5-15-2020

Comparisons of Patellar Bone Mineral Density Between Individuals with and without Patellofemoral Pain

Chris Khuu
University of Nevada, Las Vegas

Allina Cummins
University of Nevada, Las Vegas

Steven Shepherd
University of Nevada, Las Vegas

Follow this and additional works at: <https://digitalscholarship.unlv.edu/thesesdissertations>

Part of the [Physical Therapy Commons](#)

Repository Citation

Khuu, Chris; Cummins, Allina; and Shepherd, Steven, "Comparisons of Patellar Bone Mineral Density Between Individuals with and without Patellofemoral Pain" (2020). *UNLV Theses, Dissertations, Professional Papers, and Capstones*. 3773.
<http://dx.doi.org/10.34917/18162612>

This Dissertation is protected by copyright and/or related rights. It has been brought to you by Digital Scholarship@UNLV with permission from the rights-holder(s). You are free to use this Dissertation in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you need to obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/or on the work itself.

This Dissertation has been accepted for inclusion in UNLV Theses, Dissertations, Professional Papers, and Capstones by an authorized administrator of Digital Scholarship@UNLV. For more information, please contact digitalscholarship@unlv.edu.

COMPARISONS OF PATELLAR BONE MINERAL DENSITY BETWEEN INDIVIDUALS
WITH AND WITHOUT PATELLOFEMORAL PAIN

By

Allina Cummins

Chris Khuu

Shane Parker

Steven Shepherd

A doctoral project submitted in partial fulfillment
of the requirements for the

Doctor of Physical Therapy

Department of Physical Therapy
School of Integrated Health Sciences
The Graduate College

University of Nevada, Las Vegas
May 2020

Copyright by Allina Cummins, Chris Khuu, Shane Parker, and Steven Shepherd, 2020

All Rights Reserved

Doctoral Project Approval

The Graduate College
The University of Nevada, Las Vegas

May 16, 2020

This doctoral project prepared by

Allina Cummins

Chris Khuu

Shane Parker

Steven Shepherd

entitled

Comparisons of Patellar Bone Mineral Density Between Individuals with and Without
Patellofemoral Pain

is approved in partial fulfillment of the requirements for the degree of

Doctor of Physical Therapy
Department of Physical Therapy

Daniel Young, Ph.D.
Research Project Coordinator

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Dean

Kai-Yu Ho, Ph.D.
Research Project Advisor

Merrill Landers, Ph.D.
Chair, Department of Physical Therapy

Abstract

Background: Although bone stress injuries have been reported in individuals with patellofemoral pain (PFP), especially within the lateral patella, it remains unclear whether persons with PFP exhibit altered patellar regional bone mineral density (BMD). The primary purpose of this study was to compare BMD of the patella (lateral, medial, and total regions) between individuals with and without PFP using quantitative computed tomography (QCT). The secondary aim was to examine the associations between patellar regional BMD and patellofemoral joint (PFJ) alignment.

Methods: Ten individuals with retropatellar pain and 10 sex, age, weight, height, and activity matched pain-free controls underwent a QCT scan to obtain patellar BMD. To quantify PFJ alignment, patellar lateral displacement was measured using bisect-offset (BSO) index and lateral tilt was quantified using patellar tilt angle (PTA). A two-factor repeated-measures ANOVA was used to compare BMD across the three patellar regions and between the two groups. Pearson correlation coefficient analyses were used to evaluate the associations between BMD and PFJ alignment of all participants.

Results: There was no difference in BMD between the two groups. However, BMD was highest within the lateral patella and was lowest within the medial patella across both groups. There were significant moderate to large correlations between BSO index/PTA and BMD within lateral, medial, and total regions.

Conclusions: While individuals with PFP and pain-free controls have similar patellar BMD, the lateral patella exhibits the highest BMD. Additionally, higher patellar regional BMD is related to increased patellar lateral displacement and lateral tilt.

Key Words: bone mineral density; patella; patellofemoral pain; alignment; quantitative computed tomography

Acknowledgements

This research study was made possible by the Graduate and Professional Student Association Grant and the University of Nevada, Las Vegas Physical Therapy Department Grant. The authors would like to thank Kai-Yu Ho, PT for her excellent guidance as principle investigator of this study.

