



## Original Article

## Pelvic region bone density, soft tissue mass, and injury frequency in female professional ballet dancers and soccer athletes

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## ABSTRACT

We recently observed a high prevalence of low pelvic bone mineral density (BMD) in female professional ballet performers. Because this population is susceptible to musculoskeletal overuse injuries, we aimed to determine which regions of the pelvis may be at greatest risk compared to general population females (GENPOP) as well as professional female soccer players (SOCCER, a comparison to other elite athletes regularly subjected to high degrees of loading). Three groups of age-matched females [(GENPOP;  $n = 38$ ,  $27 \pm 1$  yrs), (BALLET; single company,  $n = 36$ ,  $26 \pm 3$  yrs), (SOCCER; single NWSL® club,  $n = 34$ ,  $25 \pm 1$  yrs)] consented to have their BMD and body composition assessed (DEXA, GE®). In addition to soft tissue and total and regional BMD analyses, a segmental analysis of the pelvis was performed to determine site-specific BMD for the iliac fossa, iliac fossa/iliac crest/ilium combined, pubic bone, ischium, and sacrum. A mixed-model ANOVA followed by a Tukey's post-hoc test was used to compare the groups (Type-I error;  $\alpha = 0.05$ ). The BALLET group had lower pelvic BMD for all measures (Avg. % Diff. = 15%–27%,  $p < 0.001$ ) compared to the SOCCER group and for the ischium (Avg. % Diff. = 8%;  $p = 0.007$ ) and sacrum (Avg. % Diff. = 7%;  $p = 0.028$ ) compared to the GENPOP group. The BALLET group had lower lean mass for all measures compared to the other groups (Avg. % Diff. = 12%–18%;  $p < 0.01$ ). Professional ballet performers exhibit reduced pelvic region soft tissue and site-specific BMD not previously detected using standard DEXA analyses. These findings highlight which pelvic regions may benefit from preventative strength training and/or nutritional interventions.

## Introduction

In accordance with their training, professional ballet performers have been observed to undergo high volumes of physical activity starting in adolescence and into early adulthood often during times of skeletal development.<sup>1</sup> As previously reported in this population, inadequate nutritional intake and low body weight have been associated with late onset menarche, menstrual dysfunction, a corresponding risk of developing low bone mineral density (BMD), and an increased risk of musculoskeletal injuries.<sup>1–4</sup> Some have also reported a negative effect on bone metabolism.<sup>5–7</sup>

As dancing is also a weightbearing exercise, protective effects of

musculoskeletal loading have been reported in skeletal areas regularly impacted during training.<sup>8,9</sup> For example, in a recent study of elite professional ballet dancers who underwent total body BMD analysis using dual-energy-x-ray-absorptiometry (DEXA) by our group, it was observed that BMD was above average in the extremities, but below average in the pelvis and spine in female dancers relative to general population norms.<sup>1</sup> Interestingly, when follow-up scans were done on those with low pelvic BMD using the standard dual hip and femur scan often used in clinical settings (Fig. 1), none of the dancers identified as having low pelvic BMD met the accepted clinical criteria for osteopenia or osteoporosis (defined by either age matched z-scores or young adult t-scores of  $< -1$  or  $< -2.5$  respectively).<sup>1,10</sup> Importantly, the standard site-specific hip and femur

**Abbreviations:** 95%CI, 95% Confidence Interval; BALLET, Professional Female Ballet Performers; BMD, Bone Mineral Density (g/cm<sup>2</sup>); DEXA, Dual-Energy X-Ray Absorptiometry; ES, Effect Size (Cohen's *d* for continuous data, Phi statistic for frequency comparisons); Fossa, Iliac Fossa; GENPOP, General Population Females; ICC, Interclass Correlation Coefficient; IC-F-I, iliac crest, iliac fossa, ischium, combined; LMI, Lean Mass Index (Lean Mass, kg / height, m<sup>2</sup>); FMI, Fat Mass Index (Fat Mass, kg / height, m<sup>2</sup>); SOCCER, Professional Female Soccer Athletes (Major League Soccer, MLS®).

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# Example Dual Hip & Femur Scan

