Title

Relation of Step Length to Magnetic Resonance Imaging–Detected Structural Damage in the Patellofemoral Joint: The Multicenter Osteoarthritis Study

Journal

Arthritis Care & Research, 68(6)

ISSN

2151-464X

Authors

Stefanik, Joshua J
Gross, K Douglas
Guermazi, Ali
et al.

Publication Date

2016-06-01

DOI

10.1002/acr.22738

Peer reviewed

Author Manuscript
Author Manuscript
Author Manuscript

HHS Public Access
Author manuscript
Arthritis Care Res (Hoboken). Author manuscript; available in PMC 2017 June 01.

Published in final edited form as:
Arthritis Care Res (Hoboken). 2016 June ; 68(6): 776–783. doi:10.1002/acr.22738.

The relation of step length to MRI detected structural damage in the patellofemoral joint: The Multicenter Osteoarthritis Study

Joshua J. Stefanik, MSPT, PhD[1], **K. Douglas Gross, DPT, ScD**[1,2], **Ali Guermazi, MD**[1], **David T. Felson, MD, MPH**[1], **Frank W. Roemer**[3], **Jingbo Niu, DSc**[1], **John A. Lynch, PhD**[4], **Neil A. Segal, MD**[5], **Cora E. Lewis, MD**[6], and **Cara L. Lewis, PT, PhD**[1]

[1]Boston University, Boston, Massachusetts

[2]MGH Institute of Health Professions, Boston, Massachusetts

[3]Department of Radiology, Klinikum Augsburg, Augsburg, Germany

[4]University of California, San Francisco, CA

[5]University of Iowa, Iowa City, IA

[6]University of Alabama, Birmingham, AL

Abstract

Objective—Investigate the relation of step length to the sex-specific prevalence and worsening of MRI-detected structural damage in the patellofemoral joint (PFJ) among a cohort of older women and men with or at risk for knee osteoarthritis (OA).

Methods—The Multicenter Osteoarthritis (MOST) Study is a cohort study of persons aged 50-79 years with or at risk for knee OA. Step length was assessed using the GAITRite system at the 60-month visit and cartilage damage and bone marrow lesions (BMLs) were graded on MRI at the 60 and 84-month visits. We divided step length into sex-specific quintiles and examined the relation of step length to the prevalence and worsening of cartilage damage and BMLs in the PFJ using logistic regression, adjusting for age, body mass index (BMI), leg length and tibiofemoral joint structural damage.

Results—4094 and 4083 PFJ subregions from 1053 knees were studied for the cartilage and BML analyses, respectively. Mean age was 65.6 (±8.1) years and mean BMI was 29.1 (±4.7) kg/m^2; 62% were female. In women, compared to those with the shortest step length those with the longest step length had 0.62 (0.43, 0.88) and 0.59 (0.40, 0.87) times the odds of cartilage damage and BMLs, respectively. There was no cross-sectional association in men, and no longitudinal association in either sex.

Conclusion—Women with PFJ structural damage may adapt their gait by shortening their step length, but this may not be sufficient to reduce risk of worsening damage over time.

Corresponding Author: Joshua Stefanik, MSPT, PhD, Boston University College of Health and Rehabilitation Sciences: Sargent College, 635 Commonwealth Avenue, Boston, MA 02215, ; Email: stefanik@bu.edu

Dr. Guermazi is President, shareholder Boston Imaging Core Lab (BICL), LLC; and Consultant to MerckSerono, TissueGene, OrthoTrophix and Genzyme. Dr. Roemer is CMO, shareholder Boston Imaging Core Lab (BICL), LLC.

Aberrant joint loading during gait is one potential mechanism for development of knee osteoarthritis (OA), which can result in cartilage and bone damage. While studies of tibiofemoral joint (TFJ) OA have identified altered joint loading and / or risk of structural joint damage in association with gait alterations that include aberrant trunk lean, pelvic drop, and toe out angle (1-3), far fewer studies have investigated the effects of gait alterations on risk of patellofemoral joint (PFJ) damage. Increased hip internal rotation, hip adduction, and knee valgus have been previously described in younger individuals with patellofemoral pain (PFP) (4-12), but it is not yet clear whether these same alterations are present in older persons with PFJ OA (13, 14). Nor is it clear from these cross-sectional investigations whether the gait alterations identified in persons with PFP are a cause or consequence of PFJ pathology.

