement of the time required for an ultrasound wave to travel through the subject's heel; velocity.[7] BUA is a measure of the reduction in intensity of specific ultrasound frequency components,[7] and, as such, is representative of bone structure. BUA is an index of elasticity in the calcaneus through frequency attenuation of the ultrasound signal of the subject's heel. The stiffness index (SI), is a unitless, clinical index of bone health used by LUNAR^R calculated by combining the 2 ultrasound measurements of SOS and BUA.[7]

In a cross-sectional study of 230 white healthy women the nondominant os calcis using ultrasound bone densitometry was measured in the 1st, 2nd, and 3rd trimesters.[8] Results from this study indicated a linear reduction of ultrasound bone density (SOS, BUA, and SI) measurements throughout pregnancy, which was significant by the 3rd trimester. That study by Paparella did not evaluate the effect of exercise.

While walking is a load-bearing activity, by our definition, exercise is only for load-bearing above and beyond day-to-day activities. There are no published studies documenting bone metabolism for tennis players during pregnancy, nor prospective studies on effects of exercise on maternal bone mineral density during pregnancy. The current study tests the hypothesis that maternal bone mineral density (BMD) and ultrasound derived stiffness index (SI) changes are attenuated in pregnant women participating in recreational tennis compared with sedentary controls. We compared pregnant women

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who only exercised by playing recreational tennis versus control pregnant women who did not participate in any physical sports activity

This study has potential important public health implications regarding recommendations for continuation of activity during pregnancy. We hope to show objective measurements of the benefit of exercise for bone health during pregnancy. Higher bone mineral measures in early adulthood have been related to reduced risk of osteoporosis in later life[9] so maintaining a healthy life-style during pregnancy may help for later life bone health

Materials and Methods

This was a prospective cohort study, a pilot involving 18 healthy pregnant women, 8 tennis players, and 10 sedentary controls. Recruiting was done at 10 Greater Cincinnati Indoor Tennis Clubs, Greater Cincinnati area local and community newspapers, and by word of mouth. Eligibility criteria for the tennis players were: pregnancy of less than or equal to 12 weeks gestation, age 18 to 39 years, currently playing tennis and had been playing tennis at least for a year before pregnancy, and a member of a local racquet club. Exclusion criteria for the tennis players were: current participation in any regular exercise other than tennis, a United States Tennis Association (USTA) rating below 2.5, and playing tennis less than twice a week or less than 30 minutes at a time**.** We have no data on type of nonregular exercise in study subjects, where regular exercise was defined as a regularly planned or scheduled physical exertion, at least 1 time per week.[10] We excluded any potential subject with history of diabetes, parathyroid disease, chronic hypertension, osteoporosis, rheumatoid, or osteo-arthritis; or kidney stone, multiple gestation, maternal heart disease, serious clinical complications in a past pregnancy, prescription medication which might interfere with the study, or subjects taking calcium supplement other than 200 mg of calcium citrate as contained in the standard prenatal Prenate Ultra™ (which we subsequently provided). Inclusion and exclusion criteria were the same for the nonathletes except for those specific for tennis playing. The activity level of the women who did not exercise was defined to include taking care of a household and the daily duties of going to work, housework, child care, and running errands. No exercise was defined as, not having a scheduled routine event which would elevate the heart rate and maintain the heart rate elevation for over 20 minutes per day and would not introduce skeletal stress through ground-reaction (ie, jogging), or joint-reaction (ie, weight-lifting) activities. Over an 18-month period 59 potential subjects inquired and were screened for the study.

The study was carried out in accordance with approved protocol from Cincinnati Children's Hospital Medical Center (CCHMC) and the University of Cincinnati Medical Center (UCMC) Institutional Review Boards, which included UCMC Radiation Safety Notification approval. Subjects' obstetricians were notified and all participants signed informed consent before enrollment. Four visits were scheduled (12 weeks, 20 to 24 weeks, and 33 to 36 weeks gestations and 2 to 4 weeks postpartum) at the CCHMC, National Institutes of Health (NIH) General Clinical Research Center, where each participant received prenatal vitamins, underwent anthropometric measurements, and review was made of the tennis log sheet (for tennis players). At each of the 4 scheduled appointments, subjects were taken to the UCMC, Department of Nuclear Medicine for calcanei ultrasound measurements. The subjects were also taken there during their 1st and 4th visits for their left os calcis dual energy x-ray absorptiometry (DXA) measurements.

