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Mid-humerus adaptation in fast pitch softballers and the impact of throwing mechanics

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Abstract

Purpose—Throwing is a vigorous activity that generates large internal loads. There is limited evidence of the effect of these loads on bone adaptation. The aim of this study was to investigate the: 1) magnitude of bone adaptation within the midshaft humerus of female fast-pitch softball players and 2) influence of throwing mechanics (windmill vs. overhand throwing) on the magnitude of adaptation.

Methods—Midshaft humeral bone mass, structure and estimated strength were assessed via peripheral quantitative computed tomography in fast-pitch softball players (throwers; n=15) and matched controls (controls; n=15). The effect of throwing was examined by comparing dominant-to-nondominant differences in throwers to controls, while the influence of mechanics was determined by comparing dominant-to-nondominant differences in throwers who primarily play as pitcher (windmill thrower), catcher (overhand thrower) or fielder (overhand thrower).

Results—Throwers had greater dominant-to-nondominant difference in midshaft humeral bone mass, structure and estimated strength relative to controls (all $P < 0.05$). The largest effect was for estimated torsional strength with throwers having a mean dominant-to-nondominant difference of 22.5% (range, 6.7% to 43.9%) compared to 4.4% (range, -8.3% to 17.5%) in controls ($P < 0.001$). Throwing mechanics appeared to influence the magnitude of skeletal adaptation, with overhand throwers having more than double dominant-to-nondominant difference in midshaft humeral bone mass, structure and estimated strength than windmill throwers (all $P < 0.05$).

Conclusion—Throwing induces substantial skeletal adaptation at the midshaft humerus of the dominant upper extremity. Throwing mechanics appears to influence the magnitude of adaptation as catchers and fielders (overhand throwers) had twice as much adaptation as pitchers (windmill throwers). The latter finding may have implications for skeletal injury risk at the midshaft humerus in throwing athletes.

Keywords

BIOMECHANICS; BONE; EXERCISE; GROWTH AND DEVELOPMENT; MECHANICAL LOADING; OSTEOPOROSIS

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Introduction

Throwing is a vigorous, whole-body activity with the objective of accelerating the hand to generate ball velocity. This is achieved in overhand throwing via a highly coordinated sequence of motions wherein energy is transferred within the kinetic chain from the lower extremities, to the trunk, and finally the upper extremity and ball. As each segment rotates, the succeeding segment is taken into a wound-up or 'cocked' position increasing passive tension in connective tissues which, coupled with active muscular tension, is used to generate subsequent motion. Most notably, the upper extremity is cocked during overhand throwing by shoulder external rotation and abduction. As the shoulder approaches its cocked position, the hand and ball continue to move backward exerting an external rotation force on the distal humerus at the elbow. Simultaneous active tension in the shoulder internal rotator muscles limits shoulder external rotation range and begins rapid and forceful internal rotation exerting an internal rotation force on the proximal humerus. The two opposing rotatory forces at either end of the humerus results in the generation of substantial torque within the bone, which has been estimated at approximately 48% of humeral strength during fast-ball pitches thrown by professional baseball players (26) and modeled to contribute to spontaneous spiral fractures (or so-called 'ball-thrower's fractures') in throwing athletes (27).

Considering the magnitude and speed at which forces are introduced to the humerus during overhand throwing, and knowing that bone is a mechanosensitive tissue that preferentially adapts in response to high strain magnitudes and rates, it is not a complete surprise that the humerus exhibits adaptation to the forces generated during throwing. For instance, overhand throwing athletes have been shown to have greater bone mass, size and estimated strength within the humerus of their dominant upper extremity compared to non-dominant upper extremity (13, 16, 19, 28, 35, 36). However, what is of interest is the magnitude of adaptation that overhand throwers exhibit, with collegiate level baseball players having on average 40% and up to 92% greater estimated torsional strength at the midshaft humerus in their dominant upper extremity compared to non-dominant upper extremity (35, 36). These dominant-to-nondominant differences are 4-8 times greater than those due to habitual loading associated with general arm dominance observed in sedentary individuals (36).

The effect of overhand throwing on humeral skeletal adaptation in male athletes has been explored; however, to our knowledge no studies have reported on the skeletal effects of throwing in female athletes or the influence of different throwing mechanics on the magnitude of skeletal adaptation induced. Fast-pitch softball players represent a unique model to address these questions as fast-pitch softball is a popular sport among females and players exhibit vast differences in throwing mechanics according to playing position. For instance, fast-pitch softball players who play as catcher or fielder throw with a conventional overhand action, whereas pitchers use a windmill motion wherein the arm is extended around the body so that the ball is thrown from below the level of the hip with an underarm motion. By assessing skeletal adaptation occurring with the different forms of throwing, an indication as to where loads are placed during throwing may be garnered which may contribute to understanding the etiology of skeletal injuries in throwing athletes.