Table of Contents

Abstract	iii
Acknowledgements	iv
1. Introduction	1
2. Materials and Methods	3
2.1 Participants.....	3
2.2 Procedure	4
2.3 Data analysis	4
2.3.1 BMD measurement	4
2.3.2 PFJ alignment measurement	6
2.4 Measurement reliability	6
2.5 Statistical analyses	7
3. Results	8
4. Discussion	10
5. Conclusions	13
References	14
Curriculum Vitae	18

1. Introduction

Patellofemoral pain (PFP) is a common musculoskeletal problem that affects 25% of the general population²⁴ with the hallmark symptom being retropatellar pain¹⁰. It has been demonstrated that individuals with PFP exhibit patellar bone stress injuries^{6,14,15} and reduced cartilage thickness^{8,17}, especially on the lateral aspect of the patella^{8,14,17}. While the cause of PFP is thought to be multi-factorial, these tissue injuries have been suggested to be related to patellofemoral joint (PFJ) malalignment (e.g., lateral tilt and lateral displacement of the patella) and/or repetitive overloading of the PFJ²⁶.

From a mechanical perspective, it has been suggested that local subchondral bone hardening due to overloading leads to cartilage degeneration via altered force distributions across the articular-bone interface^{27,28}. This sclerotic bone is less capable of shock-absorption, increasing the forces placed upon the articular cartilage, thereby hastening cartilage breakdown and joint degeneration^{27,28}. It has been reported that increased systemic bone mineral density (BMD) is associated with the development of cartilage loss/defects³⁰ and osteophytes¹² of the knee. In addition, increased focal subchondral BMD is associated with more severe articular structural changes in periphery joints^{1,12}. To date, although patellar bone stress injuries^{6,14,15} and cartilage thinning^{8,17} have been reported in individuals with PFP, there is little evidence to support the premise that persons with PFP would exhibit altered patellar BMD when compared to pain-free controls. In addition, it is unclear whether patellar malalignment would contribute to changes of patellar regional BMD.

Using dual X-ray absorptiometry (DXA) technology, Leppala et al.²¹ have found that the symptomatic limb has lower patellar BMD when compared to the non-painful side in a cohort with PFP. However, it remains unclear if patellar BMD is different between individuals with and without PFP given that they did not include a pain-free control group. Additionally, DXA estimates BMD by calculating bone mass within a surface area, rather than taking a volumetric measure of a bone region²⁹. As such, quantitative computed tomography (QCT) is deemed a more appropriate tool for the analyses of focal patellar BMD as it yields voxel-based BMD and can provide more regional details within an individual bone^{4,16,23}. Therefore, the primary purpose of this study was to use QCT to compare focal BMD of the

patella (lateral, medial, and total regions) between individuals with and without PFP. The secondary purpose was to examine the relationship between PFJ alignment and patellar regional BMD.

2. Materials and Methods

2.1 Participants

Ten individuals with PFP and 10 pain-free controls between 18 and 40 years old were recruited for this study (Table 1). The data from an existing study was used to estimate the sample size for detecting changes in bone stress injuries of the patella between individuals with and without PFP¹⁴. With 95% power and an α level of 0.05, we estimated that 10 individuals per group would be needed to detect a significant difference between groups. This study was approved by the Institutional Review Board of University of Nevada, Las Vegas. Informed consent was obtained from all individual participants included in the study.

Individuals with PFP were admitted to the study if they reported retropatellar pain for a minimum three months during at least three of the following activities: stair climbing, squatting, running, cycling, or sitting for a prolonged period with the knee flexed. Persons with PFP were excluded from participation if they reported having any of the following: 1) history of knee surgery; 2) history of knee injury (fractures, connective tissue injuries, and muscle injuries), 3) history of patellar dislocation, or 4) increased risk with QCT radiation exposure (pregnancy, active cancer/tumor, and/or history of cancer/tumor). To confirm eligibility of participation, participants were screened through physical examination to rule out concomitant sources of pain. This process included palpation of the soft tissues around the PFJ to identify the location of pain. If the source of pain was localized to the quadriceps tendon, patellar tendon, patella bursa, patella fat pad, tibiofemoral joint, or the lateral and medial joint line, the participant was excluded from the study.

Participants in the control group were sex, age, height, weight, and activity matched (10% difference) to those in the PFP group. Participants' physical activity levels were determined based on the World Health Organization's Global Physical Activity Questionnaire (GPAQ)³. Participant selection for the control group was based on the same criteria as the PFP group except that these participants had no history of PFP.

Table 1. Participant characteristics.

	PFP (n = 10)	Control (n = 10)	P value
Sex	8 Female 2 Male	8 Female 2 Male	n/a
Age, years	26.6 ± 6.0	27.2 ± 5.3	0.825
Height, cm	169.0 ± 10.0	166.7 ± 9.2	0.619
Weight, kg	71.3 ± 13.9	69.4 ± 15.6	0.787
GPAQ, weekly activity level	1 Low 3 Moderate 6 High	1 Low 3 Moderate 6 High	n/a
VAS maximum pain	7.0 ± 1.0	n/a	n/a
VAS average pain	3.0 ± 1.3	n/a	n/a
AKPS	76.3 ± 6.9	n/a	n/a
Duration of symptoms, months	56.6 ± 59.3	n/a	n/a

All values expressed as mean ± standard deviation.