All subjects were supplied with Prenate Ultra™ (200 mg of calcium citrate taken daily) by Sanofi Pharmaceuticals, Inc., at each clinic visit: 12 weeks, 20 to 24 weeks, and 33 to 36 weeks of gestation. At each return visit the number of pills remaining were counted for compliance purposes. A self-administered questionnaire was completed by each subject at the 12- and 33-to-36 week visits, for health, nutrition, and exercise history; and tennis playing questions for players. All pregnancy medications, including vitamin and mineral supplements (dose/day) were recorded as potential confounders for BMD. Dietary calcium intake was estimated from an established Block's food frequency instrument, modified to incorporate calcium fortified beverages.[11,12] Weight was obtained using the Scale-tronix®, an electronic digital scale, with subjects dressed in light clothes, and shoes removed. Height was obtained upright without shoes against a wall-mounted, Holtain Limited® stadiometer.

Each tennis player was given tennis log sheets at enrollment, and at each visit, for recording: time of play, court surface, and type of tennis played (lessons, singles, or doubles) throughout pregnancy. The previous period log sheet was collected at the time of each study visit. Recruitment and tennis playing occurred year round.

Maternal Bone Density and Calcanei Ultrasound Measurements

DXA measurement of the os calcis is a site-specific low dose safe radiation level method to measure the bone mineral density of the calcaneus.[13,14] Calcaneal bone mineral density which is mostly trabecular, is suggested to reflect spinal BMD.[15]

Bone density BMD assessments were carried out at 2 different visits. The woman's abdomen was covered by a lead apron to ensure minimal fetal exposure. The 1st measurement was a baseline measurement taken at 12 weeks gestation and the 2nd measurement was taken at 2 to 4 weeks postpartum using the GE LUNAR® PIXI Bone Densitometer, P/N 30700, software version 1.3; coefficient of variation (cv) 2%.[16] Since lumbar spine DXA measurements in pregnancy raise ethical concerns, we measured just the calcaneus by DXA, to represent potential changes in bone. In addition, to minimize radiation, only the left calcaneus was measured. Since most people are dominant right handed,[17] the left calcaneus would have higher impact from playing tennis, as the left foot would be used in the forehand stroke. Dominant left handed persons are either dominant left or right footed.[17] All tennis players and 8 of the 10 controls in our study were dominant right handed.

Ultrasound measurements of both calcanei of all subjects were measured at all 4 visits (<12, 20 to 24, and 33 to 36 weeks of gestation, and 2 to 4 weeks postpartum) of the study using the GE LUNAR® Achilles+™ instrument. This measurement takes approximately 6 minutes per foot once the subject's foot has been placed in the water bath. Once the measurement was taken, the foot was removed and this procedure was repeated for the other foot. An ultrasound quality control test was performed at the beginning of the day of each patient scan. With the subject's heel immersed in a waterbath, an ultrasonic signal is sent from one transducer, through the subject's heel to another transducer on the opposite side of the heel.[7] A variable frequency burst of ultrasound excites the transmitting transducer, and the amplitude of the resulting ultrasonic signal received is recorded. Comparison of the amplitude spectrum obtained with the heel positioned between the transducers with that for water alone yields a linear relationship between ultrasonic attenuation and frequency.[18]

The SOS, the velocity of the sound pulses through the specimen, is influenced by the density and structure of the trabecular bone and expressed as (m/s).[19] The BUA is the slope of the attenuation of the ultrasound frequency spectra after the spectral beam passes through the specimen and is expressed as (dB/MHz).[19] A technique used by LUNA® combines these 2 ultrasound measurements of SOS and BUA to a clinical unitless index called the stiffness index (SI).[7] SI was calculated using the GE LUNAR® SI formula: $SI = 0.67\times(BUA) + 0.28\times(SOS)-420$, and then expressed as a unitless Z-score referent to females of similar age, weight, and race.[8] The coefficient of variation for duplicate measures of SOS and BUA are 0.3% and 1.7%, respectively.