Recent studies of runners with and without PFP found that, when instructed to run with a 10% increase in step length, PFJ stress increased 18-31% with each step (15, 16). The measured increase in PFJ stress corresponded to an increased internal knee extensor moment. This increase in the knee extensor moment would, in turn, increase the demands on the quadriceps muscle to prevent the knee from further flexing. The additional contraction of the quadriceps would increase PFJ stress. If step length can affect PFJ stress so profoundly, then individuals with a longer step length during walking may be at increased risk of PFJ OA. However, the mechanics of running and walking differ, and the pattern that emerges during both types of gait is likely to be different between sexes as well (4, 5, 17-21).

Gait retraining may be a simple means of intervening in individuals where specific gait abnormalities are found to affect risk of knee joint structural damage. Targeted gait retraining interventions have previously been shown to improve movement patterns and decrease pain in runners with patellofemoral pain (25-28) and older subjects with medial TFJ OA (29-31). In some instances, very modest changes in gait can have a profound effect on joint loading and stress. These interventions can redistribute mechanical stress at the knee, and limit the risk of worsening structural damage. If longer step length is related to PFJ OA, shortening an individual’s step length may reduce PFJ loading and stress.

The purpose of this study was to investigate the relation of step length during walking to the sex-specific prevalence and longitudinal risk of worsening MRI-detected PFJ structural damage among a cohort of women and men that have or are at risk for knee OA.

Methods

Study Sample

The Multicenter Osteoarthritis (MOST) Study is a NIH-funded cohort study of older adults who have or are at risk of knee OA. 3,026 participants were recruited from the geographic areas around Iowa City, Iowa and Birmingham, Alabama. The institutional review boards at the University of Alabama at Birmingham, University of Iowa at Iowa City, University of California at San Francisco, and Boston University Medical Center approved the study protocol.

Step length and gait speed assessment

To be eligible for the walking exam at the 60-month follow-up visit, participants had to be able to walk independently over short indoor distances without a walking aid or orthotic knee brace. Participants with recent (< 6 weeks) lower limb injury resulting in restricted weight-bearing for ≥ 1 week, recent hospitalization for a cardiovascular or respiratory disorder, lower limb amputation proximal to the toes, or difficulty walking because of a neurological condition were excluded. Following a practice trial, each participant completed 4 walking trials over a 4.9 meter long instrumented GAITRite walkway (CIR Systems, Inc., Havertown, PA). Participants wore their customary walking shoes and were instructed to "walk in your usual way at a pace that feels comfortable and unhurried." To exclude the initial acceleratory and terminal decelerating steps, subjects began walking from a point 1.5 meters in front of the walkway and stopped at a point 1.5 meters beyond the walkway. For each footfall, step length was measured to the nearest tenth of a centimeter (cm) along the length of the walkway as the distance from the heel center of the current footprint to the heel center of the previous footprint of the opposite foot. Negative values were measured in the rare instance that a subject failed to bring the heel center of the advancing foot forward of the stationary foot. Concurrent validity of the GAITRite for the measurement of step length in a comparable population was previously shown to be high (ICC ≥ 0.99) in comparison to 3-dimensional motion analysis (36). In a subset of 58 randomly selected participants in the MOST study (stratified to achieve a balanced representation of sexes and clinic sites), the 14-day test-retest reliability was also very high, with an ICC = 0.93 (95% CI: 0.90, 0.95) for the measurement of mean step length. Gait speed was measured concurrently by the GAITRite as the distance covered in centimeters between the initial and terminal footfalls divided by the time in seconds between these two events. In previous studies of persons with knee OA, gait speed has shown high reliability, with a same-day ICC value of 0.93 (95% CI: 0.88, 0.96) (37). Concurrent validity between the stopwatch–footfall count method and GAITRite was also found to be high (r= 0.97) for both gait speed and stride length (r =0.85) measures (38).