The aims of this cross-sectional cohort study were to investigate the: 1) magnitude of bone adaptation within the midshaft humerus of female fast-pitch softball players, and; 2) influence of throwing mechanics [windmill vs. overhand throwing] on the magnitude of adaptation. The former was assessed by comparing the dominant-to-nondominant difference in midshaft humeral bone properties in fast-pitch softball players to age-matched controls. The latter was investigated by comparing the dominant-to-nondominant difference in

midshaft humeral bone properties in fast-pitch softball players principally participating as pitcher (windmill thrower), catcher (overhand thrower) or fielder (overhand thrower).

Methods

Study design and participants

Two cohorts of female subjects were recruited—fast-pitch softball players (thrower group; $n=15$) and age-matched controls (control group; $n=15$). Throwers were included if they were: 1) currently competing or practicing in fast-pitch softball at least twice per week and 2) begun playing fast-pitch softball at least two years prior to their adolescent growth spurt. The latter criterion was used to ensure throwers were exposed to loading during critical periods of growth when the skeleton appears most responsive to mechanical loading/exercise (3, 12). Exclusion criteria for subjects in both the thrower and control groups were: 1) age < 16 yrs; 2) known metabolic bone disease; 3) administration of pharmacological agents known to influence skeletal metabolism; 4) participation more than twice per month for longer than six months in an athletic or vocational activity that primarily involves unilateral upper limb use [except fast-pitch softball in the throwing group], and; 5) previous history of a humeral fracture or stress fracture. The study was approved by the Institutional Review Board of Indiana University-Purdue University Indianapolis and all subjects provided written informed consent prior to participation.

Questionnaires

Both activity groups completed general health, activity and estimated calcium intake questionnaires, while the thrower group also completed a throwing questionnaire. The questionnaires were used to establish subject eligibility, obtain demographic characteristics, and determine group comparability. Age at puberty was estimated from the age of menarche which has been shown to be concomitant with the peak in bone mineral content velocity (17), whereas arm dominance was determined as the arm one does or would throw a ball with.

Anthropometric measures

Anthropometric measures were taken to determine comparability between the thrower and control groups. Height and weight were measured using a wall-mounted digital stadiometer and electronic balance scale, respectively. Body mass index (BMI, kg/m^2) was derived as mass divided by the square of height. Humeral length was measured in triplicate using a sliding anthropometer as the distance between the lateral border of the acromion and the radiohumeral joint line.

Shoulder range of motion

Range of shoulder internal and external rotation were assessed using a standard plastic goniometer with 10 inch arms. The participant actively rotated their shoulder into full internal or external rotation from a start position of 90° shoulder abduction and range was measured in triplicate.

Shoulder muscle strength

Bilateral concentric shoulder external and internal rotation torques were assessed using a Biodex System 2 isokinetic dynamometer (Biodex Medical Systems Inc., Shirley, NY). Subjects were positioned in prone, and performed full range shoulder internal and external rotation at 180°/s from a starting position of 90° shoulder abduction, 90° elbow flexion and neutral forearm pronation/supination. Ten warm-up and 10 test repetitions were performed

with a 60 s rest period between sets. The five peak torque (Nm) values in each rotation direction during test repetitions were averaged and normalized for body mass (Nm/kg).

Dual-energy x-ray absorptiometry

Body composition was assessed via dual-energy X-ray absorptiometry (DXA) using a Hologic Discovery-W machine (Hologic, Inc., Waltham, MA, USA) equipped with Hologic Apex v2.3 software. The manufacturer's standard positioning, scan and analysis protocols were implemented to acquire measures of whole body areal bone mineral density (aBMD, g/cm²), bone mineral content (BMC), lean mass (kg) and percent fat mass (%). Sub-regional analyses were performed to obtain dominant and nondominant whole arm lean mass, with the glenohumeral joint being the landmark for the division of the upper extremity from the trunk.

Peripheral quantitative computed tomography

Peripheral quantitative computed tomography (pQCT) of the midshaft humerus was performed bilaterally using a Stratec XCT 2000 machine (Stratec Medizintechnik GmbH, Pforzheim, Germany) equipped with Stratec software version 6.20C. Subjects were positioned in supine with their shoulder positioned in 90° abduction and upper arm centred within the gantry of the pQCT machine. A scout scan was performed to visualize the radiohumeral joint and a reference line was placed through the joint at the distal edge of the humeral capitulum. A tomographic slice (thickness=2.3 mm; voxel size=600 µm; scan speed=12 mm/s) was taken at 50% of humeral length (midshaft) from this reference line, with humeral length being assessed earlier using a sliding anthropometer.

Analysis of tomographic slices was restricted to cortical bone parameters as trabecular bone is not present at the midshaft humeral site. Cortical specific analyses were achieved by analysing the slices using cortical mode 1 with the threshold set to 710 mg/cm³. In addition, the tomographic slice was assessed for tissue composition by filtering the image using a 7×7 kernel filter to remove noise, and analysing using contour mode 3 (threshold=-101 mg/cm³) to locate the skin surface and peel mode 2 (threshold=40 mg/cm³) to locate the subcutaneous fat-muscle boundary.

