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Association of hip and pelvic geometry with tibiofemoral osteoarthritis: Multicenter Osteoarthritis Study (MOST)

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SUMMARY

Objective: Lateral tibiofemoral osteoarthritis (OA) is overall less common than medial tibiofemoral OA, but it is more prevalent in women. This may be explained by sex differences in hip and pelvic geometry. The aim of this study is to explore sex differences in hip and pelvic geometry and determine if such parameters are associated with the presence of compartment-specific knee OA.

Methods: This case-control study reports on 1,328 hips/knees from 664 participants and is an ancillary to the Multicenter Osteoarthritis Study (MOST). Of the 1,328 knees, 219 had lateral OA, 260 medial OA, and 849 no OA. Hip and pelvic measurements were taken from full-limb radiographs on the ipsilateral side of the knee of interest. After adjusting for covariates, means were compared between sexes and also between knees with medial and lateral OA vs no OA using separate regression models.

Results: Women were shown to have a reduced femoral offset (FO) (mean 40.9 mm vs 45.9 mm; $P = 0.001$) and more valgus neck-shaft angle (mean 128.4° vs 125.9°; $P < 0.001$) compared to men. Compared to those with no OA, knees with lateral OA were associated with a reduced FO ($P = 0.012$), increased height of hip centre (HHC) ($P = 0.003$), more valgus neck-shaft angle ($P = 0.042$), and increased abductor angle ($P = 0.031$). Knees with medial OA were associated with a more varus neck-shaft angle ($P = 0.043$) and a decreased abductor angle ($P = 0.003$).

Conclusion: These data suggest anatomical variations at the hip and pelvis are associated with compartment-specific knee OA and may help to explain sex differences in patterns of knee OA.

Introduction

Primary knee osteoarthritis (OA) tends to affect a single compartment at the outset, most commonly the medial tibiofemoral compartment[1–3]. Most activities of daily living generate a greater load in the medial compared to the lateral compartment of the knee[4–6]. This difference in loading has been used to explain the finding that medial knee OA is overall more prevalent than lateral knee OA. However, it is interesting to note that when lateral OA does occur, it is more common in women[2,3]. Among subjects with knee OA in the Framingham Osteoarthritis Study, the ratio of prevalence of medial to lateral disease was roughly 5 to 1 in women, and 8–9 to 1 in men[2]. A difference in hip morphology between sexes may help to explain this finding.

Women have been shown to exhibit decreased hip abductor muscle strength and increased hip adduction in comparison to men[7–9]. A decreased hip abductor peak torque in women correlates with valgus displacement and an increased abduction moment at the knee[7,10,11]. The mechanism of injury related to hip abductor weakness – increased hip adduction and knee valgus displacement – has been associated previously with other knee pathologies, such as patellofemoral pain syndrome and iliotibial band syndrome[12–14]. One explanation is that reduced hip abductor strength decreases proximal control of the hip, which then translates into abnormal knee kinematics[7]. Overall, these findings support an association between decreased abductor muscle strength and increased valgus loading in the knee joint.

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Impaired abductor muscle strength may be intrinsic, inherent to the muscle itself, or extrinsic, the result of local anatomical geometry. Extrinsically induced impairment has been described in relation to variations in the geometry of femoral component prostheses used in total hip replacement surgery[15–17]. More specifically, anatomical variations that shorten the effective lever arm of the abductor muscles (e.g., reduced femoral offset (FO), coxa valga) result in a reduction in their moment-generating capacity[18]. Therefore, variations in hip geometry that reduce the mechanical advantage of the abductors may lead to abductor muscle weakness and pathological mechanics similar to those described above. It is possible women have been shown to have decreased abductor muscle strength compared to men due to differences in pelvic/hip morphology, rather than due to other underlying causes of muscle insufficiency (muscle composition, volume, activation, etc.).

Given that knee malalignment has been shown to be a risk factor for the development and progression of knee OA[19–21], the higher prevalence of valgus knee malalignment in women is an alternative and simpler explanation for why lateral OA is more common in women[3]. However, this is not a straightforward explanation, as there exist conflicting reports about the ability of malalignment to predict knee OA[22,23], as well as evidence to suggest a discrepancy in the level of risk for varus vs valgus malalignment. In one study, varus but not valgus malalignment was associated with the incidence of knee OA[24]. It is also important to note that even if knee malalignment contributes to the difference in prevalence of lateral OA between men and women, differences in hip geometry and their associated biomechanics may also contribute to the discrepancy.