MRI acquisition and structural damage assessment

A 1.0 Tesla extremity MRI system (OrthOne™, ONI Medical Systems, Wilmington, MA) was used with a phased array knee coil to obtain the following sequences: Fat-suppressed fast-spin echo proton density-weighted (PD) sequences in two planes, sagittal (TR 4800 ms, TE 35 ms, 3 mm slice thickness, 0 mm interslice gap, 32 slices, 288 × 192 matrix, 140 mm2 FOV, echo train length 8) and axial (TR 4680 ms, TE 13 ms, 3 mm slice thickness, 0 mm interslice gap, 20 slices, 288 × 192 matrix, 140 mm2 FOV, echo train length 8) and a STIR sequence in the coronal plane (TR 6650 ms, TE 15 ms, TI 100 ms, 3 mm slice thickness, 0 mm interslice gap, 28 slices, 256 × 192 matrix, 140 mm2 FOV, echo train length 8). Two musculoskeletal radiologists (FWR, AG) used the Whole-Organ Magnetic Resonance Imaging Score (WORMS) (39) to assess cartilage morphology and BMLs in the PFJ and TFJ. Any cartilage damage was defined as WORMS scores ≥2. Full-thickness cartilage damage was defined by WORMS scores of 2.5, 5, or 6, which denote full-thickness damage of increasing area within a subregion. Any size BMLs and large BMLs were defined as WORMS scores of ≥1 and ≥2, respectively. In MOST, the inter-reader reliability (weighted kappa) for cartilage and BMLs were 0.85 and 0.89, respectively.

Statistical analysis

We restricted our analysis to PFJ subregions (4 per knee) from 1053 participants who underwent knee MRI at both 60 and 84-month study visits and had step length and leg length assessed at the 60-month visit. 4094 and 4083 subregions from 1053 individuals were studied for the cartilage and BML analysis, respectively (Figure 1). Risk factors for knee OA clearly are different between sexes (22-24), it may also be true that alterations in step length during walking and their impact on PFJ structure may differ in women as compared to men. Given this, we carried out sex-specific analyses. Step length was divided into quintiles, and we determined the relation of step length to *prevalent* full-thickness cartilage loss and BMLs in PFJ subregions using logistic regression with generalized estimating equations, while adjusting for age, BMI, leg length (measured from long limb films from center of femoral head to center of talus) and tibiofemoral joint (TFJ) structural damage. We adjusted for TFJ structural damage (the same feature that was the outcome in the PFJ) in order to be sure the relationship between step length and PFJ damage was not due to coexisting TFJ structural damage. Additionally, we recognize that gait speed may influence step length. We found step length and gait speed to be highly correlated ($r=0.86$; $p<0.0001$); because of this collinearity, we did not adjust for gait speed in our logistic regression models.

Cross-sectional associations between gait parameters such as step length and measures of structural joint damage could be due to causation or compensation. Structural damage within pain-producing joint tissues could cause a person to adjust their step length in order to minimize PFJ stress. To address this, we tried to determine causal effects in two ways. First, in a longitudinal analysis, we determined the relation of step length to the risk of *worsening* cartilage damage and BMLs during the 60 to 84-month follow-up period. For the longitudinal analysis of worsening cartilage damage risk, if a knee had any subregion with a WORMS score of 5 or 6 at 60 months, the entire knee (4 PFJ subregions) was removed from the analysis. Knees with grade 5 or 6 cartilage scores could be considered to have end-stage disease, and although changes can still be detected longitudinally, there is risk of collider bias when studying risk factors for knees with established disease (40, 41). In the longitudinal analysis of worsening BML risk, subregions that demonstrated an improved WORMS score over time were regarded as equivalent to those that did not worsen. Second, in a sensitivity analysis, we excluded all knees from the cross-sectional analysis for which frequent ipsilateral knee pain (i.e. pain, aching or stiffness on most days of the last month) was reported at the 60-month clinic visit.

Results

The mean (±SD) age and BMI of the 1053 participants at the 60-month visit were 66.9 (±7.5) years and 29.6 (±4.7) kg/m^2, respectively, and 62% were female. The mean (±SD) age, BMI, and step length (cm) in females was 67.1 (7.4), 29.2 (4.9), and 63.1 (±7.1), respectively. In males, it was 66.5 (7.7), 30.1 (4.5), and 69.7 (±8.0) cm..