Outcomes recorded included cortical volumetric BMD (Ct.vBMD, mg/cm³), cortical BMC (Ct.BMC, mg/mm) and bone structure. Bone structure measures included total bone area (Tt.Ar, mm²), cortical area (Ct.Ar, mm²), average cortical thickness (Ct.Th, mm), and periosteal (Ps.Pm, mm) and endosteal (Es.Pm, mm) perimeters. Bone strength was subsequently estimated according to Gere and Timoshenko (8) by the derivation of the minimum (I_{MIN} , cm⁴) and maximum (I_{MAX} , cm⁴) second moments of area, and polar moment of inertia (I_p , cm⁴). I_{MIN} and I_{MAX} represent the distribution of bone material about the planes of least and most bending resistance, respectively. They estimate the ability of the bone structure to resist bending in orthogonal planes. I_p is the sum of I_{MIN} and I_{MAX} , and estimates the ability of the bone structure to resist torsion. In addition, the ratio of I_{MAX} to I_{MIN} was derived to provide an indication of diaphyseal shape, with a I_{MAX}/I_{MIN} ratio closer to one representing a more circular bone cross-section. Finally, upper arm lean cross-sectional area (CSA, cm²) was derived by subtracting bone and marrow area from the area within the subcutaneous fat-muscle boundary.

Statistical analyses

Analyses were performed using PASW Statistics software (Version 17.0.2; SPSS Inc., Chicago, IL, USA), and comparisons were two-tailed with a level of significance set at 0.05. Demographic and anthropometric characteristics between activity groups (throwers vs. controls) were determined using independent samples t-tests. Dominance effects (dominant

vs. nondominant) on upper extremity lean measures, shoulder range of motion and strength, and midshaft humeral properties were assessed within each activity group (throwers and controls) by calculating mean percent differences ($[(\text{dominant} - \text{nondominant}) / \text{nondominant} \times 100\%]$) and their 95% confidence intervals (CI). 95% CI not crossing 0% were considered statistically significant, as determined by single sample t-tests on the mean percent differences with a population mean of 0%. Throwing effects were determined by comparing the percent difference values between activity groups (throwers vs. controls) using independent sample t-tests.

To investigate the influence of throwing mechanics on dominant-to-nondominant differences, participants in the thrower group were trichotomized into pitchers (windmill throwers), catchers (overhand throwers) and fielders (overhand throwers). Individuals were designated as a pitcher or catcher if they reported playing these positions at anytime (no pitcher reported playing as catcher or vice versa). Fielders were individuals who never reported playing as catcher or pitcher. One-way ANOVAs followed by Fisher's protected least significant difference for pairwise comparisons were used to explore differences according to playing position on demographic and anthropometric characteristics, and dominant-to-nondominant differences in upper extremity lean measures, shoulder range of motion and strength, and midshaft humeral properties. Years throwing was used as a covariate in ANOVA analyses and values corrected for this variable reported as years throwing was the strongest independent predictor of dominant-to-nondominant difference in midshaft humerus bone properties in our previous study in male throwing athletes (36).

Results

Participant characteristics, and effect of throwing on upper extremity lean measures, and shoulder range of motion and strength

There were no differences between the thrower and control groups for all demographic and whole body anthropometric characteristics (all $p = 0.07$ - 0.80 ; Table 1). The dominant upper extremity had greater lean measures and shoulder muscle strength than the nondominant upper extremity irrespective of activity group (all $p < 0.05$, Table 2). The dominant upper extremity in throwers also had greater range of shoulder external rotation and reduced range of shoulder internal rotation relative to their nondominant upper extremity (all $p < 0.001$, Table 2). There were significant effects of activity on dominant-to-nondominant differences, with throwers having greater dominant-to-nondominant differences in whole arm lean mass, range of shoulder external rotation and strength of the shoulder internal rotators, and reduced dominant-to-nondominant differences in range of shoulder internal rotation than controls (all $p < 0.05$ Fig. 1A).

Magnitude of bone adaptation within the midshaft humerus

Representative images of the midshaft humerus in the non-dominant and dominant upper extremities of individuals in the control and thrower groups are shown in Fig. 1B. There were no dominant-to-nondominant differences in properties of the midshaft humerus in the control group (all $p = 0.06$ - 0.45 ; Table 3). The dominant upper extremity in throwers had greater midshaft humerus BMC, Tt.Ar, Ct.Ar, Ct.Th, Ps.Pm, I_{MIN} , I_{MAX} , and I_{P} , and lower Ct.vBMD and Es.Pm than in the nondominant upper extremity (all $p < 0.05$; Table 3).