While there is a substantial literature illustrating how variations in hip geometry can alter abductor muscle forces, there is limited evidence to suggest whether such variations are associated with compartment-specific knee OA or knee malalignment. There remains a need to examine associations between hip geometry, knee alignment, and knee OA. This study has three aims:

1. Compare hip/pelvic geometry and knee alignment between men and women among a cohort of subjects with and without knee OA.
2. Explore whether variations in hip/pelvic geometry are associated with the presence of medial vs lateral compartment knee OA.
3. Determine if variations in hip/pelvic geometry are associated with differences in knee alignment, assessed as the mechanical axis of the knee.

Methods

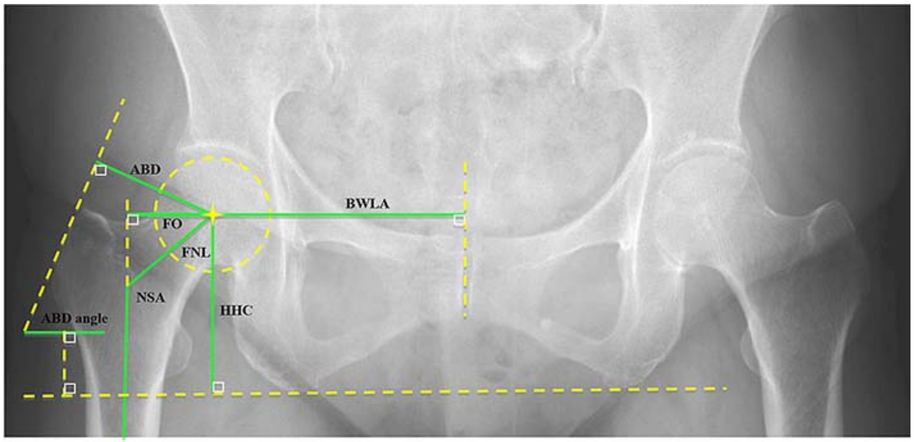
This nested case–control study was conducted ancillary to the Multicenter Osteoarthritis Study (MOST). MOST is an NIH-funded observational study of risk factors for individuals who either had or were at elevated risk of knee OA at baseline. The study includes 3026 participants, aged 50–79 years at enrolment, that were recruited from two US communities, Birmingham, Alabama and Iowa City, Iowa. A detailed description of the study population has been published previously[25,26]. For the current study, participants were excluded if they had undergone a joint replacement in the hip, knee, or ankle. Additionally, the MOST cohort excluded participants if they screened positive for rheumatoid arthritis, ankylosing spondylitis, psoriatic arthritis, reactive arthritis, or were unable to walk without the help of another person or walker.

The population for the current study was determined by first selecting all participants at the MOST baseline visit with either unilateral or bilateral lateral OA ($N = 168$). Unilateral OA was defined as positive radiographic OA in one knee and negative radiographic OA in the contralateral knee; bilateral OA was defined as positive radiographic OA in both knees. An equal number of participants with medial OA ($N = 168$) and twice the number of control participants ($N = 336$) were then randomly selected, matched for age, sex and body mass index (BMI). Case knees (positive radiographic OA) were identified as having Kellgren/Lawrence (K/L) ≥ 2 with joint space narrowing (JSN) score ≥ 1 (0–3 OARSI atlas scale) in the specified compartment with no JSN in the adjoining compartment. Control participants were identified as those with negative radiographic OA (K/L = 0,1 and JSN = 0) in both knees. All measurements were then performed by an author (AB) blinded to knee OA status. Unreadable (due to poor image quality) radiographs ($N = 8$) were discarded prior to unblinding. After unblinding, the eight discarded films were determined to all be from participants with lateral OA. Therefore, the final participant population used for subsequent analyses in the current study consisted of 160 participants with lateral OA (101 unilateral/59 bilateral), 168 participants with medial OA (76 unilateral/92 bilateral), and 336 control participants. On a limb basis, this equated to 1,328 hips/knees: 219 knees with lateral OA, 260 knees with medial OA, and 849 knees with no OA.