Among women, 2594 and 2597 patellar and anterior femoral subregions were included for the cartilage and BML analyses, respectively. PFJ subregions in knees with the longest step length had the lowest *prevalence* of any cartilage damage and any size BML. There was a 38% and 41% significant reduction in the odds of having any cartilage damage and any size

BML after adjusting for confounding variables (Table 1). There was also a significant linear trend (p=0.01), across quintiles of step length for any cartilage damage and any BML, respectively, with the odds of structural damage decreasing as step length increased (Table 1). There was no association found when using more severe definitions of cartilage damage or BMLs (Table 1).

Among men, 1500 and 1486 patellar and anterior femoral subregions were included for the cartilage and BML analyses, respectively. We found no association between step length and cartilage damage or BMLs in men (Table 2).

In longitudinal analyses, there was no association between step length and *worsening* PFJ cartilage damage and BMLs in women (Table 3) or men (Table 4). When removing knees with frequent knee pain at 60 months, the prevalence analysis effect estimates were, in general, stronger for women and weaker for men.

Discussion

Biomechanical changes in gait have been investigated in younger individuals with PFP (25-28). However, there are few studies that have investigated abnormal gait patterns that are potential targets for gait retraining in older individuals at risk for PFJ OA. We found that among older women, cartilage damage (WORMS ≥2) and BMLs (WORMS ≥1) were *less* prevalent in knees with a longer step length. However, there was no relation of step length to prevalent damage in males, or worsening of cartilage damage or BMLs longitudinally in either sex.

In young female runners with and without PFP, Willson et al. found running with a 10% increase in step length, PFJ stress increased 31% with each step (15). These runners demonstrated an increased peak knee flexion angle and peak internal knee extensor moment as step length increased. The increased knee extensor moment would be expected to increase the demands on the quadriceps muscle to resist further knee flexion, and thereby increase PFJ stress. While it is hypothesized that ambulating with a longer step length would increase PFJ stress and lead to PFJ structural damage, we found that women who ambulate with a longer step length actually had a 38% and 41% reduction in the odds of prevalent cartilage damage and any size BML, respectively. Our results were not consistent with the hypothesis stated above based on Willson et al. (15). This inconsistency may reflect that, in contradiction to Willson et al., we did not investigate changes in step length, nor did we investigate running. It may be that the effect of step length on PFJ stress is different between running and walking due to inherent differences between these modes of locomotion. Running includes an aerial phase and generates much greater ground reaction forces than walking (42). Additionally, the mechanisms that cause PFP pain in young individuals may differ from mechanisms that cause PFJ OA in older individuals.

An alternate explanation for our results may be that individuals with a longer step length are more mobile and overall healthier and because of this we observed a lower prevalence of cartilage damage and BMLs in the PFJ in these individuals. As we found that step length and gait speed are highly correlated (r=0.86), it may be that a longer step length is a marker for increased gait speed. It is known that individuals that walk with a higher gait speed have less knee OA, knee pain and functional limitation (43-45). Because of the high correlation between step length and gait speed we did not adjust our analyses for gait speed and it is difficult to disentangle which gait variable is contributing to our findings of lower odds of PFJ structural damage. Taken as a whole older individuals with or at risk for knee OA should be encouraged to remain physically active to prevent functional decline and decline in overall health.

In contrast to our cross-sectional findings, we found no longitudinal association between step length and risk of worsening of PFJ cartilage damage and BMLs. One possible way of reconciling our cross-sectional and longitudinal findings may be that older women with prevalent disease may shorten their step length in order to reduce PFJ stress and pain. In other words, the shorter step length that we identified among women with prevalent PFJ damage may be compensatory rather than causal (i.e. they already shortened their step length due to structural damage). To further explore this possibility, in sensitivity analyses we removed knees from our cross-sectional analyses that had frequent pain and found similar results. Thus, even in those without current pain (who would be less likely to modify their gait due to pain), the increased prevalence of PFJ structural damage in knees with a shorter step length persisted. Of course, we could not rule out the possibility that women who previously experienced pain as a result of PFJ damage may have already succeeded in eliminating their frequent knee pain by adaptively shortening their step length during walking. It must be noted also that in our longitudinal analyses, there were a limited number of knees with worsening structural damage (typically, <10%). This relatively low rate of worsening damage could be due to a short follow up duration (24 months) or it may be that individuals in the MOST Study who had not already developed structural damage by the 60-month visit may be largely “immune” to disease.