There was no dominant-to-nondominant difference in midshaft humerus bone density with Ct.vBMD not differing between throwers and controls ($p = 0.06$; Fig. 1C). However, throwers had greater dominant-to-nondominant difference in midshaft humerus bone mass, structure and estimated strength relative to controls (Fig. 1C). Throwers had 14.7% (95% CI, 10.4-18.9%) greater difference in dominant-to-nondominant midshaft humerus Ct.BMC than

controls ($p < 0.001$; Fig. 1C). The enhanced bone mass in the absence of enhanced volumetric bone density resulted in throwers having greater dominant-to-nondominant difference in midshaft humerus bone structure relative to controls. Throwers had 15.9% (95% CI, 11.3-20.4%) and 18.1% (95% CI, 13.7-22.5%) greater dominant-to-nondominant difference in Ct.Ar and Ct.Th at the midshaft humerus compared to controls, respectively (all $p < 0.001$; Fig. 1C). These changes resulted from combined periosteal expansion and endosteal contraction. This was evident by throwers having 3.2% (95% CI, 0.9-5.5%) greater dominant-to-nondominant difference in midshaft humerus Ps.Pm and 6.2% (95% CI, 1.7-10.6%) smaller dominant-to-nondominant difference in midshaft humerus Es.Pm (all $p < 0.01$; Fig. 1C).

The superior bone mass and structure at the midshaft humerus within the dominant upper extremity of throwers endowed this site with enhanced estimated strength (based on analyses of moment of inertia). Throwers had 17.5% (95% CI, 10.1-24.9%) and 18.4% (95% CI, 10.4-26.4%) greater dominant-to-nondominant difference in I_{MIN} and I_{MAX} at the midshaft humerus, respectively ($p < 0.001$; Fig. 1C). These equivalent increases in estimated strength in orthogonal bending planes contributed to throwers having 18.2% (95% CI, 11.7-24.7%) greater dominant-to-nondominant difference in midshaft humerus I_p compared to controls ($p < 0.001$; Fig. 1C). There was no difference between throwers and controls for circularity of the midshaft humeral shape with the I_{MAX}/I_{MIN} ratio in the dominant upper extremity of both groups being equivalent (throwers = 1.62 ± 0.21 vs. 1.65 ± 0.22 [following correction to nondominant upper extremity values]; $p = 0.60$). There were no bivariate correlations between percent difference in dominant-to-nondominant midshaft humerus estimated strength and percent difference in dominant-to-nondominant upper extremity lean measures, and shoulder range of motion and strength (all $p > 0.05$, analyses not shown).

Influence of throwing mechanics on the magnitude of midshaft humerus adaptation

Pitchers and catchers reported playing these positions 83% (range, 50%-100%) and 87% (range, 60%-100%) of the time, respectively. The remainder of time was spent as a fielder, with no pitcher playing as a catcher or vice versa. Fielders reported playing this position 100% of the time. There were no differences between playing positions in terms of demographic or whole body anthropometric characteristics (all $p = 0.18$ -0.97); however, both catchers and pitchers had greater dominant-to-nondominant differences in whole arm lean mass than fielders (all $p < 0.05$) (Table 4).

There was no influence of playing position on dominant-to-nondominant difference in midshaft humerus bone density with Ct.vBMD being equivalent between pitchers, catchers and fielders ($p = 0.55$). However, catchers and fielders had more than double dominant-to-nondominant difference in bone mass (Ct.BMC), structure (Tt.Ar, Ct.Ar) and estimated strength (I_{MIN} , I_{MAX} , I_p) of the midshaft humerus compared to pitchers (all $p < 0.05$; Fig. 2). There was no effect of playing position on circularity of the midshaft humeral shape with the I_{MAX}/I_{MIN} ratio in the dominant upper extremity of being equivalent between playing positions ($p = 0.75$).

Discussion

This cross-sectional cohort study confirms throwing athletes exhibit substantial skeletal adaptation at the midshaft humerus within their dominant upper extremity, and furthers the body of knowledge by demonstrating that such adaptation also occurs in female throwing athletes and may be influenced by throwing mechanics. Female fast-pitch softball players were found to have increased bone mass, size and estimated strength at the midshaft humerus in their dominant upper extremity relative to nondominant upper extremity, with the dominant-to-nondominant differences observed in throwers being larger than those

observed in a cohort of controls. In addition, it was found that playing position influenced the magnitude of skeletal adaptation with individuals primarily playing as catcher or fielder having greater dominant-to-nondominant differences at the midshaft humerus relative to pitchers. This later finding suggests throwing mechanics influences midshaft humeral adaptation as individuals playing as catcher or fielder predominantly throw with a conventional overhand motion, whereas those who play as pitcher use an underarm windmill motion.