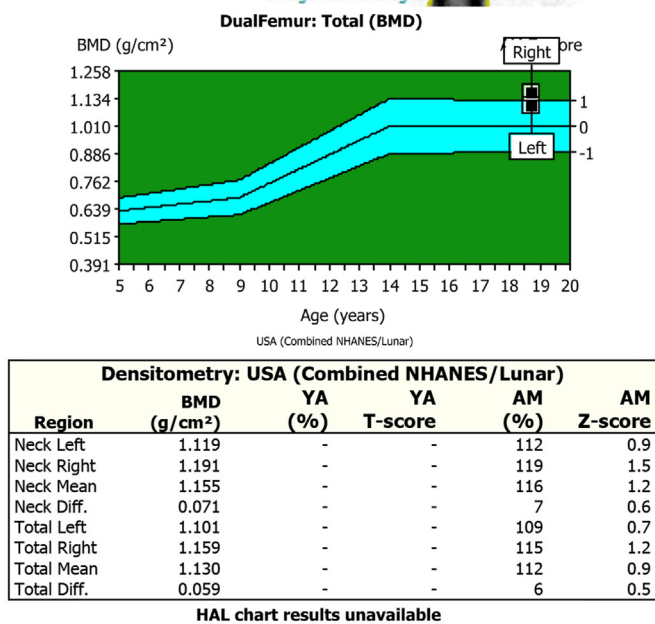
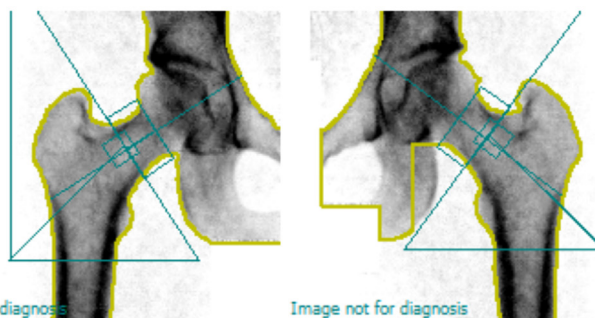


Fig. 1. Dual-hip and femur scan example (iDXA, GE®).

scan does not consider the entire pelvis and is limited to the femoral neck, trochanter, femoral head, and portions of the ischium. Therefore, the exact regions of the pelvis where BMD deficiencies were present was not determined.

Considering the normal BMD measures observed among the site-specific dual hip and femur scans, regardless of low overall pelvic BMD, we hypothesized that some areas of the pelvis which are under repetitive loads (landing, jumping), such as the femoral neck, may have preserved BMD while other areas of the pelvis not subjected to the same chronic loading may have reduced BMD and thus, partially explain low total pelvic BMD observed in the previous investigation.<sup>1</sup> While this may be a protective adaptation to commonly loaded portions of the hip joint, information on BMD deficiencies in other pelvic regions could identify potential areas of injury risk that may occur either during performance or during activities of daily living. In addition, while no pelvic regional soft tissue analysis was performed in the previous investigation, lower extremity fat and lean tissue mass was observed to be in the lowest ~4<sup>th</sup> and ~34<sup>th</sup> percentiles (respectively) relative to general population norms.<sup>1</sup> Therefore, it is possible that the combination of low regional BMD and reduced soft tissue mass in the pelvic region (particularly lean tissue) may result in elevated risk for musculoskeletal injuries to the hip joint, pelvic structures, and the lumbosacral spine (L5-S1). However, to our knowledge, no segmental analyses of the pelvic region have been previously reported in this population nor have any comparisons been made to age-matched general population females (commonly used in other BMD metrics to assess risk) or to other female professional athletes regularly subjected to high degrees of mechanical loading.

In light of our previous findings and a paucity of data in the literature, the purpose of this study was to characterize region-by-region pelvic

BMD and pelvic region soft tissue composition in professional female ballet dancers and compare those metrics with both age-matched active general population females and another highly athletic age-matched female cohort who also engage in an intensive physical training regimen (professional soccer players). Based on previous literature, we hypothesized that female ballet performers would exhibit reduced site-specific pelvic region BMD measures and soft-tissue mass compared to both the general and professional soccer populations. We also sought to compare pelvic region injury frequencies between the professional ballet and soccer athletes. Findings presented in the results to follow are clinically important for 1) highlighting the potential pitfalls of only utilizing standard total body DEXA scan metrics to assess BMD in high performance athletes, 2) identifying physiologic responses to reduced energy availability combined with high degrees of musculoskeletal activity/loading, and 3) providing clinicians, as well as strength and conditioning professionals, with potential areas to target with preventative activity or nutrition-based strategies.

## Materials and methods

### Subjects

All procedures performed in this investigation were reviewed and approved by the institutional review board for research involving human subjects at Houston Methodist Hospital (IRB# PRO00024667). All participants provided informed consent for the use of their data for research purposes prior to participating in the experimental procedures. In this retrospective analysis, 108 women who underwent body composition and bone densitometry analysis via dual-energy-x-ray-absorptiometry

scan (DEXA: iDXA, GE®, Boston, MA) between 2017 and 2019 in our laboratory were included in this study. Participants were selected in three age-matched groups: professional ballet dancers actively employed by a professional dance company (BALLET;  $n = 36$ ), professional soccer athletes actively employed by a National Women's Soccer League (NWLS®) organization in the United States (SOCCER;  $n = 34$ ), and recreationally active women within our database reporting to perform regular exercise training 3 or more days per week (GENPOP). For the general population group exclusion criteria were: body mass index (BMI) > 30 kg/m<sup>2</sup>, known cardiopulmonary disease, history of cancer within the past 2 years, diabetes, known endocrine disorders, known contra-indications to strenuous activity. Within our database, 38 women met criteria for inclusion for the GENPOP group.