Statistical Analysis

Descriptive statistics were produced, and initial bivariate analyses were done using Student's *t* test and Fisher's Exact test. Assessment of change over time was done using a generalized random effects mixed model; this allows those subjects with a missing value to be included in the analysis. The covariance structure assumed for this model was autoregressive as it is anticipated to have correlation between successive measurements within individuals. This methodology allowed incorporation of the information from the individuals who did not have baseline measures of BMD due to unavailability of the machine, which is assumed to be random. Due to strong association between body weight and bone parameters, analyses were performed using body weight as a covariate. SAS®, version 9.1, software was used for data analysis.[20] A p-value of < 0.05 was considered statistically significant.

Results

Baseline Data

Baseline demographic information for tennis players and controls is shown in Table 1. Age, height, and weight were not different between groups. Although the study was open to any race, our study subjects were all Caucasian. Gestation and weight at each visit and postpartum, were not different between groups. Seven tennis players successfully completed the study and continued their pregnancy to term (≥37 weeks gestation), 1 delivered at 36 weeks gestation. All 8 tennis players were included in the analysis. One of the 10 controls experienced spontaneous abortion a few weeks after enrollment, and did not complete the study. The remaining 9 subjects completed the study and delivered at term. Dietary calcium intake, excluding supplementation, was not different between tennis players and controls, at enrollment (12 weeks gestation), $P = .61$ and at 33 to 36 weeks, $P = .34$. Calcium intakes exclusive of supplements, at 12 weeks gestation, shown in Table 1,

Table 1 Baseline and Late Pregnancy Maternal Characteristics

	Tennis player	Control	*p*-value
N	8	9*	
Age (years)	34.0 ± 2.4	33.0 ± 3.4	0.31
Dominant right hand	8 (100%)	7 (78%)	0.47
Gestation at enrollment (weeks)	10.3 ± 1.5	9.1 ± 1.8	0.20
Pre-pregnancy weight (kgs)	61.9 ± 8.0	70.8 ± 16.5	0.18
12 weeks pregnant weight (kgs)	63.4 ± 7.8	72.3 ± 17.2	0.20
12 weeks pregnant height (cms)	165.8 ± 6.2	166.7 ± 5.7	0.76
12 weeks pregnant calcium intake (mg)	1288 (894, 1716)	1468 (1043, 1647)	0.61
33–36 weeks pregnant weight (kgs)	75.7 ± 13.58	78.8 ± 16.49	0.72
33–36 weeks pregnant calcium intake (mg)	3159 (1502, 3920)	2259 (1490, 2727)	0.34

Note. Data presented as mean ± SD, median (25th percentile, 75th percentile), or n (%).

* The control subject who experienced a spontaneous abortion is not included.

compared well with recommended daily allowance (RDA) of 1200 mg per day.[21]

Tennis Playing Questionnaire

Tennis players self-reported their skill level using the USTA National Rating Program scale from 1.0 to 7.0. When participants enrolled, they ranged from 2.5 (beginner) through 4.5 (intermediate) in skill, median 3.5. The number of years playing ranged from 1.5 to 10 years, median 3.6. There was no recording of weekly time spent playing tennis before the study. Using paired *t* test, there was a reduction in the number of hours of tennis played in the 2nd (2.89 ± 1.07 hours per week) versus 3rd (1.50 ± 0.80 hours per week) trimesters, (*P* = .003). All tennis players self-reported dominant right handedness in everyday activities and tennis. None switched to their left hand to play tennis. All tennis players self-reported 1-handed, forehand ground strokes using dominant right hand to swing and contact the ball and a 2-handed backhand ground stroke.