Abbreviations: PFP = patellofemoral pain; GPAQ = Global Physical Activity Questionnaire; VAS = Visual Analog Scale for Pain (out of 10); AKPS = Anterior Knee Pain Scale (out of 100)

2.2 Procedure

Each participant underwent a QCT scan. The QCT scan was applied to the symptomatic knee in participants who had unilateral pain or the more symptomatic knee for those who had bilateral symptoms. For the control participants, the limb being examined was matched to that of their counterpart in the PFP group. The system settings for the QCT scan were 80 kVp and 210 mAs. The QCT sampling matrix was 512 x 512 (voxel size= 0.313 x 0.313 x 2 mm³)¹⁶. Participants were positioned supine and a calcium hydroxyapatite (CHA) calibration phantom made from a water equivalent solid resin matrix and four chambers with CHA densities of 0, 0.05, 0.1 and 0.2 g/cc (Image Analysis, Inc., Columbia, Kentucky, USA) was placed under the participant's knee during the QCT exam¹⁶.

2.3 Data analysis

2.3.1 BMD measurement

Patella BMD was processed using a custom Matlab program script (Mathworks, Natick, Massachusetts, USA) by four trained investigators (AC, CK, SP, and SS). From the QCT data, average Hounsfield units were measured for each of the calibration standards (Figure 1a). The average Hounsfield

unit values were then plotted against the known CHA concentration. Based on the fitted regression line between Hounsfield unit and CHA concentration, CHA equivalent densities of all other bone voxels were determined (Figure 1b)¹⁶. To quantify regional BMD, regions of interests (ROIs) that represent the lateral and medial patella were manually determined and the average BMD within each of the ROIs were computed. Specifically, the median ridge of the patella was used as the landmark to separate the medial and lateral aspects of the patella (Figure 1b). The ROI of the total patella was estimated by summing the ROIs of medial and lateral aspects of the patella. The procedure was repeated across all slices that encompass the patella and the following equation was used to quantify the average regional (total, lateral, and medial) BMD of all images measured.

$$\text{BMD (g/cc)} = \frac{\sum_1^n (\text{BMD (n)} \times \text{area of ROI (n)})}{\sum_1^n \text{area of ROI (n)}}$$

, where n is number of images.

Figure 1. (a) Sample quantitative computed tomography (QCT) image with four calcium hydroxyapatite (CHA) concentrations (0, 0.05, 0.1, and 0.2 g/cc) of QCT calibration phantom; (b) quantification of patellar bone mineral density (BMD) on a bone mineral density map. The red and yellow regions represent the regions of interest (ROIs) of the lateral and medial patella, respectively.

Figure 2. (a) Measurement of patellar lateral displacement using bisect-offset (BSO) index = $[\text{length}(AB) / \text{length}(AC)] \times 100\%$; (b) measurement of patellar mediolateral tilt using patellar tilt angle (PTA). In this figure, A and C represent the most lateral and medial points of the patella, respectively. L and M indicate lateral and medial, respectively.

2.3.2 PFJ alignment measurement

PFJ alignment was measured on the slice with the greatest mediolateral width of the patella³¹ using ImageJ software (National Institutes of Health, Bethesda, Maryland, USA). The bisect-offset (BSO) index, which represents the percentage of the patellar width lateral to the deepest point of the trochlear groove, was used to quantify the patellar lateral displacement (Figure 2a)³¹. A larger BSO index value typically represents more lateral displacement of the patella³¹. The patellar tilt angle (PTA), which is defined as the angle formed between the line connecting the widest points of the patella and a line joining the posterior femoral condyles, was used to assess patellar mediolateral tilt (Figure 2b)³¹. A larger PTA value indicates a higher degree of lateral patellar tilt³¹. The PFJ alignment was measured by the same trained investigator (KH).

2.4 Measurement reliability

Four investigators (AC, CK, SP, and SS) performed a reliability study to determine inter- and intra-rater reliability for quantifying patellar BMD. The investigator responsible for PFJ alignment (KH) performed a repeatability study to obtain intra-rater reliability. The investigators performed measurements on five sets of images on two separate days at least a week apart. Intraclass correlation coefficient (ICC)

and standard error of measurement (SEM) were used to determine intra-/inter-rater reliability of image processing. The SEM was estimated by multiplying the standard deviation by $\sqrt{1 - \text{reliability coefficient}}$.