**DEXA analysis**

All participants underwent a single total-body DEXA scan. All scans were analyzed using enCORE (GE®, v.18) analysis software. Within the scan, total body, trunk, pelvic region (gynoid), and leg regions were analyzed for measures of lean mass and fat mass using standardized procedures specified by the manufacturer. Standard total and regional (spine, pelvis, legs) BMD measures were also collected. Next, two trained laboratory technicians and a trained orthopedic surgeon independently (blinded) performed a customized site-specific bilateral BMD analysis of the pelvis from the total body scan image in the following regions (iliac fossa (fossa); iliac crest, iliac fossa, ischium (IC-F-I) combined; pubic bone; ischium, and sacrum (See Fig. 2 for illustrations of these regions). The interclass correlation coefficient for triplicate measurements was high (ICC; > 0.9) for all measures indicating agreement between reviewers.<sup>11</sup> Anatomical locations were selected by our collaborating physician team based on predominant boney structures of the pelvis that could be easily identified and accurately traced on the two-dimensional DEXA image. Within the analysis software, each region was manually traced (bilaterally) using the software's custom "region of interest" (ROI) feature. Following this, bilateral measures were averaged. Customized segmented analysis performed in this fashion has been previously observed to have a high rate of repeatability with measurement error between < 1% and 6%.<sup>12</sup>

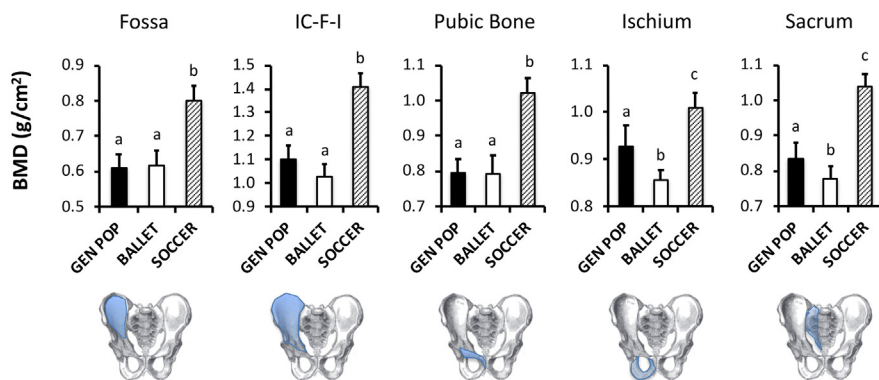
**Injury history**

Within the same year of DEXA measurement, medical history of soft tissue and bone injuries of the pelvis, hip joint, lumbosacral spine, and sacrum were obtained from patient records for the BALLET and SOCCER groups with permission from the athletes and their respective participating professional organizations. Injuries were classified as follows: Level 3 – Musculoskeletal Complaint with Full Participation (athlete sought medical treatment from a licensed physician but was fully able to participate in activities); Level 2 – Musculoskeletal Complaint with Modified Participation (anatomic tissue-level impairment as diagnosed by a licensed physician resulting in activity modification but no time loss); Level 1 – Injury (anatomic tissue-level impairment as diagnosed by a licensed physician that resulted in full time loss from activity for one or more days). Injury data were recorded as total (total number of injuries), soft tissue (muscle, ligament, tendon injuries) and bone injuries within the pelvic region. The total number of injuries (total) as well as how many unique individual athletes experienced at least one injury was also recorded. Of note, we were unable to obtain similar records for the GENPOP group as those in our physician team were not primary orthopedic physicians for participants in that group. Therefore, injury history comparisons were only able to be made between the SOCCER and BALLET groups.

**Statistical analysis**

All statistical analyses were completed using SPSS Statistics (Version 26, IBM Statistics, Armonk, NY). Comparison of the three groups for demographics, regional pelvic BMD, as well as pelvic lean and fat mass was performed using a mixed-model analysis of variance. Significant interactions indicated by Type III tests of fixed effects were followed by a Tukey's post hoc test for pairwise comparisons. Comparison of injury frequencies between the BALLET and SOCCER groups was performed using a Fischer's exact test. Type-I error was set at  $\alpha=0.05$  for all statistical analyses. For statistically significant pairwise differences between groups for demographics, regional BMD, injury frequencies, site-specific pelvic BMD measures, and soft tissue distribution ( $p < 0.05$ ), effect size (ES) was calculated using either a Cohen's  $d$  statistic ( $[\text{Mean1} - \text{Mean2}] / \text{Pooled SD}$ ) (continuous data) or a Phi statistic (frequency comparisons) whereby effect sizes were interpreted as follows: < 0.1, negligible (N);

**REGIONAL PELVIC BMD**



**Fig. 2.** Regional Pelvic BMD. Data are presented as means±95%CI for regional pelvic bone mineral density (BMD, g/cm<sup>2</sup>) analysis at the following sites: Iliac fossa (fossa); combined - Iliac crest, iliac fossa, and ilium (IC-F-I); Pubic bone; Ischium; Sacrum. Like letters = not significantly different between groups ( $p < 0.05$ ).  $p$ -values (Sig.) are provided below each figure for pairwise comparisons in addition to effect sizes (ES) reported as Cohen's  $d$  statistics for all significant comparisons interpreted as: < 0.1, negligible effect size (N); 0.1-0.3, small effect size (S); 0.5-0.7, large effect size (L); and > 0.7, very large effect size (VL).