Maternal Left Os Calcis BMD Measurements

As the LUNAR® PIXIE™ instrument for os calcis measures was not operational, only 7 of the 8 tennis players, and 6 of the 10 controls, had BMD measurements at enrollment, (Table 2). All 8 tennis players, and the 9 controls completing the study had BMD measurements at 2 to 4 weeks postpartum, (Table 2). As shown in Table 2, at 12 weeks gestation, left calcaneus BMD was significantly higher in tennis players than controls 0.57 ± 0.02 vs. 0.43 ± 0.03 g/cm^2, (analysis of covariance, *P* = .003); the Z-score for left calcaneous BMD of tennis players was significantly higher than that for controls, (*P* = .002). However there was no difference between tennis players and controls at 2 to 4 weeks postpartum for either BMD raw score or BMD Z-score, (*P* = .06 and 0.08, respectively). As there was no statistically significant time by group interaction, *P* = .53 and *P* = .57 respectively for BMD raw score and BMD Z-score, the groups were combined. There was a significant decrease over time for BMD raw score and BMD Z-score combined tennis players and controls (*P* = .047 and 0.03, respectively). To remove potential footedness effects, the 2 left-handers were deleted and data were reanalyzed, interpretation of the results remained unchanged.

Calcaneus Ultrasound Measurements

Measurements were obtained for all 8 tennis players and the 9 controls completing the study, at all 4 visits. Stiffness Index (SI) and Z-scores for the left feet of tennis players were significantly higher at all 4 measurements versus controls (Tables 3 and Figure 1). Mean SI and SI Z-score for right calcaneus was significantly higher in tennis players versus controls at all visits except 20 to 24 weeks (Tables 3 and Figure 1), and left calcanei ultrasound Z-scores fell for the tennis players during pregnancy (*P* = .02).

All the calcaneus measurements taken of both feet (SI Z-score, SI, SOS, and BUA), fell significantly over pregnancy for combined tennis players and nontennis players (*P* ≤ .02 for all), except for the left BUA (*P* = .07). Similarly the difference between tennis players and nontennis players was statistically significant at *P* ≤ .02 for all except right BUA (*P* = .05). The interaction between group and visit was not statistically significant (Tables 3 and Figure 1).

Comment

Load-bearing activities stimulate bone growth so that bone is laid down where it is "needed" to withstand physical load (Wolff's law).[22] Physical activity, in particular load-bearing exercise maintained for a long period, may maintain or increase bone mineral density. Bone responds to applied strain through bone formation or sustained bone maintenance.[24] High impact, such as mechanical loading and short intermittent stimulation, in particular, increases bone density.[23–25]

Table 2 Left Os Calcis BMD*

Group	12 weeks gestation	2–4 weeks postpartum
BMD (g/cm^2)		
Tennis	0.57 ± 0.02, [N = 7]	0.54 ± 0.03, [N = 8]
Control	0.43 ± 0.03, [N = 6]	0.45 ± 0.03, [N = 9]
p-value	0.003	0.06
Z-score**		
Tennis	0.89 ± 0.31, [N = 7]	0.21 ± 0.37, [N = 8]
Control	–0.93 ± 0.33, [N = 6]	–0.78 ± 0.35, [N = 9]
p-value	0.002	0.08

Abbreviations: BMD, Bone Mineral Density.

Note. Analysis of covariance was used to adjust for body weight. Data presented as mean ± SD, and N [ ]. (measurement value) – (age, weight, and race – matched population mean).

* LUNAR^R PIXI Bone Mineral Densitometer.

** Z-score = (age, weight, and race –matched population SD).

Table 3 Stiffness Index, (SI) = 0.67 × BUA + 0.28 × SOS–420*

SI group & foot	12 weeks	20–24 weeks	33–36 weeks	2–4 weeks postpartum
Tennis left (N = 8)	107.9 ± 5.5	104.4 ± 5.5	100.1 ± 5.6	100.7 ± 5.1
Control left (N = 9)	83.8 ± 5.2	84.9 ± 5.2	80.5 ± 5.2	82.6 ± 4.8
p-value	0.008	0.02	0.02	0.02
Tennis right (N = 8)	105.0 ± 6.5	102.5 ± 6.5	101.6 ± 5.34	98.0 ± 6.08
Control right (N = 9)	84.1 ± 6.1	84.0 ± 6.1	79.2 ± 5.0	79.5 ± 5.71
p-value	0.04	0.06	0.010	0.049

Note. Analysis of covariance was used to adjust for body weight. Data presented as mean ± SD.