The pattern of skeletal adaptation observed in female throwing athletes in the current study is consistent with that observed in male throwing athletes (19, 28, 35, 36) and with an improved ability of the midshaft humerus to resist torsional forces. They are also consistent with studies in racquet sport players (3, 9, 14) where adaptation of humeral mechanical properties has been modelled to occur in response to applied torsional loads (30). Throwers exhibited increased bone mass within the midshaft humerus of their dominant upper extremity. The extra bone was deposited on the periosteal and endosteal surfaces, as opposed to intra-cortically. This was evident by combined periosteal expansion and endosteal contraction at the midshaft humerus, with no change in bone density. The net result of the surface-specific deposition of additional bone was an 18% thicker cortex at the midshaft humerus in the dominant upper extremity of throwers relative to their nondominant upper extremity and relative to dominant-to-nondominant differences observed in controls. The combination of mass and structural changes resulted in throwers having 17-18% greater dominant-to-nondominant differences in midshaft humeral I_{MIN} and I_{MAX} than controls. These equivalent increases in estimated strength in orthogonal bending planes suggest throwing exposes the midshaft humerus to torsion. Supporting this hypothesis, throwers had 18% greater difference in dominant-to-nondominant midshaft humeral I_p compared to controls. However, as there were no differences between throwers and controls in the ratio of I_{MAX} to I_{MIN} at the midshaft humerus, the dominant upper extremity of throwers did not have a more circular cross-section at this skeletal site which would confirm optimization to resist torsional forces (6).

The pattern of adaptation in the midshaft humerus of fast-pitch softball players was consistent with that observed in male baseball players; however, the magnitude of adaptation in the former appears less. For instance, female fast-pitch softball players who reported primarily playing as catcher exhibited 42% less dominant-to-nondominant difference in I_p at the midshaft humerus relative to that previously reported in male baseball players playing the same position (mean $\pm$ SD = $27.1 \pm 7.6\%$ vs. $46.7 \pm 6.4\%$, respectively) (36). As female fast-pitch softball and male baseball players who play as catcher throw with relatively the same mechanics (overhand throwing), exhibit great dominant-to-nondominant differences at the midshaft humerus within their respective genders, and played for approximately the same number of years (mean $\pm$ SD = 13.2 ± 3.3 years vs. 15.6 ± 3.2 years, respectively) (36), other mechanisms are required to explain the apparent difference between genders in terms of the magnitude of throwing-induced skeletal adaptation. Potential contributors include: 1) throwing speed and distance which may influence engendered bone strain magnitudes and rates; 2) differing levels and influences of sex hormones, and; 3) frequency of throwing sessions and number of throwing repetitions within each throwing session. These factors require further investigation as they could not be adequately assessed using our retrospective study design, and because animal studies indicate that mechanically-induced bone adaptation is enhanced at higher strain magnitudes and rates (18, 25, 31, 32), potentially in males (11), and with an increase in the number of bone loading bouts and loading cycles per bout (7, 21, 33).

An interesting observation in the current study was the difference in the magnitude of adaptation of the midshaft humerus according to playing position. Fast-pitch softball players

who played as a catcher or fielder had more than double dominant-to-nondominant difference in midshaft humerus properties compared to those who played as pitcher. This observation contrasts data in male baseball players where pitchers demonstrated the greatest dominant-to-nondominant differences (36). The hypothesized explanation for the contrasting observations is that throwing mechanics influences midshaft humeral adaptation. Pitchers in fast-pitch softball throw with an underarm windmill motion, as opposed to the conventional overhand action utilized by catchers and fielders, and male baseball pitchers. Although pitchers in fast-pitch softball do throw overhand (for instance, when throwing to first base), they focus most of their time perfecting underarm windmill throwing and throw overhand with less frequency relative to fielders and catchers.

The biomechanics of windmill softball pitching remains scantily investigated relative to overhand throwing, and some investigators have reported commonalities between the two forms of throwing in terms of kinetics and relative risk for injuries of the pitching arm (1, 15, 24, 39, 40). However, there are obvious kinematic differences between windmill and overhand throwing which likely influence where internal loads are placed and resultant tissue adaptation. During fast-pitch softball pitching, hand and ball velocity are generated by rapid circumduction of the upper extremity about the shoulder with the arm close to the body in the frontal plane and elbow remaining relatively straight (39). These kinematics rotate the upper extremity about the glenohumeral joint through an axis that is relatively perpendicular to the humeral diaphysis. With the elbow maintained relatively straight, the net result is that the hand and ball move through a large arc without placing substantial torsional forces on the humerus. In contrast, in overhand throwing the shoulder is abducted away from the body such that the upper extremity is rotated about the glenohumeral joint through an axis that is relatively parallel to the humeral diaphysis. With the elbow flexed, these kinematics contribute to the generation of opposing rotatory forces on the proximal and distal ends of the humerus resulting in the generation of substantial torque within the bone. As skeletal adaptation to mechanical loads is highly site-specific and occurs where mechanical demands are greatest (10, 34), these kinematic differences theoretically explain the differing midshaft humeral adaptation observed between fast-pitch softball players who principally throw with windmill and overhand mechanics.