The intra-rater reliability of measuring focal patellar BMD for the 4 responsible investigators was excellent (medial region: ICC = 0.996-1.00; SEM = 0.001-0.003 g/cc; lateral region: ICC = 0.997-0.999; SEM = 0.001-0.002 g/cc, and total region: ICC = 0.997-1.00; SEM = 0.001-0.003 g/cc). The inter-rater reliability of patellar BMD measurements was excellent (medial region: ICC = 0.975; SEM = 0.007 g/cc; lateral region: ICC = 0.964; SEM = 0.008 g/cc, and total region: ICC = 0.975; SEM = 0.007 g/cc). The investigator responsible for PFJ alignment measures also demonstrated excellent reliability for the measurements of BSO index (ICC = 0.995; SEM = 0.009%) and PTA (ICC = 0.974; SEM = 1.55°).

2.5 Statistical analyses

A 2-factor repeated-measures ANOVA was used to compare BMD across the three regions (lateral, medial, and total) and between the two groups (PFP and control). If a significant region-by-group interaction or a significant main effect was found, post hoc testing (paired *t* tests with a Bonferroni correction) was employed. Pearson correlation coefficient analyses were used to evaluate the associations between BMD and PFJ alignment measures of all participants. Correlation was defined as small 0.1-0.3, moderate 0.3-0.5, large 0.5-0.7, very large 0.7-0.9, extremely large > 0.9¹⁹. All statistical analyses were performed with the use of SPSS 24.0 statistical software (International Business Machines Corp, Armonk, New York). A significant difference was defined as *P* smaller than 0.05.

3. Results

A 2-factor repeated measures ANOVA showed that there was not a significant main effect of group on patellar BMD ($P = 0.350$). There was also no group-by-region interaction effect ($P = 0.503$). However, there was a significant main effect of region on patellar BMD ($P < 0.001$). When both groups were combined, post-hoc pairwise comparison analyses with Bonferroni corrections revealed that patellar BMD was highest in the lateral region when compared with the medial and total regions (lateral: 0.53 ± 0.08 g/cc vs. medial: 0.43 ± 0.06 g/cc, $P < 0.001$; lateral: 0.53 ± 0.08 g/cc vs. total: 0.49 ± 0.07 g/cc, $P < 0.001$). In addition, the BMD of the total patellar region was significantly higher than that of the medial region ($P < 0.001$) (Figure 3).

Figure 3. Comparison of bone mineral density in lateral, medial, and total patellar regions between participants with patellofemoral pain (PFP) and pain-free controls. Error bars indicate standard deviations.

* indicates a significant difference from medial patellar BMD using a 2-factor ANOVA with repeated-measures and post-hoc paired t test with a Bonferroni correction ($P < 0.01$).

indicates a significant difference from total patellar BMD using a 2-factor ANOVA with repeated measures and post-hoc paired t test with a Bonferroni correction ($P < 0.01$).

Pearson correlation coefficient analyses revealed significantly large, positive correlations between patellar lateral displacement (i.e., BSO index) and BMD in the lateral ($R = 0.529$; $P = 0.017$), medial ($R = 0.507$; $P = 0.023$), and total ($R = 0.532$; $P = 0.016$) regions of the patella (Figure 4. a.-c.). In addition, there were significantly moderate, positive associations between patellar mediolateral tilt (i.e., PTA) and BMD in the lateral ($R = 0.470$; $P = 0.036$), medial ($R = 0.460$; $P = 0.041$), and total ($R = 0.471$; $P = 0.036$) regions of the patella (Figure 4. d.-f.).

Figure 4. The correlations between bisect-offset (BSO) index and (a) lateral patellar density; (b) medial patellar density; (c) total patellar density, and between patellar tilt angle (PTA) and (d) lateral patellar density; (e) medial patellar density; (f) total patellar density. *indicates a significant correlation ($P < 0.05$) using Pearson correlation coefficients. Abbreviation: PFP = patellofemoral pain.

4. Discussion

To the authors' knowledge, this is the first study examining patellar BMD profiles in individuals with and without PFP using a QCT technique. The primary purpose of this study was to compare focal patellar BMD between individuals with PFP and pain-free controls. Our findings suggested that BMD was similar between individuals with and without PFP across lateral, medial, and total regions. However, the lateral aspect of the patella exhibited the highest BMD when compared to the medial and total regions of the patella across all participants. The secondary purpose of this study was to investigate the associations between patellar regional BMD and PFJ alignment, including patellar lateral tilt and lateral displacement. Our data showed that higher patellar regional BMD was related to increased patellar lateral displacement and patellar lateral tilt.