Comparison	Fossa		IC-F-I		Pubic Bone		Ischium		Sacrum	
	Sig.	ES	Sig.	ES	Sig.	ES	Sig.	ES	Sig.	ES
GEN POP vs BALLET	0.777	NS	0.062	NS	0.951	NS	0.007	0.6(L)	0.028	0.4(M)
GEN POP vs SOCCER	<0.001	1.5(VL)	<0.001	1.7(VL)	<0.001	1.8(VL)	0.008	0.6(L)	<0.001	1.5(VL)
BALLET vs SOCCER	<0.001	1.4(VL)	<0.001	2.2(VL)	<0.001	1.6(VL)	<0.001	1.8(VL)	<0.001	2.3(VL)

0.1-0.3, small (S); 0.5-0.7, large (L); and > 0.7, very large (VL).<sup>13</sup>

**Results**

*Demographics*

Demographics for each group are presented in Table 1. For the professional athlete groups, contracted practice and performance hours as well as regional injury history frequencies are also listed. Results for all primary analyses are presented as means ± 95%CI along with p-values (sig.) and effect sizes (ES). Significant differences were observed between groups for height, weight, BMI, and %Fat (p < 0.05).

For total body BMD measures, differences were observed between all groups for the total, spine, and whole pelvis measures (p<0.01) with the following group order from lowest to highest BMD values: BALLE, GENPOP, SOCCER. For legs BMD, the SOCCER group was observed to have the highest BMD compared to the BALLE and GENPOP groups (p<0.001). No difference was observed between the BALLE and GENPOP group for legs BMD.

**Table 1**  
Demographics.

DEMOGRAPHICS	MEAN ±95%CI			PAIRWISE COMPARISONS (Sig./Effect Size)		
	GEN POP (n=38)	BALLE (n=36)	SOCCER (n=34)	GEN POP vs. BALLE	GEN POP vs. SOCCER	BALLE vs. SOCCER
Age (yrs)	27 ± 1	26 ± 3	25 ± 1	ns	ns	ns
Height (cm)	168.4 ± 2.8	164.7 ± 1.4	167.1 ± 1.9	p<0.05   ES=0.5(M)	ns	p<0.05   ES=0.4(M)
Weight (kg)	68.8 ± 4.2	51.5 ± 1.5	62.6 ± 1.9	p<0.001   ES=1.9(VL)	p<0.05   ES=0.6(L)	p<0.001   ES=2.0(VL)
BMI (kg/m <sup>2</sup> )	24.1 ± 1.0	19.0 ± 0.4	22.4 ± 0.5	p<0.001   ES=2.2(VL)	p<0.01   ES=0.7(VL)	p<0.001   ES=2.5(VL)
%Fat	29.5 ± 2.0	20.6 ± 1.4	22.2 ± 1.3	p<0.001   ES=1.7(VL)	p<0.001   ES=1.4(VL)	ns
Total Body BMD (g/cm <sup>2</sup> )	1.22 ± 0.03	1.15 ± 0.02	1.38 ± 0.03	p<0.001   ES=0.9(VL)	p<0.001   ES=1.8(VL)	p<0.001   ES=3.0(VL)
Spine BMD (g/cm <sup>2</sup> )	1.12 ± 0.04	1.03 ± 0.04	1.25 ± 0.04	p<0.01   ES=0.8(VL)	p<0.001   ES=1.1(VL)	p<0.001   ES=1.8(VL)
Pelvis BMD (g/cm <sup>2</sup> )	1.14 ± 0.04	1.05 ± 0.03	1.35 ± 0.04	p<0.001   ES=0.8(VL)	p<0.001   ES=1.8(VL)	p<0.001   ES=2.8(VL)
Legs BMD (g/cm <sup>2</sup> )	1.24 ± 0.04	1.19 ± 0.03	1.45 ± 0.03	ns	p<0.001   ES=1.9(VL)	p<0.001   ES=2.9 (VL)
<b>PELVIC REGION INJURIES</b>		<b>BALLE</b>	<b>SOCCER</b>	<b>BALLE vs. SOCCER</b>		
<i>Pelvic Region Injuries</i>						
Total (n)		26	1			
Unique Athletes (n)		13	1			
%Athletes in Group		36%	3%	p<0.001   ES=0.4(M)		
Level 1 (n)		1	0			
Level 2 (n)		4	0			
Level 3 (n)		21	1			
<i>Soft Tissue Injuries</i>						
Total (n)		21	1			
Unique Athletes (n)		12	1			
%Athletes in Group		33%	3%	p<0.001   ES=0.4(M)		
Level 1 (n)		0	0			
Level 2 (n)		2	0			
Level 3 (n)		19	1			
<i>Bone Injuries</i>						
Total (n)		5	0			
Unique Athletes (n)		3	0			
%Athletes in Group		8%	0%	ns		
Level 1 (n)		1	0			
Level 2 (n)		2	0			
Level 3 (n)		2	0			
<b>ACTIVITY</b>						
GEN POP	Moderate to vigorous physical activity >30 min on 3 or more days/week for recreational fitness training					
BALLE	Contracted for performance or rehearsal: 6 h/day; 5-6 days/week; 43 weeks/year; ~1290-1548 h/year					
SOCCER	Contracted for practice or performance: 2.5 h/day; 5-6 days/week; 30 weeks/year; ~375-450 h/year					