The observation that mechanics influences the extent of throwing-induced adaptation within the midshaft humerus may have implications in terms of skeletal injury risk. The greater adaptation within the midshaft humerus of overhand throwers suggests that this skeletal site is relatively overloaded in comparison to in windmill throwers. The consequence is that the midshaft humerus maybe at greater risk of mechanical failure in overhand throwers. Supporting this, there are numerous reports of midshaft humeral stress and complete fractures in overhand throwers (4, 5, 20, 29), yet no reports of such injuries at this site in windmill throwers. However, fast-pitch softball pitchers may be at heightened risk of a midshaft humeral stress fracture if they play most of their career as a pitcher before changing to an alternative position. This results from the incomplete adaptation of their midshaft humerus to forces associated with overhand throwing, with bone adaptation in response to mechanical loading enhancing skeletal fatigue resistance (37).

Strengths of the current study include its assessment of the skeletal effects of throwing within-subject by using the nondominant upper extremity as an internal control and the comparison of dominant-to-nondominant differences in throwers to those measured in matched controls. The investigation of throwing effects within-subject partially protected the cross-sectional nature of this study against the impact of potential systemic factors on midshaft humeral bone properties which may explain skeletal differences if a between-subjects study design was implemented. In terms of comparing dominant-to-nondominant differences in throwers to those measured in matched controls, this enabled the skeletal

effects of throwing to be isolated from the influence of side-to-side differences in habitual loading associated with arm dominance.

Although the current study possessed a number of strengths, it also had limitations. The use of a within-subject study design does not control for the impact of systemic factors on the magnitude of skeletal adaptation induced by throwing. This area requires further investigation as systemic factors influence mechanosensitivity (2, 22, 23, 38). Further limitations include the relatively small sample size, particularly for the investigation of the influence of throwing mechanics on skeletal adaptation, and the restriction of assessments to the midshaft humerus. Small sample sizes elevate the risk of committing a type-II statistical error; however, the effect sizes for throwing and throwing mechanics in the current study were of sufficient magnitude to detect group differences despite the small number of subjects. The inclusion of additional subjects may strengthen analyses, but we do not believe their addition would have impacted overall findings. In terms of the restriction of assessments to the midshaft humerus, future studies need to consider bone adaptation at alternative sites. A previous study demonstrated throwing also potentially influences trabecular adaptation within the proximal humerus (19). Assessment of this site would be clinically relevant considering it is a site prone to osteoporotic fracture during aging.

In summary, this study demonstrates that female fast-pitch throwing athletes exhibit skeletal adaptation at the midshaft humerus within their dominant upper extremity, with the adaptation being in the form of enhanced bone mass, structure and estimated strength. Throwing mechanics appeared to influence the magnitude of skeletal adaptation, with individuals who primarily throw overhand having more than double dominant-to-nondominant difference in midshaft humeral bone properties than those who primarily throw underarm with a windmill motion. The latter finding indicates that the skeleton is loaded differently during different forms of throwing which may have implications for skeletal injury risk.

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FIGURE 1.

Effect of throwing on: A) upper extremity lean measures, and shoulder range of motion and strength, and; B) & C) midshaft humerus bone density, mass, structure and estimated strength. A) Throwing had no effect on upper arm lean CSA (cross-sectional area) or strength of the shoulder external rotators, but enhanced whole arm lean mass, range of shoulder external rotation and strength of the shoulder internal rotators, and reduced range of shoulder internal rotation. B) Peripheral quantitative computed tomography images of midshaft humerus structure in the nondominant and dominant upper extremities of representative individuals in the control and thrower groups. Note the larger bone with thicker cortex in the dominant upper extremity of the thrower. C) Throwing had no effect on

cortical volumetric bone mineral density (Ct.vBMD), but enhanced cortical bone mineral content (Ct.BMC), total bone area (Tt.Ar), cortical area (Ct.Ar), cortical thickness (Ct.Th), periosteal perimeter (Ps.Pm), minimum (I_{MIN}) and maximum (I_{MAX}) second moments of area, and polar moment of inertia (I_p). Throwing also reduced midshaft humerus endosteal perimeter (Es.Pm). Data in A) and C) represent the difference between throwers and controls for mean percent difference in dominant-to-nondominant upper extremity measures, with error bars indicating 95% confidence intervals. Confidence intervals greater than 0% indicate greater dominant-to-nondominant upper extremity differences in throwers, whereas those below 0% favor controls. Significance is indicated by: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$, as determined by single sample t-tests with a population mean of 0%.

FIGURE 2.

Effect of playing position within the thrower group on midshaft humerus properties. Catchers and fielders (overhand throwers) had greater percent difference in dominant-to-nondominant cortical bone mineral content (Ct.BMC), total (Tt.Ar) and cortical (Ct.Ar) bone areas, minimum (I_{MIN}) and maximum (I_{MAX}) second moments of area, and polar moment of inertia (I_P) than pitchers (windmill throwers). Catchers also had greater percent difference in dominant-to-nondominant cortical thickness (Ct.Th) and periosteal perimeter (Ps.Pm) compared to pitchers. There were no group differences in endosteal perimeter (Es.Pm). Data represent the mean percent difference between dominant and nondominant midshaft humeral measures, with error bars indicating 95% confidence intervals. Significance is indicated relative to pitchers by: * $p < 0.05$; ** $p < 0.01$, as determined by one-way ANOVA followed by Fisher's protected least significant difference for pairwise comparisons with years throwing as a covariate.