Prior studies examining BMD in healthy patellae have shown that the lateral region of the patella exhibits higher BMD than the medial region^{7,18}, likely due to long-term high stresses experienced by the lateral aspect of patella^{14,15}. This finding was confirmed by our results showing increased BMD in the lateral patella across participants with and without PFP. Our data did not show a statistically significant difference in patellar BMD between individuals with and without PFP. The insignificant findings might be attributed to the large standard deviations (Figure 3) and wide ranges of BMD values (Figure 4) observed in our study. Leppala et al.²¹ examined patellar BMD in people with PFP and found that patella BMD was lower in the symptomatic knee. The different findings in patellar BMD changes in individuals with PFP between our study and Leppala et al.'s work may be explained by the fact that Leppala et al.²¹ compared side-to-side differences in participants with PFP, whereas our study compared the most symptomatic knee of participants with PFP to the matched limb of pain-free controls. As BMD can be influenced by a number of factors, such as age²⁰, sex², body weight¹¹, genetics²⁰, physical activity level and type²⁰, medications²⁰, calcium intake²⁰, alcohol use²⁰, and smoking²⁰, the side-to-side comparisons within-subject used by Leppala et al.²¹ is thought to account for the variations of these contributing factors, leading to a statistically significant difference between sides. While we attempted to control age, sex, weight, and activity level between groups, not all factors contributing to BMD were accounted for,

such as genetics, life-style habits, and environmental factors. Nevertheless, our work provided the information regarding QCT-based, patellar regional BMD in individuals with PFP and pain-free controls.

While increased BMD is thought to be a potential indicator of PFJ degeneration, Li et al.²² discuss potential different subchondral bone adaptations in the development and progression of joint degeneration. Specifically, initial stages of joint degeneration are often associated with thinning of the subchondral plate and increased porosity, which results in decreased BMD²². Later stages, however, are associated with subchondral thickening and increased bone volume resulting in increased BMD²². These temporal differences in subchondral bone remodeling may in part explain why our results showed no differences in BMD between the PFP and control groups. The existing literature has revealed that about 16% to 62% of individuals of PFP present with magnetic resonance imaging (MRI)-detected, articular structural degeneration (e.g., cartilage defects, osteophytes)³². Thus, it is possible that different stages of bone remodeling and joint degeneration took place in our participants. As the QCT technique does not provide detailed joint degeneration markers (e.g., cartilage defect, bone marrow lesions, inflammation)^{22,32}, future study is required to examine how different stages of joint degeneration may impact patellar focal BMD.

Our study showed that patellar lateral displacement and tilt were moderately to largely associated with increased focal BMD. This relationship may be explained by the fact that the PFJ exhibits a higher loading in the presence of PFJ malalignment²⁶. Specifically, increased patellar lateral tilt/displacement is thought to cause a reduction in PFJ contact area²⁶, thereby elevating the stress within the PFJ (defined as PFJ reaction force per unit area of contact of the patella against the femur)²⁶ and bone stress injuries^{14,15}. Increased stress to subchondral bone produces a cascade of events ultimately resulting in increased bone formation and decreased bone resorption in the area of stress^{5,28}. Furthermore, the existing literature has also demonstrated that PFJ malalignment is related to cartilage defects and osteophytes of the PFJ^{13,32}. Based on our data and previous studies, it is believed that PFJ malalignment plays a critical role in the development of PFJ degeneration and bone remodeling across both PFP and pain-free individuals.

With respect to the findings of the current study, several limitations must be considered. First, our participants were relatively young (Table 1), which could limit the generalizability of our data to older populations with PFP. Second, although our study contained the necessary number to meet the pre-calculated effect size, a larger sample size may yield better understanding of the patellar focal BMD changes in this population. Furthermore, participant positioning during the CT scan consisted of laying supine with the knee extended in a relaxed position, which might not reflect the PFJ alignment during weight-bearing²⁵. Therefore, the relationships between weight-bearing PFJ alignment and focal patellar BMD may be different from the associations reported in this work.

5. Conclusions

While our study suggests that individuals with PFP and pain-free controls had similar patellar BMD, the lateral patellar region exhibited the highest BMD when compared to medial and total regions across both groups. Additionally, higher patellar regional BMD was related to increased patellar lateral displacement and patellar lateral tilt. The findings suggest that altered patellar BMD may not be explained by the presence of patellofemoral joint symptoms. As patellar malalignment is associated with increased patellar BMD, PFJ alignment should be considered when managing PFJ conditions.