Values are presented as means ± 95%CI for age (years), height (centimeters, cm), weight (kilograms, kg), body mass index (BMI, kg/m<sup>2</sup>), and %body fat (%fat) and bone mineral density (BMD, g/cm<sup>2</sup>; Total Body, Spine, Pelvis, Legs). Data are also presented for pelvic region injury frequencies (and counts by level of injury) for the BALLE and SOCCER groups (all injuries, soft tissue injuries, and bone injuries). Injury level defined as: Level 3 – Musculoskeletal Complaint with Full Participation (athlete sought medical treatment from a licensed physician but was fully able to participate in activities); Level 2 – Musculoskeletal Complaint with Modified Participation (anatomic tissue-level impairment as diagnosed by a licensed physician resulting in activity modification but no time loss); Level 1 – Injury (anatomic tissue-level impairment as diagnosed by a licensed physician that resulted in full time loss from activity for one or more days). Injury data are expressed as total, soft tissue (muscle, ligament, tendon) and bone injuries within the pelvic region. Injury data are also tabulated as the total number of injuries (total) as well as how many unique individual athletes experienced at least one injury. Results of pairwise post-hoc comparisons are shown on the right. Type I Error set at α=0.05 for all comparisons. For significant pairwise comparisons, effect sizes (ES) are interpreted as follows: < 0.1, negligible (N); 0.1-0.3, small (S); 0.5-0.7, large (L); and > 0.7, very large (VL).

*Injury history*

Injury history data are also presented in Table 1. For comparison in pelvic region injury frequencies between the BALLE and SOCCER groups, percentage of athletes experiencing injuries within the same year of DEXA analysis was significantly higher in the BALLE group compared to the SOCCER group (p < 0.001). A similar finding was observed between groups (p < 0.001) for just the soft-tissue injuries which occurred more frequently (on average) than bone injuries. Soft tissue injuries for the BALLE group consisted of 29% abductor/adductor injuries, 25% groin, 26% impingement or tendinitis injuries, and 20% low back injuries (lumbar/lumbosacral region). Although not observed to be statistically different (p = 0.054), 5 bone injuries were experienced in the BALLE group (all to the lumbosacral spine & sacrum) compared to none in the SOCCER group.

*Site-specific pelvic BMD measures*

Bilateral regional pelvic measures of BMD are presented in Fig. 2

averaged across the left and right sides. A significant interaction of group was observed for all regional BMD analyses ( $p < 0.05$ ). Compared to the GENPOP group, the BALLETT group was observed to have significantly lower BMD in the ischium (Avg. %Diff. = 8%;  $p = 0.007$ ) and sacrum (Avg. %Diff. = 7%;  $p = 0.028$ ) regions. While not significant, a trend was observed for the BALLETT group to also have lower BMD than the GENPOP group in the IC-F-I regional measure (Avg. %Diff. = 7%;  $p = 0.062$ ). Compared to the SOCCER group, the BALLETT group was observed to have significantly lower pelvic region BMD for all measures (Avg. %Diff. = 15%-27%,  $p < 0.001$ ). Although not to the same magnitude of difference, this was also the case for the GENPOP group compared to the SOCCER group (Avg. %Diff. = 8%-24%,  $p < 0.01$ ).

**Soft tissue analysis**

Data for soft tissue analyses are presented in Fig. 3 with all measures presented relative to height: Lean Mass Index (LMI) = lean mass (kg)/Height ( $m^2$ ); Fat Mass Index (FMI) = fat mass (kg)/Height ( $m^2$ ). A significant interaction of group was observed for all soft tissue analyses ( $p < 0.05$ ). Compared to both the SOCCER and GENPOP groups, the BALLETT group had significantly lower lean mass for all measures (Avg. %Diff. = 12%-18%;  $p < 0.01$ ; Fig. 3A). Compared to the GEN POP group, the BALLETT and SOCCER groups had significantly lower fat mass for all measures (Avg. %Diff. = 34%-54%;  $p < 0.001$ ; Fig. 3B). Compared to the

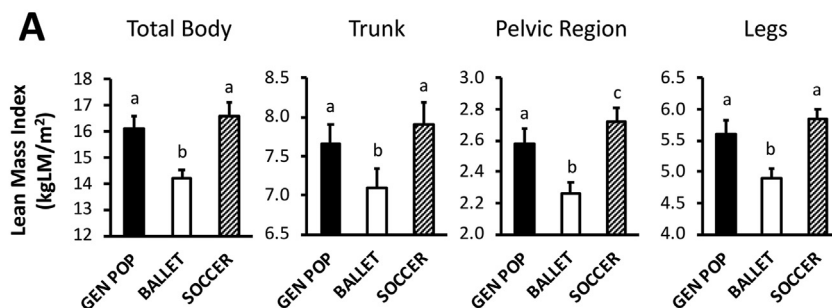
SOCCER group, the BALLETT group had significantly lower fat mass in the total body (Avg. %Diff. = 23%;  $p < 0.001$ ), trunk (Avg. %Diff. = 24%;  $p < 0.001$ ), pelvic region (Avg. %Diff. = 23%;  $p < 0.001$ ), and legs (Avg. %Diff. = 24%;  $p < 0.001$ ) measures (Fig. 3B).