Table 1
Participant demographic and anthropometric characteristics

	Controls ^a	Throwers ^a	<i>p</i> ^b
Demography			
Age (yr)	22.5 ± 3.3	21.3 ± 1.5	NS
Age at puberty (yr)	12.6 ± 1.7	13.0 ± 1.4	NS
Calcium intake (mg/d)	1395 ± 794	1608 ± 699	NS
Starting age of throwing (yr)	—	8.9 ± 2.7	—
Years throwing (yr)	—	12.4 ± 2.6	—
Highest level of competition			
High school (<i>n</i>)	—	1	—
College (<i>n</i>)	—	14	—
Playing position ^c			
Pitcher (<i>n</i>)	—	4	—
Catcher (<i>n</i>)	—	3	—
Fielder (<i>n</i>)	—	8	—
Whole body anthropometry			
Height (m)	1.64 ± 0.07	1.65 ± 0.06	NS
Mass (kg)	65.6 ± 13.2	64.6 ± 7.9	NS
BMI (kg/m ²)	24.3 ± 4.4	23.7 ± 2.4	NS
BMC (kg)	2.39 ± 0.37	2.58 ± 0.16	NS
aBMD (g/cm ²)	1.23 ± 0.11	1.27 ± 0.04	NS
Lean mass (kg)	43.1 ± 6.3	44.8 ± 3.4	NS
Fat (%)	29.9 ± 6.8	26.2 ± 5.0	NS

^aData are mean ± SD (except for frequency data)

^bIndependent samples t-test

^cIndividuals were designated as a pitcher or catcher if they reported playing these positions at anytime (no pitcher reported playing as catcher or vice versa). Fielders were individuals who never reported playing as catcher or pitcher.

Table 2
Percent difference in dominant-to-nondominant upper extremity lean measures, and shoulder range of motion and muscle strength

	Controls			Throwers		
	Nondominant ^a	Dominant ^a	% difference (95% CI) ^b	Nondominant ^a	Dominant ^a	% difference (95% CI) ^b
Lean measures						
Whole arm lean mass (kg) ^c	1.98 ± 0.36	2.17 ± 0.43	9.6% (6.6, 12.7%) ***	2.16 ± 0.19	2.47 ± 0.23	14.5% (10.7, 18.4%) ***
Upper arm lean CSA (cm ²) ^d	28.7 ± 5.0	30.0 ± 5.3	3.6% (0.8, 6.3%) *	29.1 ± 2.6	31.5 ± 3.5	8.3% (3.8, 12.8%) **
Shoulder range of motion						
External rotation (°)	89.9 ± 12.9	92.7 ± 9.6	4.4% (-3.6, 12.4%)	95.5 ± 10.6	109.9 ± 12.1	15.5% (10.0, 21.1%) ***
Internal rotation (°)	58.0 ± 10.3	56.6 ± 13.5	-1.6% (-14.1, 11.0%)	71.3 ± 11.9	60.1 ± 10.2	-14.7% (-21.6, -7.9%) ***
Shoulder muscle strength						
External rotators (Nm/kg)	0.28 ± 0.08	0.29 ± 0.08	8.1% (0.1, 16.3%) *	0.30 ± 0.06	0.33 ± 0.06	8.5% (1.0, 15.9%) *
Internal rotators (Nm/kg)	0.37 ± 0.13	0.39 ± 0.13	7.6% (0.3, 15.0%) *	0.39 ± 0.07	0.47 ± 0.10	20.6% (21.1, 5.3%) **

^aData are mean ± SD

^bMean percent differences between dominant and nondominant were assessed using single sample t-tests with a population mean of 0.

* Significance is indicated by: $p < 0.05$,

** $p < 0.01$,

*** $p < 0.001$

^c Assessed using DXA

^d Assessed using pQCT

Table 3
Percent difference in dominant-to-nondominant upper extremity bone density, mass, structure and estimated strength