References

1. Barr, A.J., et al., *A systematic review of the relationship between subchondral bone features, pain and structural pathology in peripheral joint osteoarthritis*. Arthritis Res Ther, 2015. **17**: p. 228.
2. Blunt, B.A., et al., *Sex differences in bone mineral density in 1653 men and women in the sixth through tenth decades of life: the Rancho Bernardo Study*. J Bone Miner Res, 1994. **9**(9): p. 1333-8.
3. Bull, F.C., T.S. Maslin, and T. Armstrong, *Global physical activity questionnaire (GPAQ): nine country reliability and validity study*. J Phys Act Health, 2009. **6**(6): p. 790-804.
4. Cann, C.E., *Quantitative CT for determination of bone mineral density: a review*. Radiology, 1988. **166**(2): p. 509-22.
5. Dittmer, K.E. and E.C. Firth, *Mechanisms of bone response to injury*. J Vet Diagn Invest, 2017. **29**(4): p. 385-395.
6. Draper, C.E., et al., *Patients with patellofemoral pain exhibit elevated bone metabolic activity at the patellofemoral joint*. J Orthop Res, 2012. **30**(2): p. 209-13.
7. Eckstein, F., M. Muller-Gerbl, and R. Putz, *Distribution of subchondral bone density and cartilage thickness in the human patella*. J Anat, 1992. **180 (Pt 3)**: p. 425-33.
8. Farrokhi, S., P.M. Colletti, and C.M. Powers, *Differences in patellar cartilage thickness, transverse relaxation time, and deformational behavior: a comparison of young women with and without patellofemoral pain*. Am J Sports Med, 2011. **39**(2): p. 384-91.
9. Frost, H.M., *Wolff's Law and bone's structural adaptations to mechanical usage: an overview for clinicians*. Angle Orthod, 1994. **64**(3): p. 175-88.

10. Fulkerson, J.P., *Awareness of the retinaculum in evaluating patellofemoral pain*. Am J Sports Med, 1982. **10**(3): p. 147-9.
11. Hamilton, K.C., et al., *The effects of weight loss on relative bone mineral density in premenopausal women*. Obesity (Silver Spring), 2013. **21**(3): p. 441-8.
12. Hardcastle, S.A., et al., *Osteoarthritis and bone mineral density: are strong bones bad for joints?* Bonekey Rep, 2015. **4**: p. 624.
13. Hinman, R.S. and K.M. Crossley, *Patellofemoral joint osteoarthritis: an important subgroup of knee osteoarthritis*. Rheumatology (Oxford), 2007. **46**(7): p. 1057-62.
14. Ho, K.Y., et al., *Recreational runners with patellofemoral pain exhibit elevated patella water content*. Magn Reson Imaging, 2014. **32**(7): p. 965-8.
15. Ho, K.Y., et al., *Running-induced patellofemoral pain fluctuates with changes in patella water content*. Eur J Sport Sci, 2014. **14**(6): p. 628-34.
16. Ho, K.Y., et al., *Measuring bone mineral density with fat-water MRI: comparison with computed tomography*. J Magn Reson Imaging, 2013. **37**(1): p. 237-42.
17. Ho, K.Y., J.H. Keyak, and C.M. Powers, *Comparison of patella bone strain between females with and without patellofemoral pain: a finite element analysis study*. J Biomech, 2014. **47**(1): p. 230-6.
18. Hoechel, S., D. Wirz, and M. Muller-Gerbl, *Density and strength distribution in the human subchondral bone plate of the patella*. Int Orthop, 2012. **36**(9): p. 1827-34.
19. Hopkins, W.G., et al., *Progressive statistics for studies in sports medicine and exercise science*. Med Sci Sports Exerc, 2009. **41**(1): p. 3-13.
20. Krall, E.A. and B. Dawson-Hughes, *Heritable and life-style determinants of bone mineral density*. J Bone Miner Res, 1993. **8**(1): p. 1-9.

21. Leppala, J., et al., *Bone mineral density in the chronic patellofemoral pain syndrome*. Calcif Tissue Int, 1998. **62**(6): p. 548-53.
22. Li, G., et al., *Subchondral bone in osteoarthritis: insight into risk factors and microstructural changes*. Arthritis Res Ther, 2013. **15**(6): p. 223.
23. Lian, K.C., et al., *Differences in hip quantitative computed tomography (QCT) measurements of bone mineral density and bone strength between glucocorticoid-treated and glucocorticoid-naïve postmenopausal women*. Osteoporos Int, 2005. **16**(6): p. 642-50.
24. MacIntyre, N.J., et al., *Patellofemoral joint kinematics in individuals with and without patellofemoral pain syndrome*. J Bone Joint Surg Am, 2006. **88**(12): p. 2596-605.
25. Powers, C.M., et al., *Patellofemoral kinematics during weight-bearing and non-weight-bearing knee extension in persons with lateral subluxation of the patella: a preliminary study*. J Orthop Sports Phys Ther, 2003. **33**(11): p. 677-85.
26. Powers, C.M., et al., *Evidence-based framework for a pathomechanical model of patellofemoral pain: 2017 patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester, UK: part 3*. Br J Sports Med, 2017. **51**(24): p. 1713-1723.
27. Radin, E.L., I.L. Paul, and R.M. Rose, *Role of mechanical factors in pathogenesis of primary osteoarthritis*. Lancet, 1972. **1**(7749): p. 519-22.
28. Radin, E.L. and R.M. Rose, *Role of subchondral bone in the initiation and progression of cartilage damage*. Clin Orthop Relat Res, 1986(213): p. 34-40.