**Discussion**

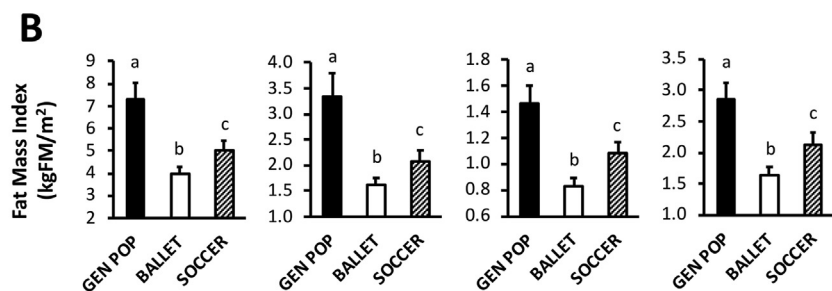
Using customized bilateral site-specific DEXA analysis of the pelvis, we observed overall lower BMD in the pelvic area among professional ballet dancers compared to age-matched general population women (whole pelvis, ischium and sacrum) and professional female soccer players (all measures) (Fig. 2). Overall, these findings were observed in tandem with lower lean and fat tissue (total, trunk, pelvis, and legs) relative to both the GEN POP and SOCCER groups. In this unique population of performers where musculoskeletal injuries are common, identifying potentially high-risk areas of the pelvis region for injury may help to develop nutritional or training-based interventional strategies to mitigate bone and soft tissue injury risk, either now or later in life. As standard of care based dual-hip and femur DEXA scans did not detect osteopenia or osteoporosis in professional ballet dancers from the same company in our previous investigation,<sup>1</sup> the findings from our segmented analysis of the pelvis highlight the potential need for examining the pelvis outside of only the loading regions in populations with unique physiologic demands. For example, given that all of the bone injuries

**REGIONAL SOFT TISSUE DISTRIBUTION**

**Fig. 3.** Regional Soft Tissue Distribution. Data are presented as means±95%CI for regional (A) lean and (B) fat tissue distribution expressed as lean mass index (lean mass, kg/height,  $m^2$ ) and fat mass index (fat mass, kg/height,  $m^2$ ). Like letters = not significantly different between groups ( $p < 0.05$ ). P-values (Sig.) are provided below each figure for pairwise comparisons in addition to effect sizes (ES) reported as Cohen's *d* statistics for all significant comparisons interpreted as: < 0.1, negligible effect size (N); 0.1-0.3, small effect size (S); 0.5-0.7, large effect size (L); and > 0.7, very large effect size (VL).



Comparison	Sig.	ES	Sig.	ES	Sig.	ES	Sig.	ES
GEN POP vs BALLETT	<0.001	1.4(VL)	0.001	0.8(VL)	<0.001	1.3(VL)	<0.001	1.3(VL)
GEN POP vs SOCCER	0.138	NS	0.200	NS	0.043	0.5(L)	0.105	NS
BALLETT vs SOCCER	<0.001	2.3(VL)	<0.001	1.1(VL)	<0.001	2.1(VL)	<0.001	2.1(VL)



Comparison	Sig.	ES	Sig.	ES	Sig.	ES	Sig.	ES
GEN POP vs BALLETT	<0.001	1.9(VL)	<0.001	1.7(VL)	<0.001	2.0(VL)	<0.001	2.0(VL)
GEN POP vs SOCCER	<0.001	1.2(VL)	<0.001	1.2(VL)	<0.001	1.1(VL)	<0.001	1.2(VL)
BALLETT vs SOCCER	<0.001	1.2(VL)	<0.001	0.9(VL)	<0.001	1.2(VL)	<0.001	1.1(VL)

occurred in the sacrum and lumbosacral spine in the BALLE group (Table 1), this may be the area where site-specific deficiencies (Fig. 2) may have the most impact. Lastly, these findings contribute to understanding of the site-specific selective preservation of bone during periods of high activity coupled with reduced nutrient intake observed to be common in elite level female ballet performers.<sup>1,2,14</sup>