* LUNAR^R Achilles+ Calcanei Ultrasound.

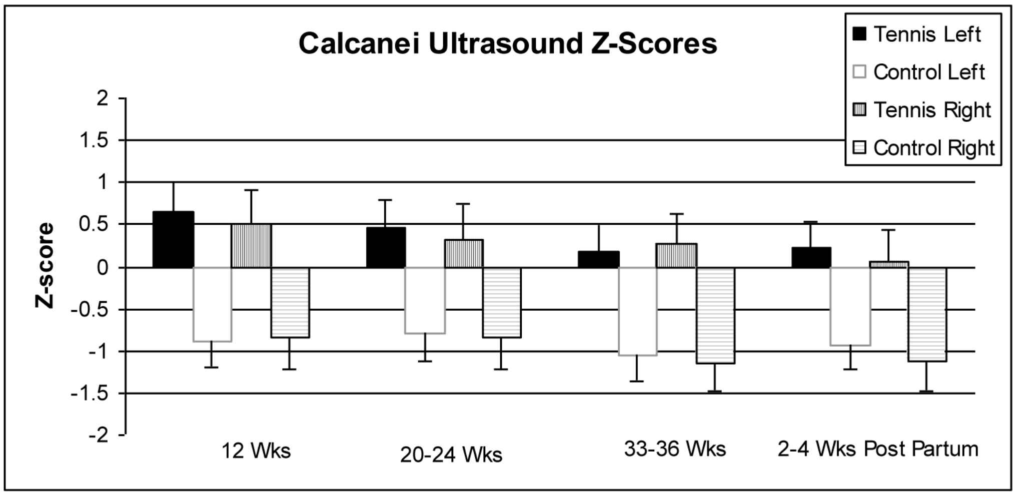

Figure 1 — Calcanei Ultrasound Z-Scores. Analysis of covariance was used to adjust for body weight. Differences between Tennis and control group, by side, all significant at $P < .05$, except for right side at 20 to 24 weeks of gestation ($P = .06$). Data presented as mean ± SD. *LUNAR^R Achilles+ Calcanei Ultrasound. (measurement value) – (age, weight, and race – matched mean) **Z-score = (age, weight, and race – matched population SD).

Weight gain is associated with pregnancy. Added weight is a load-bearing strain. In theory, the added load-bearing weight gain during pregnancy might result in increased BMD. If the added load-bearing due to weight gain occurs in conjunction with regular exercise, such as tennis, which generates high impact, short intermittent mechanical loading, this combination could potentially lead to an even greater increase in BMD. Investigation of this theory was the aim of our study of pregnant women, comparing those who participated in a load-bearing exercise during pregnancy with those who did not. In contrast, pregnancy poses particular stresses on the overall body calcium economy. Fetal calcium demand rates increase as do the calculated calcium rates incorporated into the fetal skeletons.[26]

There have been no prior prospective studies on the effects of exercise on maternal bone mineral density during pregnancy. However, Taaffe et al compared the calcaneus of young, healthy, female gymnasts compared with the calcaneus of controls who participated in regular weight-bearing activity. Thus comparing the effect of exercise similar to our study, both ultrasound and DXA parameters were higher in the gymnasts than in the controls for Taaffe's study.[27] The current study quantified BMD, BUA, SOS, and SI in the calcaneus of both tennis playing and sedentary women during pregnanThe study reflected year-round tennis play in enclosed indoor, and on outdoor facilities. Because the calcaneus receives ground reaction forces from sudden starts and stops at heel strike during tennis play, we focused on measuring BMD and SI of the calcaneus. The left calcaneus BMD was higher in tennis players versus controls at 12 weeks gestation which is consistent with exercise related increase in bone mineralization. However, BMD fell to values not different from controls at 2 to 4 weeks postpartum. Left and right calcaneus ultrasound SI values in tennis players were higher than in controls for all time points. However SI for both groups decreased significantly over pregnancy.