Measurements of hip/pelvic geometry and knee alignment were taken from full-limb, standing radiographs using OsiriX software (Orthopaedic Studio (customized version), Spectronic Medical AB, Helsingborg, Sweden). Full-limb radiographs were obtained using a strict protocol defined by previously described methods[27]. Knee alignment was assessed as the hip-knee-ankle angle (HKA-mechanical axis), defined as the angle between a line connecting the centre of the femoral head and the centre of the femoral intercondylar notch and another line between the centre of the tibial plateau and the centre of the tibial plafond. Hip/pelvic measurements included the abductor angle (ABD angle), femoral neck-shaft angle (NSA), FO, femoral neck length (FNL), height of hip centre (HHC), body weight lever arm (BWLA), and abductor lever arm (ABD) (Fig 1). All hip measurements were taken from the ipsilateral side of the knee in interest. In order to account for the potential influence of pelvic width, femoral head size, and/or hip JSN on hip geometry, the femoral head-to-femoral head (FH-FH) length was measured and used as a covariate in our regression models. The FH-FH length was defined as the distance between the centre of the right and left femoral heads.

Fifty radiographic examinations of the lower limb were used to evaluate the intra-class correlation coefficient (ICC) for both intra- and inter-observer variability. To determine intra-observer variability, the same observer measured the radiographs after an interval of 6 months. For inter-observer variability, an independent, non-author observer then repeated the same measurements. The ICC values, as well as the coefficient of variation for each variable, are listed in Table I.

Binomial logistic regression was used to compare hip geometry and knee alignment between sexes. Variables included in the binomial logistic regression model were age, height, BMI, and FH-FH length. We evaluated the association of hip/pelvic geometry with the presence of compartment-specific knee OA using logistic regression models. We analysed both limbs from all participants and used the bivariate outcome of compartment-specific OA vs no OA. Two separate models were used to compare knees with medial OA vs no OA and knees with lateral OA vs no OA. Variables included in the multivariable logistic regression models were age, sex, height, BMI, and FH-FH length. We used generalized estimating equations (GEE) to account for the correlation between hips and knees within a person. Odds ratios were calculated per the standard deviation (SD) of difference in the parameter of interest. A Pearson bivariate correlation analysis was performed to determine the



Legend: **ABD** – abductor lever arm; **ABD angle**- abductor angle; **NSA** – femoral neck-shaft angle; **FO** – femoral offset; **FNL** – femoral neck length; **HHC** – height of hip centre; **BWLA** – body weight lever arm.

Fig. 1. Radiological assessment of hip geometry.

direction, strength, and significance of any relationships between hip variables and knee alignment.

Results

Of the 664 participants included in this study, 474 (71%) participants were women. The participants' mean age and BMI ± SD was 63.3 ± 8.2 years and 30.4 ± 5.7 respectively. A breakdown of the demographics and distribution of knee OA by sex is listed in Tables II–III.

Sex differences in hip geometry and knee alignment

After adjusting for age, height, BMI, and FH-FH length, binomial logistic regression showed the only significant differences in hip geometry and knee alignment between sexes were FO, NSA, and HKA (Table IV). Compared to women, men had an increased FO (OR 1.09, 95% CI 1.04–1.14; $P = 0.001$), a decreased (more varus) NSA (OR 0.90, 95% CI 0.86–0.95; $P < 0.001$), and a decreased (more varus) HKA (OR 0.79, 95% CI 0.73–0.86; $P < 0.001$).

Association between hip geometry and knee OA

Adjusting for age, sex, height, BMI, and FH-FH length, the presence of compartment-specific knee OA was associated with variations in hip geometry (Table V). Compared to knees with no OA, knees with lateral compartment OA were associated with a reduced FO (OR 0.96, 95% CI 0.92–0.99; $P = 0.012$), increased HHC (OR 1.06, 95% CI 1.02–1.10; $P = 0.003$), increased abductor angle (OR 1.03, 95% CI 1.00–1.06; $P = 0.031$), and an increased (more valgus) NSA (OR 1.03, 95% CI 1.00–1.07; $P = 0.042$). There was no significant difference in the lever arm ratio or FNL between knees with no OA compared to those with lateral OA.

Compared to knee with no OA, knees with medial compartment OA were associated with a reduced ABD angle (OR 0.96, 95% CI 0.94–0.99; $P = 0.003$) and a decreased (more varus) NSA (OR 0.97, 95% CI 0.94–1.00; $P = 0.043$). There was no significant difference in the lever arm ratio, FO, FNL, or HHC between knees with no OA compared to knees with medial OA.