#### *Bone density & injury risk*

In our previous study we observed above average BMD in extremities and below average BMD in pelvic and spine area in professional ballet dancers relative to general population norms.<sup>1</sup> In the present study we observed a similar result of reduced spine and pelvic BMD when comparing the BALLE group to the GENPOP group (although with no difference in legs BMD) (Table 1). Given that professional ballet performers have been commonly observed to undergo periods of nutrient restriction in order to maintain aesthetic requirements for performance,<sup>15,16</sup> we hypothesized that there would be a tendency to preserve BMD in the regions which experience more impact load while less loaded regions would show deficiency compared to the GENPOP or SOCCER groups. In the present study we observed significantly lower BMD in ischium and sacrum in the BALLE group compared to the GENPOP group while the SOCCER group had higher measures in all regions (Fig. 2). As elite professional athletes, both the BALLE and SOCCER groups spend considerable amounts of time per week training with different sports-specific strategies related to their performance demand. However, for the populations observed here, the annual frequency and duration of training for the BALLE group across a given year is markedly higher than those in the SOCCER group (Table 1). As a result of high training volumes and reduced nutrient intake during the performance seasons, caloric deficits of almost 1000 kcals per day have been previously reported in similar groups of ballet performers in collegiate settings.<sup>17</sup> Considering the overall training requirements, we believe our data further indicate preferential bone resorption in some areas to maintain the bone quality in other locations with regard to mechanical loading which may be a concern. These findings are in agreement with Amorim et al.<sup>2</sup> who reported higher BMD in impacted sites and lower BMD regions less subjected to repetitive loading. Although overuse injuries typically occur in skeletal regions that experience more direct repetitive load, spine and sacral injuries are also common in ballet dancers<sup>18</sup> and were observed to be the most prominent bone injuries in the BALLE group for the present study (Table 1). Additionally, reduced BMD in the specific regions of the pelvic ring also increases risk of fracture during falling incidents or other types of impacts not directly related to performance. Of note, the differences observed between groups for regional BMD (Fig. 2) were similar with regard to whole pelvis BMD (Table 1). Therefore, for health professionals and clinicians who may only have access to a single DEXA report and are unable to perform regional analysis, it may still be possible to infer that similar regional BMD trends are present. However, study is required to determine this.

#### *Soft tissue distribution*

Both lean and fat tissue mass were significantly lower in the BALLE group compared to the other groups (Fig. 3). Similar to the goals of maintaining bone quality, optimizing nutritional intake through education and counseling may be required to both maintain performance standards while also reducing the risks of negative energy balance. For example, reduced energy intake paired with high training volumes has been previously associated with delayed puberty and menstrual disorders among female ballet dancers.<sup>19</sup> In our previous investigation of the same ballet company, we observed oligomenorrhea in 60% of female dancers.<sup>1</sup> In the same population, relative to population norms, female professional ballet dancers were also observed to be lower than the 2<sup>nd</sup> percentile for %body fat.<sup>1</sup> Within the present study, incidence of soft tissue injuries were markedly higher in the BALLE group compared to the SOCCER

group (Table 1). Both fat and muscle tissue play an important role in the adaptive responses to training and are heavily paired joint stability and bone metabolism during development, in response to training, and during times of low energy availability.<sup>20–23</sup> Therefore, maintenance of optimal lean mass and essential fat is critically paired with reducing risk of musculoskeletal injury. In this instance, the difference in lean mass between the SOCCER and BALLE groups was the greatest contributor (on average) to soft tissue differences between groups (Fig. 3). Therefore, it is possible that with regard to injury in BALLE performers, lean mass development and maintenance in this region should be a focus of preventative training or intervention.

Fracture risk associated with low lean and fat tissue may also relate to the material properties of the tissues themselves for “bracing/padding” potential impacts. While an excess of fat tissue in cases of obesity may elevate the risk of fracture at loading sites, both lean and fat tissue play an important role in prevention of impact-based fractures such as falls.<sup>24,25</sup> Therefore, the reduced soft-tissue around the pelvic region may further elevate injury risk in female ballet performers where pelvic BMD deficiencies are already present.<sup>18,26,27</sup>

#### *Musculoskeletal injuries in ballet dancers*

The injury pattern among ballet dancers differs from many sports because of specific demands in terms of flexibility, body aesthetics and repetitive impact load in certain areas of the body. The overall injury incidence among professional dancers has been reported to be 1.24 per 1000 dance hours with 64% of injuries occurring due to overuse.<sup>28</sup> Knowing about relative distribution of injury locations is helpful to develop more focused prevention strategies. In a systematic review by Smith et al.,<sup>29</sup> the highest injury prevalence by region was for foot (~17.2%) followed by the lower back/pelvic region (~14%).<sup>30</sup> Although soft-tissue injuries to the pelvic region are common, aside from the sacrum, the bony structures of the pelvis do not commonly experience overuse injuries in ballet dancers. However, it is plausible that in traumatic situations or those not directly involving performance or rehearsal (activities of daily living), weak areas with lower BMD might be at significantly higher risk. Also, our observation that some areas of the pelvis have greater BMD deficiencies compared to others highlights which regions are less preserved as a result of regular ballet training and performance. Regarding BMD deficiencies observed in the sacrum as well as low pelvic region lean tissue mass, we did observe that the primary bone injuries within the BALLE group occurred in the lumbosacral spine and sacrum and that 20% of region-specific soft tissue injuries occurred around the lumbosacral region. Therefore, based on these analyses, this portion of the pelvic region may be most at risk in the presence of BMD and soft-tissue (particularly lean tissue) deficiencies for this population.