Tennis players generally stopped playing in the 3rd trimester by their own choice, as recorded on their log sheets, even though players were fully accustomed to this type and volume of activity. The tennis record sheet was used to document and quantify the type, intensity, frequency, and duration of tennis played on the average throughout pregnancy, however the reason for stopping was not recorded. During the period when the amount of tennis playing was reduced, bone mineral measures appeared to fall also. Increase in load-bearing exercise may lead to higher BMD and decrease in exercise may lead to bone loss.[25,28,30] As participation in load-bearing activity decreases, disuse effects occur, and bone loss may occur, and possibly be rapid. Detraining may undo positive benefits, as happens in extended bed rest, weightlessness (astronauts), or when bone experiences less than normal weight-bearing loads, which result in increased bone resorption, bone loss, and lower BMD.[28–31] However, there may have been an unmeasured reduction in amount and level of tennis playing at the beginning of pregnancy which may be reflected by measurements late in our study. Also, there were no blood or urine specimens taken in our study to evaluate bone marker turnover, hormonal changes, or supplement compliance, thus limiting the understanding of the physiologic changes in bone mineralization.

Limitations

This is a pilot study and, as such, the sample size is small, limiting generalizability. Whole body bone mineral density measurements represent changes in the entire skeleton. Pregnancy, and thus potential risk of radiation exposure, made the option of a whole body DXA not possible**.** Since the last measurements were performed at 2 to 4 weeks postpartum, there might have been lactation related falls in bone mineral content.[4,32] A total of 3 subjects did not breast feed their infants (1 tennis player and 2 controls), and so the lactation effect could not be specifically examined.

As with the use of any questionnaire, there are limitations compared with direct observation. This is the 1st attempt to develop a record playing log sheet for recreational tennis. No direct verification of this method of estimation of tennis exercise was done. In other studies, questionnaires derived from exercise estimates have had generally good correlation with tachometer/electronic monitoring data.[33]

Since the mean age of subjects was over 32 years, it is likely they may have other exercise history before starting tennis, which was not recorded. Prior exercise may have effects on BMD and its response to exercise. In addition, other strenuous activities due to employment or household tasks was not measured.

Conclusion

Calcaneus bone densitometry Z-score measures and ultrasound Z-score measures were significantly higher in tennis players versus controls at 12 weeks gestation. Both calcaneus bone densitometry measures and ultrasound bone measures values fell significantly for the study population during pregnancy. Thus, bone mineral measures did not increase during pregnancy in tennis players or controls, in spite of increasing body weight.

The significance of this study is the provision of quantitative data in an unexplored area and its potential practical application. This was a pilot study which provides valuable information relevant for future research of the effect of exercise on bone health during pregnancy. Extension to this research may include measures to quantify the amount of exercise and the association with changes in bone measures.

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References

1. Etherington J, Harris PA, Nandra D, et al. The effect of weight-bearing exercise on bone mineral density: a study of female ex-elite athletes and the general population. *J Bone Miner Res*. 1996;11:1333–1338.
2. Pirnay F, Bodeusx M, Crielaard JM, Franchimont P. Bone mineral content and physical activity. *Int J Sports Med*. 1987;8(5):331–335.
3. Nigg BM. Biomechanics, load analysis and sports injuries in the lower extremities. *Sports Med*. 1985;2:367–379.
4. Sowers M. Review pregnancy and lactation as risk factors for subsequent bone loss and osteoporosis. *J Bone Miner Res*. 1996;11:1052–1060.
5. Langton CM, Palmer SB, Porter RW. The measurement of broadband ultrasonic attenuation in cancellous bone. *Eng Med*. 1984;13:89–91.
6. Zagzebski JA, Rossman PJ, Mesina C, Mazess RB, Madsen EL. Ultrasound transmission measurements through the os calcis. *Calcif Tissue Int*. 1991;49:107–111.
7. *Achilles+ Ultrasound Densitometer Operator's Manual*. Madison, WI: Lunar^R Corporation; 1995.
8. Paparella P, Giorgino R, Maglione A, et al. Maternal ultrasound bone density in normal pregnancy. *Clin Exp Obstet Gynecol*. 1995;22(4):268–278.