Association between hip geometry and knee alignment

Lateral OA was associated with a more valgus HKA (OR 1.76, 95% CI 1.60–1.94; $P < 0.001$), while medial OA was associated with a more varus HKA (OR 0.67, 95% CI 0.62–0.73; $P < 0.001$). All hip variables except for lever arm ratio had a significant but weak relationship with HKA (Table VI). As the FO, FNL, or HCC decreased, or as the ABD angle or NSA increased (more valgus), the HKA also increased (more valgus).

Discussion

Hip and pelvic geometry were associated with the presence of compartment-specific knee OA. A reduced FO, increased HHC, increased abductor angle, and increased (more valgus) neck-shaft angle were associated with lateral compartment OA. A reduced abductor angle and decreased (more varus) neck-shaft angle were

Table I
Intra- and inter-observer reliability

	ICC		CV (%)
	Intra-observer	Inter-observer	
FH-FH length	0.99	0.99	5.6
BWLA	0.99	0.99	6.0
Abductor lever arm	0.95	0.98	11.3
FO	0.99	0.99	14.0
FNL	0.94	0.92	9.9
Height hip centre	0.99	0.99	7.8
Femoral NSA	0.98	0.98	4.9
Abductor angle	0.91	0.91	11.5
HKA angle	0.99	0.99	NA*

CV (%) = (SD/Mean) × 100.
* Not applicable due to scale.

Table II
Demographics by sex

	Women		Men	
	N	Mean (SD)	*N*	Mean (SD)
Age (years)	948	65 (8)	380	60 (8)
Height (cm)	948	163 (10)	380	178 (6)
BMI (kg/m^2)	948	30 (6)	380	31 (5)

Table III
Distribution of knee OA by sex

	Knee OA status (*N*)			Total
	No OA	Medial OA	Lateral OA	
Women	595	191	162	948
Men	254	69	57	380
Total	849	260	219	**1,328**

associated with medial compartment OA. Variations in hip and pelvic geometry were also shown to differ significantly between sexes. The cohort in this study was predominantly women (71%) because it was determined by first selecting all participants with lateral OA at the MOST baseline visit. This is an expected sex distribution as the increased prevalence of lateral OA in women has already been shown in this cohort[3].

After adjusting for age, height, BMI, and FH-FH length, the only significant differences in hip geometry between sexes were FO and NSA. More specifically, women were found to have a reduced FO compared to men. After adjusting for covariates, our results demonstrated that a reduced FO was also associated with lateral knee OA. The association between a reduced FO and lateral knee OA contrasts with a previous study by Weidow *et al.* that found no difference in FO between those with and without lateral OA, but an increased FO in subjects with medial OA vs controls[28]. Given that the study by Weidow *et al.* was underpowered and was limited by selection bias, those results should be interpreted with caution.

In addition to a reduced offset, women were found to have a more valgus NSA compared to men. This finding contrasts with previous studies that revealed no difference in NSA between sexes[29,30] and that men had an increased NSA compared to women[31–33]. It has been shown that NSA variation across populations correlates with differences in lifestyle and environmental exposure[30], suggesting that our results may differ from previous studies due to its focus on a sub-population of individuals at an elevated risk of knee OA. It may be that the NSA in subjects with or at risk for knee OA differ due to the influence of altered biomechanics, so far as biomechanics play a role in incidence and/or progression of disease. To our knowledge, our study is the first to examine sex differences in NSA among this population. Similar to a reduced offset, a more valgus NSA will shorten the effective lever arm of the abductor muscles and could predispose to abnormal kinematics. Our finding of a significant association between a reduced FO and increased NSA to lateral OA supports this postulated mechanism. However, our results also show a more varus NSA is associated with medial OA, a finding for which no biomechanical rationale has yet been proposed.

It is important to note that Pearson correlation analyses revealed that FO and NSA correlated significantly with HKA. Reduced FO or increased NSA (more valgus) was associated with increased HKA (more valgus). Given lower limb mechanical malalignment is a well-described risk factor for knee OA[19–21], it possible the association between hip geometry and knee OA is driven by its relationship with knee alignment. Further studies are necessary to more explicitly evaluate the association between variations in hip anatomy and differences in knee alignment.