#### *Potential preventative interventions*

Based on the present findings, it may be desired for ballet performers to employ training or nutrition regimens including the strategies implemented by other sports such as the SOCCER group which was observed to have markedly higher BMD and lean mass (Figs. 2 and 3) in addition to significantly fewer injuries (Table 1). While there is no clear evidence regarding which specific exercises may improve the bone quality in specific regions in pelvic area, in a recent randomized controlled trial, Vera et al.<sup>30</sup> observed an 82% decrease in musculoskeletal injuries in professional ballet dancers who performed a year-long preventative strength training program (3 days per week/30 min per day) in addition to their weekly performance requirements. Exercises for the lower extremities, hips, and low back included the following low-impact body weight exercises: lateral stepping with a resistance band, planking, Nordic hamstring curl, prone straight leg lifts, lunges, isometric wall squats, body weight squats, and box step downs. All exercises had progression options (based on the ease of performing each exercise) that included increasing resistance or repetitions. The eccentric

portions of the movements were also heavily emphasized. Of note, these exercises did not require large equipment. Based on their investigation, strengthening programs using simple body weight exercises may be effective within this population.

Similar programs for pelvic region strengthening have also been observed to improve performance in collegiate cross-country runners, a population also prone to overuse injuries and reduced energy availability.<sup>31</sup> During a 6-week period, Clark et al.<sup>31</sup> observed that a simple body weight pelvic region strength program (3 days/week) improved both running performance as well as strength hip abduction, adduction, and extension strength (involving musculature heavily relied upon for hip stabilization). Exercises included were similar to those utilized in the investigation by Vera et al.<sup>30</sup> Notably, the development of regional muscle mass has been shown to be significantly correlated with increased regional BMD in runners.<sup>32</sup> Therefore, we find it likely that chronic lower body resistance exercise may have a similar positive impact on ballet performers for the preservation of both soft tissue and bone. However, given that overuse injuries are prevalent ballet performers, it may be advisable to not perform such resistance exercises to fatigue. Additionally, supplemental resistance training volume and nutritional intake should be monitored and adjusted to prevent reductions in energy availability that may exacerbate the deleterious effects of overtraining common to ballet performers.

#### Limitations

The present study is not without limitations. First, this was a retrospective investigation with analyses performed on patients within our DEXA database. This was a single time point measurement of body composition and BMD that included a single professional ballet company and soccer team. Additionally, the age-matched females in our GENPOP group were taken as a convenience sample of available females within our database that met inclusion criteria. Further study is required to determine how BALLET performers compare to other strength and power-based sports (softball, volleyball, gymnastics, etc) for the measures observed here. Next, in the initial study of this population,<sup>1</sup> low whole-pelvis BMD was evaluated by subsequent follow-up site-specific dual-hip and femur DEXA scans where, for the portions of the hip joint that were evaluated (femoral neck, femoral head, ischium), were not observed to have low BMD relative to population norms. As this investigation was retrospective in nature, follow-up dual-hip and femur scans were not available for the GENPOP and SOCCER groups which may have allowed us to determine if a similar finding may have been observed among other study groups. Additionally, we were only able to obtain limited injury history data from the athlete groups (BALLET, SOCCER) within this investigation. Lastly, while we find it likely that the outcomes observed here were, in part, influenced by reduced nutritional intake in the BALLET group relative to the others, the retrospective nature of this study and limited access to the professional athletes observed here prevented us from doing dietary analysis on the populations observed.

#### Conclusions

Compared to age-matched general population women, female ballet dancers exhibit reduced site-specific pelvic BMD at the ischium and sacrum in conjunction with reduced soft tissue. These differences were observed to be even greater (significant across all regions) when compared against professional female soccer athletes who may represent a more reasonable comparison given the sport-specific performance requirements. It is also possible that the reduced soft tissue and BMD measures in the pelvic region paired with high training volumes contributed, at least in part, to the corresponding injury frequencies observed among the ballet performers in this investigation. While not assessed here, these findings may also be a result of reduced energy availability commonly observed in similar populations of ballet performers. Next, these data are valuable in terms of showing the

disproportion of region-by-region BMD and soft tissue measures in professional female ballet dancers in order to distinguish the areas with potential higher risk for injury. Given the injury frequencies reported here paired with BMD and soft tissue measures, the present findings indicate that the sacrum and lumbosacral spine may be at greatest risk in this population for bony injuries in the pelvic region. Professional ballet dancers, trainers, and clinicians may consider employing new training and nutritional strategies (possibly drawn from other high impact sports) for the region-specific injury prevention. However, future studies should focus on how to best implement such interventions while minimizing additional energy expenditure and overexposure to musculoskeletal stress in athletes who are commonly at risk for overtraining-based injuries.

#### Ethical approval statement

The procedures were approved by the institutional review board for research involving human subjects (IRB# PRO00024667), and all participants provided informed consent for their data to be used for research purposes prior to participating in the experimental procedures.

#### Submission statement

The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The manuscript has not been published and is not under consideration for publication elsewhere.

#### Authors' contributions

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- Manuscript development

### Conflict of interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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