9. Kimmel DB, Slovik DM, Lane NE. Current and investigational approaches for reversing established osteoporosis. *Rheum Dis Clin North Am*. 1994;20(3):735–758.
10. *The American College of Sports Medicine's Guidelines for Exercise Testing and Prescription*. 4th ed. Baltimore, MD: Williams & Wilkins; 1991.
11. Cummings SR, Block G, McHenry K, Baron RB. Evaluation of two food frequency methods of measuring dietary calcium intake. *Am J Epidemiol*. 1987;126:796–802.
12. Block G, Hartman AM, Dresser CM, Carroll MD, Gannon J, Gardner L. A data-based approach to diet questionnaire design and testing. *Am J Epidemiol*. 1986;124(3):453–469.
13. Lang TF. Summary of research issues in imaging and noninvasive bone measurement. *Bone*. 1998;22(5):159S–160S.
14. Felsenberg D, Gowin W. Bone densitometry: applications in sports-medicine. *Eur J Radiol*. 1998;28(2):150–154.
15. Vogel JM, Wasnich RD, Ross PD. The clinical relevance of calcaneus bone mineral measurement: a review. *Bone Miner*. 1988;5:35–58.
16. *PIXI Bone Densitometer Operator's Manual*. Software version 1.3, Documentation version: 11/97B. Madison, WI: Lunar^R Corporation; 1997.
17. Peter M, Durdig BM. Footedness of left- and right-handers. *Am J Psychol*. 1979;92:133–142.
18. Sinaki M, Wahner HW, Offord KP. Relationship between grip strength & related regional bone mineral content. *Arch Phys Med Rehabil*. 1989;70:823–826.
19. Yamaga A, Michiyoshi T, Minaguchi H, Sato K. Changes in bone mass as determined by ultrasound and biochemical markers of bone turnover during pregnancy and puerperium: a longitudinal study. *J Clin Endocrinol Metab*. 1996;81:752–756.
20. *The SAS System 1989-1996.* Release 6.12 TS Level 0020 for Windows. Carey, NC: SAS Institute.
21. Lapido OA. Nutrition in pregnancy: mineral and vitamin supplements. *Am J Clin Nutr*. 2000;72(suppl):280S–290S.
22. Wolf J. *Das Gestz der Transformation der Knochen*. Berlin: A Hirschwald; 1892.
23. Frost HM. A determinant of bone architecture: the minimum effective strain. *Clin Orthop Relat Res*. 1983;175:286–292.
24. Lanyon LE. Functional strain as a determinant for bone remodeling. *Calcif Tissue Int*. 1984;36:S56–S61.
25. Whalen RT, Carter DR. Influence of physical activity on the regulation of bone density. *J Biomech*. 1988;21:825–837.
26. Hytten F, Chamberlain G. *Clinical Physiology in Obstetrics*. 2nd ed. Boston: Blackwell Scientific Publishers; 1991.
27. Taaffe DR, Duret C, Cooper CS, Marcus R. Comparison of calcaneal ultrasound and DXA in young women. *Med Sci Sports Exerc*. 1999;31(10):1484–1489.
28. Vuori I, Heinonen A, Sievänen H, Kannus P, Pasanen M, Oja P. Effects of unilateral strength training and detraining on bone mineral density and content in young women: a study of mechanical loading and deloading on human bones. *Calcif Tissue Int*. 1994;55:59–67.
29. Winters KM, Snow CM. Detraining reverses positive effects of exercise on the musculoskeletal system in premenopausal women. *J Bone Miner Res*. 2000;12:2495–2503.
30. Issekutz B, Blizzard JJ, Birkhead NC, Rodahl K. Effect of prolonged bed rest on urinary calcium output. *J Appl Physiol*. 1966;21:1013–1020.
31. Kaji T, Yasui T, Suto M, et al. Effect of bed rest during pregnancy on bone turnover markers in pregnant and postpartum women. *Bone*. 2007;40(4):1088–1094.
32. Kalkwarf HJ, Specker BL. Bone loss during lactation and recovery after weaning. *Obstet Gynecol*. 1995;86:26–32.
33. Sequeira MM, Rickenbach M, Wietlisbach V, Tullen B, Schutz Y. Physical activity assessment using a pedometer and its comparison with a questionnaire in a large population survey. *Am J Epidemiol*. 1995;142:989–999.