An increased HHC was associated with lateral but not medial OA. An increase in HHC equates to superior displacement of the hip centre. This affects the moment arm and force-length relationship of the abductor muscles, and has been shown to result in a decrease in the moment-generating capacity of the abductors[34–36]. Therefore, it would be logical to associate an increased HHC with lateral OA based on the previously described mechanism of hip abductor weakness and abnormal kinematics. As a result of the decreased mechanical advantage of the muscles, increased abductor forces are necessary to balance the weight of the body[18]. It is possible these increased forces are transmitted to the knee and predispose one to lateral knee OA.

Finally, men were shown to have a decreased abductor angle compared to women, and a decreased abductor angle was also associated with medial OA. To our knowledge, such findings have not been previously reported. The potential biomechanical relevance is that a reduced abductor angle represents a more horizontal angle of pull for the abductor muscles. The anterior fibres of the gluteus medius and gluteus minimus, which originate anterior to the centre of rotation of the hip, promote internal rotation of the femur[37]. In the single-legged stance, this allows the contralateral hip to swing forward. It is possible a more horizontal angle of pull for gluteus medius and minimus in the grounded leg would promote increased medial rotation on the femur, and produce an increased adduction moment in the knee. While a peak knee adduction moment (KAM) has been associated with increased progression and severity of medial OA[38–41], only 50% of the variability in KAM is accounted for by knee malalignment[42]. Thus, the proposed mechanism of increased internal femoral torque due to a more horizontal abductor angle offers a potential dynamic explanation to further explain increased medial load during the stance phase of gait. In addition, given men have a significantly reduced abductor angle compared to women, it would explain their reduced tendency towards lateral OA.

While this study detected a significant relationship between hip geometry and knee OA, it remains unclear if the association is due to altered hip biomechanics, an influence on knee alignment, or both. Variations in hip geometry that were associated with knee OA were also associated with knee alignment. However, while hip geometry correlated significantly to knee alignment, the strength of the relationships (Pearson's r) was weak for all variables. Therefore, it remains possible that variations in hip geometry alter hip

Table IV
Sex differences in hip geometry and knee alignment

	Women		Men		Binomial logistic regression*
	N	Mean (SD)	*N*	Mean (SD)	Men compared to women (OR (95%CI))
Lever arm ratio	780	1.82 (0.21)	197	1.67 (0.24)	0.32 (0.07, 1.46); $P = 0.141$
FO (mm)	948	40.9 (5.1)	380	45.9 (6.2)	1.09 (1.04, 1.14); $P = 0.001$
FNL (mm)	948	52.5 (4.7)	380	56.9 (5.6)	1.02 (0.97, 1.07); $P = 0.373$
Height hip centre (mm)	948	73.4 (5.1)	342	79.8 (5.3)	1.05 (0.99, 1.11); $P = 0.113$
Femoral NSA (degrees)	948	128.4 (6.2)	380	125.9 (5.9)	0.90 (0.86, 0.95); $P < 0.001$
Abductor angle (degrees)	789	70.3 (7.4)	247	67.6 (9.3)	0.97 (0.94, 1.01); $P = 0.121$
HKA angle (degrees)	835	−0.1 (4.0)	342	−2.4 (4.0)	0.79 (0.73, 0.86); $P < 0.001$

Lever arm ratio = body weight lever arm/abductor lever arm.
For HKA, negative values represent varus orientation and positive values valgus orientation.
* Binomial logistic regression controlling for age, height, BMI, and FH-FH length.