29. Stagi, S., et al., *Peripheral quantitative computed tomography (pQCT) for the assessment of bone strength in most of bone affecting conditions in developmental age: a review*. Ital J Pediatr, 2016. **42**(1): p. 88.
30. Teichtahl, A.J., et al., *Associations between systemic bone mineral density and early knee cartilage changes in middle-aged adults without clinical knee disease: a prospective cohort study*. Arthritis Res Ther, 2017. **19**(1): p. 98.
31. Teng, H.L., Y.J. Chen, and C.M. Powers, *Predictors of patellar alignment during weight bearing: an examination of patellar height and trochlear geometry*. Knee, 2014. **21**(1): p. 142-6.
32. van Middelkoop, M., et al., *Are Patellofemoral Joint Alignment and Shape Associated With Structural Magnetic Resonance Imaging Abnormalities and Symptoms Among People With Patellofemoral Pain?* Am J Sports Med, 2018. **46**(13): p. 3217-3226.

Curriculum Vitae

Allina Cummins

Department of Physical Therapy, University of Nevada, Las Vegas
4505 Maryland Parkway, Las Vegas, Nevada 89154
alcummins23@gmail.com

Education

May 2020 | Doctor of Physical Therapy | University of Nevada, Las Vegas

May 2016 | B.S. Human Physiology | Gonzaga University | Magna Cum Laude

Licensure

- Pending National Physical Therapy Examination, 2020

Certifications

- American Heart Association, BLS/CPR for Healthcare Providers – expires May 2020
- HIPAA Training – earned September 2017
- Blood-Borne Pathogens Training – earned September 2017

Clinical Affiliations

- January 2020 to March 2020
 - Providence Regional Medical Center Everett – Everett, WA
 - Inpatient Rehabilitation
- October 2019 to December 2019
 - Spring Valley Hospital – Las Vegas, NV
 - NICU and Outpatient Pediatrics
- July 2019 to September 2019
 - St. Luke's Nampa Medical Center – Nampa, ID
 - Acute Care
- June 2018 to August 2018
 - Physical Therapy and Balance Centers, Jones – Las Vegas, NV
 - Outpatient Orthopedics

Employment

- August 2018 to May 2019
 - Graduate Assistant
 - University of Nevada, Las Vegas Department of Physical Therapy
- June 2016 to March 2017
 - Rehab Therapy Technician
 - Renown Rehabilitation Hospital
- May 2013 to August 2013
 - Office Assistant
 - Barbieri Manual Physical Therapy

Research Activity

- Graduate Projects (in progress)
 - Comparisons of Patellar Bone Mineral Density Between Individuals with and without Patellofemoral Pain
 - Principle Investigator: Kai-Yu Ho, PT, MSPT, PhD
 - Presented at American Physical Therapy Association Combined Sections Meeting, Orthopaedic Platform Session, February 2020
 - Submitted for publication to *The Knee*, *accepted for publication*
 - Use of Treatment Frequency and Duration Guidelines in Outpatient Pediatric Physical Therapy Services
 - Principle Investigator: Katherine Joines, PT, DPT
 - Characterization of the spinal reflex circuit function and Achilles' tendon micromorphology in individuals with chronic post-stroke hemiparesis
 - Principle Investigator: Jing Nong Liang, PT, PhD
 - Patellar tendon morphology in trans-tibial amputees utilizing a patellar-tendon-bearing prosthesis
 - Principle Investigator: Kai-Yu Ho, PT, MSPT, PhD
- Undergraduate Projects (unpublished)
 - “Effect of Isolated Hamstring Strengthening on Unanticipated Drop-Landing Knee Kinematics in Females” – December 2015
 - Faculty mentor: Ryan McCulloch, PhD
 - Poster presentation at American College of Sports Medicine Northwest Chapter Meeting April 2016
 - “Studying While Exercising The Effects of Moderate Exercise on Long-Term Memory” – May 2015
 - Faculty mentor: David Thorp, PhD
 - Poster presentation at American College of Sports Medicine Northwest Chapter Meeting April 2016

Membership in Professional Organizations

- American Physical Therapy Association (2017 to present)
- Nevada Physical Therapy Association (2017 to present)
- American Physical Therapy Association Sections on Research, Neurology, and Pediatrics (2017 to present)