Sex differences in mechanics during running and other functional activities have been noted in younger individuals with PFP (4, 5, 17-21). Our results indicate that ambulating with a longer step length was associated with decreased odds of PFJ structural damage in women, while there was no effect in men. These differences may be due to other biomechanical or structural differences of the lower extremity between sexes. For example, in women to a greater extent than in men, quadriceps weakness has been associated with increased risk for TFJ OA (22). There also may be local structural features of the PFJ (e.g. patella alta, trochlear dysplasia, quadriceps angle, etc.) that may be different in males and females (46-49) that may modify the relationship between gait parameters and PFJ OA. Lastly, it is possible that longer step lengths, by introducing trophic dynamic stress to tissues within the knee, could actually prevent joint damage.

Step length, in most individuals, is easily modifiable and may offer a potential intervention strategy for women with PFJ structural damage. However, as already discussed, our longitudinal results do not support altering step length as a preventative intervention. Moreover, while our results are from an observational study using self-selected gait speed as the exposure variable, the effectiveness of interventions intending to modify gait parameters would be more appropriately investigated in a randomized clinical trial. As discussed previously it may be that step length is a marker for gait speed and in the setting of a clinical trial it would be possible to manipulate each gait parameter and further disentangle how step length and gait speed relate to PFJ OA.

We recognize limitations in the current study. Because of the cross-sectional nature of our main results we cannot infer causality. It is likely that pain from structural damage can cause someone to alter his or her gait pattern to avoid pain and vice versa. To address this potential reverse causation we removed knees with frequent knee pain and we found a similar pattern of results. There were also a limited number of knees with worsening structural damage over 24 months. Additionally, it would have been ideal to study incidence and not worsening but the number of eligible knees would have been even smaller (incidence occurred in approximately 3% of subregions).

In conclusion, we found in women, but not in men, that ambulating with a longer step length was associated with a reduced the odds of prevalent PFJ structural damage. However, there was no longitudinal relationship between step length and worsening of PFJ structural damage in either sex, suggesting that women with PFJ structural damage may adapt their gait by shortening their step length, but this may not be sufficient to reduce risk of worsening damage over time. Further research is needed into gait mechanics in older individuals with PFJ OA in order to determine more appropriate targets for gait-retraining interventions to prevent worsening PFJ damage.

Acknowledgments

Funding: The Multicenter Osteoarthritis Study is supported by NIH grants U01-AG18820, U01-AG18832, U01-AG18947, U01-AG19069, and P60-AR47785. Dr. Stefanik's work was supported by an Investigator Award from the Rheumatology Research Foundation. Dr. Cara Lewis was supported by NIH K23-AR063235.

References

1. Chang A, Hurwitz D, Dunlop D, Song J, Cahue S, Hayes K, et al. The relationship between toe-out angle during gait and progression of medial tibiofemoral osteoarthritis. Ann Rheum Dis. 2007; 66(10):1271–5. [PubMed: 17267516]
2. Hunt MA, Birmingham TB, Bryant D, Jones I, Giffin JR, Jenkyn TR, et al. Lateral trunk lean explains variation in dynamic knee joint load in patients with medial compartment knee osteoarthritis. Osteoarthritis Cartilage. 2008; 16(5):591–9. [PubMed: 18206395]
3. Simic M, Hunt MA, Bennell KL, Hinman RS, Wrigley TV. Trunk lean gait modification and knee joint load in people with medial knee osteoarthritis: the effect of varying trunk lean angles. Arthritis Care Res (Hoboken). 2012; 64(10):1545–53. [PubMed: 22556125]
4. Nakagawa TH, Moriya ET, Maciel CD, Serrao AF. Frontal plane biomechanics in males and females with and without patellofemoral pain. Med Sci Sports Exerc. 2012; 44(9):1747–55. [PubMed: 22460471]
5. Nakagawa TH, Moriya ET, Maciel CD, Serrao FV. Trunk, pelvis, hip, and knee kinematics, hip strength, and gluteal muscle activation during a single-leg squat in males and females with and without patellofemoral pain syndrome. J Orthop Sports Phys Ther. 2012; 42(6):491–501. [PubMed: 22402604]
6. Souza RB, Draper CE, Fredericson M, Powers CM. Femur rotation and patellofemoral joint kinematics: a weight-bearing magnetic resonance imaging analysis. J Orthop Sports Phys Ther. 2010; 40(5):277–85. [PubMed: 20436239]
7. Souza RB, Powers CM. Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. J Orthop Sports Phys Ther. 2009; 39(1):12–9. [PubMed: 19131677]