Table V
Comparison of hip geometry and knee alignment by knee OA status

	Lateral OA		Medial OA		No OA		Lateral OA vs No OA	Medial OA vs No OA
	N	Mean (SD)	*N*	Mean (SD)	*N*	Mean (SD)	OR (95% CI); *P*-value*	OR (95% CI); *P*-value*
Lever arm ratio	152	1.8 (0.2)	192	1.8 (0.2)	633	1.8 (0.2)	1.05 (0.34, 3.20); $P = 0.930$	0.81 (0.32, 2.09); $P = 0.669$
FO (mm)	219	41.3 (5.9)	260	42.8 (6.0)	849	42.4 (5.8)	0.96 (0.92, 0.99); $P = 0.012$	1.02 (0.99, 1.05); $P = 0.261$
FNL (mm)	219	53.6 (5.7)	260	53.6 (5.7)	849	53.8 (5.1)	0.98 (0.94, 1.02); $P = 0.254$	1.00 (0.96, 1.03); $P = 0.832$
Height hip centre (mm)	212	76.1 (5.7)	255	75.5 (6.0)	823	74.8 (5.8)	1.06 (1.02, 1.10); $P = 0.003$	1.03 (1.00, 1.07); $P = 0.082$
Femoral NSA (degrees)	219	129.1 (6.7)	260	126.7 (6.2)	849	127.7 (6.1)	1.03 (1.00, 1.07); $P = 0.042$	0.97 (0.94, 1.00); $P = 0.043$
Abductor angle (degrees)	166	71.0 (8.4)	199	67.5 (9.0)	671	70.0 (7.5)	1.03 (1.00, 1.06); $P = 0.031$	0.96 (0.94, 0.99); $P = 0.003$
HKA angle (degrees)	204	3.8 (3.7)	247	−4.4 (3.9)	726	−0.8 (2.8)	1.76 (1.60, 1.94); $P < 0.001$	0.67 (0.62, 0.73); $P < 0.001$

*Logistic regression with GEE; controlling for age, sex, BMI, height, and FH-FH length.

biomechanics and predispose knee OA due to pathological kinematics, and knee malalignment may merely represent the severity of disease (increased JSN). The concept that knee alignment is not a risk factor but rather a marker of disease severity and/or progression has been previously suggested[24]. Alternatively, a difference in proximal tibial geometry between sexes, specifically the coronal tibial slope, has been suggested to explain an increased valgus displacement of the knee in women[43]. Elevated tibiofemoral contact stress has been shown to predict cartilage damage, and so the increased valgus stress among women may disproportionately predispose them to lateral compartment OA[44].

One limitation of this study was the cross-sectional design. While we found that hip geometry is associated with both knee alignment and presence of knee OA, we cannot comment on the direction of the relationship. While it is more likely that hip geometry contributed to knee OA rather than the reverse, longitudinal analyses are currently underway to clarify this relationship. Second, our study assessed only static alignment in one anatomical plane and dynamic alignment may be an important factor in the relationships we have investigated. Third, we did not evaluate femoral anteversion, although it may influence both knee alignment and the abductor lever arm. Finally, while we accounted for variations in hip JSN by adjusting our models for FH-FH length, there was no formal assessment of hip OA. The relationship between hip OA and hip geometry is likely complex and may include indirect factors such as genetics, for which we were unable to adjust.

There are several strengths to this study. We utilized standing, full-limb radiographs acquired from a large, multi-center cohort. Without manual manipulation of the subject, supine pelvic films are associated with external rotation of the femur and can affect perceived measures on antero-posterior films. Therefore, our use of standing, full-limb films increases the likelihood of accurate measures. Also, the MOST cohort is large and well-characterized using standardized measures, strengthening confidence in our results.

In conclusion, our study offers novel information about differences in hip geometry between sexes, and also how variations in hip geometry are associated with compartment-specific knee OA.

Table VI
Association between hip geometry and lower limb mechanical alignment

	HKA angle
Lever arm ratio	$r = 0.04$, $P = 0.288$
FO	$r = -0.22$, $P < 0.001$
FNL	$r = -0.17$, $P < 0.001$
Height hip centre	$r = -0.08$, $P = 0.023$
Femoral NSA	$r = 0.17$, $P < 0.001$
Abductor angle	$r = 0.27$, $P < 0.001$

These findings are clinically relevant as they may be used to identify individuals at elevated risk for lateral knee OA. Potential strategies have been proposed to alter gait and reduce aberrant loading of the knee joint[40], but further explanation of all factors contributing to the mechanical insult will enable formulation of preventative treatment strategies and help to identify patients who would benefit most.

Author contributions

Conception and design: Boissonneault, Lynch, Murray, Nevitt, Pandit.
Collection and assembly of data: Boissonneault, Lynch.
Analysis and interpretation: All.
Drafting of article: Boissonneault, Nevitt, Pandit.
Critical revision: All.
Final approval: All.

Role of the funding source

The National Institutes of Health had no role in the study design, collection, analysis, or writing of the manuscript.

Conflict of interest

The authors have no conflict of interest to disclose with respect to this work. The funding agencies did not participate in the study conception, data collection, analyses, interpretations or decision to publish.

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