	Controls			Throwers		
	Nondominant ^d	Dominant ^d	% difference (95% CI) ^b	Nondominant ^d	Dominant ^d	% difference (95% CI) ^b
Density						
Ct.vBMD (mg/cm ³)	1136.5 ± 25.8	1132.6 ± 28.2	-0.3% (-1.0, 0.3%)	1143.7 ± 12.4	1129.1 ± 20.3	-1.3% (-2.0, -0.5%) **
Mass						
BMC (mg/mm)	211.6 ± 28.5	213.0 ± 26.0	0.9% (-1.6, 3.3%)	215.3 ± 17.0	248.0 ± 15.2	15.5% (11.9, 19.1%) ***
Structure						
Tt.Ar (cm ²)	2.29 ± 0.43	2.33 ± 0.38	2.3% (-0.1, 4.7%)	2.26 ± 0.26	2.49 ± 0.27	10.4% (8.4, 12.5%) ***
Ct.Ar (cm ²)	1.86 ± 0.25	1.88 ± 0.22	1.2% (-1.0, 3.4%)	1.88 ± 0.15	2.20 ± 0.14	17.1% (13.1, 21.1%) ***
Ct.Th (mm)	3.98 ± 0.54	3.92 ± 0.57	-1.6% (-4.1, 1.0%)	4.13 ± 0.27	4.81 ± 0.34	16.5% (12.8, 20.3%) ***
Ps.Pm (mm)	53.7 ± 5.0	54.3 ± 5.2	1.1% (-0.4, 2.7%)	53.3 ± 3.1	55.6 ± 3.7	4.4% (2.6, 6.1%) ***
Es.Pm (mm)	31.3 ± 6.6	32.0 ± 6.9	2.4% (-0.4, 5.2%)	29.0 ± 3.5	27.9 ± 3.9	-3.8% (-7.4, -0.1%) *
Strength						
I _{MIN} (cm ⁴)	0.40 ± 0.12	0.41 ± 0.11	2.7% (-2.0, 7.4%)	0.42 ± 0.07	0.51 ± 0.07	20.2% (14.2, 26.2%) ***
I _{MAX} (cm ⁴)	0.67 ± 0.20	0.70 ± 0.16	5.6% (-0.2, 11.4%)	0.63 ± 0.12	0.77 ± 0.15	24.0% (18.1, 29.9%) ***
I _P (cm ⁴)	1.07 ± 0.31	1.10 ± 0.26	4.4% (-0.1, 8.8%)	1.05 ± 0.18	1.28 ± 0.21	22.5% (17.5, 27.6%) ***

^aData are mean ± SD

^bMean percent differences between dominant and nondominant were assessed using single sample t-tests with a population mean of 0.

* Significance is indicated by: $p < 0.05$,

** $p < 0.01$,

*** $p < 0.001$

Table 4
Effect of playing position within the thrower group on demographic and anthropometric characteristics, and percent difference in dominant-to-nondominant upper extremity lean measures, and shoulder range of motion and muscle strength

	Pitchers ^a (n = 4)	Catchers ^a (n = 3)	Fielders ^a (n = 8)	p ^b
Demography				
Age (yr)	21.0 ± 0.7	22.5 ± 1.1	21.0 ± 1.7	NS
Age at puberty (yr)	12.8 ± 1.0	12.7 ± 0.6	13.3 ± 1.5	NS
Calcium intake (mg/d)	1524 ± 742	1729 ± 591	1628 ± 738	NS
Starting age of throwing (yr)	9.3 ± 3.5	10.3 ± 2.3	8.1 ± 2.5	NS
Years throwing (yr)	11.7 ± 3.8	12.2 ± 3.3	12.9 ± 1.6	NS
Whole body anthropometry ^c				
Height (m)	1.67 ± 0.03	1.65 ± 0.06	1.64 ± 0.07	NS
Mass (kg)	61.7 ± 3.4	66.7 ± 1.1	65.2 ± 7.9	NS
BMI (kg/m ²)	22.1 ± 1.6	24.6 ± 1.4	24.1 ± 2.7	NS
BMC (kg)	2.55 ± 0.15	2.61 ± 0.10	2.59 ± 0.19	NS
aBMD (g/cm ²)	1.26 ± 0.06	1.27 ± 0.03	1.28 ± 0.04	NS
Lean mass (kg)	44.8 ± 1.0	44.3 ± 2.6	44.9 ± 4.4	NS
Fat (%)	23.2 ± 3.0	29.8 ± 3.7	26.3 ± 5.6	NS
Lean measures ^d				
Whole arm lean mass (%)	21.8 ± 5.6 [†]	18.4 ± 6.6 [‡]	10.0 ± 5.8 ^{†,‡}	<0.01
Upper arm lean CSA (%)	11.2 ± 9.5	7.3 ± 5.6	7.3 ± 9.3	NS
Shoulder range of motion ^d				
External rotation (%)	3.8 ± 5.2	5.7 ± 10.1	22.0 ± 12.5	NS
Internal rotation (%)	-13.7 ± 17.0	-14.0 ± 9.0	-15.5 ± 13.2	NS
Shoulder muscle strength ^d				
External rotators (%)	4.4 ± 13.2	4.1 ± 23.2	11.7 ± 11.8	NS
Internal rotators (%)	14.4 ± 16.4	33.7 ± 20.9	19.0 ± 21.6	NS

^aData are mean ± SD

^bOne-way ANOVA

^cAge included as covariate in one-way ANOVA analysis. Age corrected values are presented

^dYears playing throwing included as covariate in one-way ANOVA. Values presented are mean percent differences between dominant and nondominant upper extremities and are corrected for years throwing

[†] or [‡] indicate p < 0.05 compared to group with corresponding symbol, as indicated by Fisher's protected least significant difference for pairwise comparisons