Honors and Awards

- UNLV Graduate and Professional Student Association Research Forum – 2019
 - 2nd Place Award – Allied Health Sciences, Community Health Sciences, and Medicine Podium Session
- UNLV Graduate and Professional Student Association Research Sponsorship – 2019
- UNLVPT Department Scholarship – 2017, 2018, and 2019
- UNLVPT Student Opportunity Research Grant – 2018
- Doyle Foundation Scholarship – 2018
- UNLVPT Scholars Award – 2017

Chris Khuu

Department of Physical Therapy, University of Nevada, Las Vegas
4505 Maryland Parkway, Las Vegas, Nevada 89154
ckhuu@outlook.com

Education

May 2020 | Doctor of Physical Therapy | University of Nevada, Las Vegas – Las Vegas, NV
May 2014 | Bachelor of Science in Health Sciences | University of Arizona – Tucson, AZ
May 2012 | Associate of Science | Pima Community College – Tucson, AZ

Licensure

- Pending National Physical Therapy Examination, 2020

Certifications

- American Heart Association, BLS for Healthcare Providers (expires April 2020)
- Certified HawkGrips Practitioner Level I (September 2018)
- HIPAA Training Certified (September 2017)
- Blood-borne Pathogens Training Certified (September 2017)

Clinical Affiliations

Student Physical Therapist – Advanced Health Care of Henderson – Las Vegas, Nevada
January 2020 – March 2020

Student Physical Therapist – St. Rose Dominican Hospital, San Martin – Las Vegas, Nevada
September 2019 – December 2019

Student Physical Therapist – Rapid Rehab Physical Therapy – Las Vegas, Nevada
July 2019 – September 2019

Student Physical Therapist – ATI Physical Therapy – North Las Vegas, Nevada
June 2018 – August 2018

Employment

Physical Therapy Technician – Tucson Orthopaedic Institute, Physical Therapy – Tucson, AZ
August 2014 – May 2017

Member Services Specialist II – YMCA of Southern Arizona – Tucson, AZ
July 2013 – May 2017

Research Activity

- Cummins A, **Khuu C**, Parker S, Shepherd S, Ho KY. Comparisons of Patellar Bone Mineral Density Between Individuals With and Without Patellofemoral Pain
 - Presented at American Physical Therapy Association Combined Sections Meeting, Orthopaedic Platform Session, February 2020
 - Submitted for publication to The Knee, *accepted for publication*

Membership in Professional Organizations

- Member American Physical Therapy Association (2017 to present)
- Member Nevada Physical Therapy Association (2017 to present)

Honors and Awards

- 2019 UNLV Physical Therapy Scholarship Award
- 2009 Pima Community College Chancellor's Recognition Scholarship

Steven Shepherd

Department of Physical Therapy, University of Nevada, Las Vegas
4505 Maryland Parkway, Las Vegas, Nevada 89154
stevensshepherd23@gmail.com

Education

May 2020 | Doctor of Physical Therapy | University of Nevada, Las Vegas – Las Vegas, NV
May 2014 | Bachelor of Science in Nutritional Science | Brigham Young University – Provo, UT

Licensure

- Pending National Physical Therapy Examination, 2020

Certifications

- American Heart Association, BLS for Healthcare Providers (expires April 2020)
- HIPAA Training Certified (September 2017)
- Blood-borne Pathogens Training Certified (September 2017)

Clinical Affiliations

Student Physical Therapist – St. Rose Dominican Hospital, Siena – Henderson, Nevada
January 2020 – March 2020

Student Physical Therapist – Spring Valley Hospital – Las Vegas, Nevada
September 2019 – December 2019

Student Physical Therapist – Sunrise Hospital Pediatrics – Las Vegas, Nevada
July 2019 – September 2019

Student Physical Therapist – Concentra Physical Therapy – Henderson, Nevada
June 2018 – August 2018

Employment

Diet Technician – Utah State Hospital – Provo, UT
June 2016 – April 2017

Physical Therapy Technician – Utah Valley Physical Therapy – Provo, UT
October 2014 – May 2016

Research Activity

- Cummins A, Khuu C, Parker S, **Shepherd S**, Ho KY. Comparisons of Patellar Bone Mineral Density Between Individuals With and Without Patellofemoral Pain

- Presented at American Physical Therapy Association Combined Sections Meeting, Orthopaedic Platform Session, February 2020
- Submitted for publication to The Knee, *accepted for publication*

Membership in Professional Organizations

- Member American Physical Therapy Association (2017 to present)
- Member Nevada Physical Therapy Association (2017 to present)

Honors and Awards

- 2018 UNLV Physical Therapy Scholarship Award