8. Powers CM. The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. J Orthop Sports Phys Ther. 2003; 33(11):639–46. [PubMed: 14669959]
9. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. J Orthop Sports Phys Ther. 2010; 40(2):42–51. [PubMed: 20118526]
10. Dierks TA, Manal KT, Hamill J, Davis I. Lower extremity kinematics in runners with patellofemoral pain during a prolonged run. Med Sci Sports Exerc. 2011; 43(4):693–700. [PubMed: 20798656]
11. Willson JD, Davis IS. Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands. Clin Biomech (Bristol, Avon). 2008; 23(2):203–11.
12. Dierks TA, Manal KT, Hamill J, Davis IS. Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. J Orthop Sports Phys Ther. 2008; 38(8):448–56. [PubMed: 18678957]
13. Fok LA, Schache AG, Crossley KM, Lin YC, Pandy MG. Patellofemoral joint loading during stair ambulation in people with patellofemoral osteoarthritis. Arthritis Rheum. 2013; 65(8):2059–69. [PubMed: 23740512]
14. Pohl MB, Patel C, Wiley JP, Ferber R. Gait biomechanics and hip muscular strength in patients with patellofemoral osteoarthritis. Gait Posture. 2013; 37(3):440–4. [PubMed: 23047017]
15. Willson JD, Sharpee R, Meardon SA, Kernozek TW. Effects of step length on patellofemoral joint stress in female runners with and without patellofemoral pain. Clin Biomech (Bristol, Avon). 2014; 29(3):243–7.
16. Willson JD, Ratcliff OM, Meardon SA, Willy RW. Influence of step length and landing pattern on patellofemoral joint kinetics during running. Scand J Med Sci Sports. 2015
17. Willy RW, Manal KT, Witvrouw EE, Davis IS. Are mechanics different between male and female runners with patellofemoral pain? Med Sci Sports Exerc. 2012; 44(11):2165–71. [PubMed: 22843103]
18. Ferber R, Davis IM, Williams DS 3rd. Gender differences in lower extremity mechanics during running. Clin Biomech (Bristol, Avon). 2003; 18(4):350–7.
19. Cowan SM, Crossley KM. Does gender influence neuromotor control of the knee and hip? J Electromyogr Kinesiol. 2009; 19(2):276–82. [PubMed: 17904864]
20. Chumanov ES, Wall-Scheffler C, Heiderscheit BC. Gender differences in walking and running on level and inclined surfaces. Clin Biomech (Bristol, Avon). 2008; 23(10):1260–8.
21. Nakagawa TH, Serrao FV, Maciel CD, Powers CM. Hip and Knee Kinematics are Associated with Pain and Self-reported Functional Status in Males and Females with Patellofemoral Pain. Int J Sports Med. 2013
22. Segal NA, Glass NA, Torner J, Yang M, Felson DT, Sharma L, et al. Quadriceps weakness predicts risk for knee joint space narrowing in women in the MOST cohort. Osteoarthritis Cartilage. 2010; 18(6):769–75. [PubMed: 20188686]
23. Slemenda C, Brandt KD, Heilman DK, Mazzuca S, Braunstein EM, Katz BP, et al. Quadriceps weakness and osteoarthritis of the knee. Ann Intern Med. 1997; 127(2):97–104. [PubMed: 9230035]
24. Felson DT, Zhang Y. An update on the epidemiology of knee and hip osteoarthritis with a view to prevention. Arthritis Rheum. 1998; 41(8):1343–55. [PubMed: 9704632]
25. Willy RW, Scholz JP, Davis IS. Mirror gait retraining for the treatment of patellofemoral pain in female runners. Clin Biomech (Bristol, Avon). 2012; 27(10):1045–51.
26. Crowell HP, Davis IS. Gait retraining to reduce lower extremity loading in runners. Clin Biomech (Bristol, Avon). 2011; 26(1):78–83.
27. Noehren B, Scholz J, Davis I. The effect of real-time gait retraining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome. Br J Sports Med. 2011; 45(9):691–6. [PubMed: 20584755]
28. Willy RW, Davis IS. Varied response to mirror gait retraining of gluteus medius control, hip kinematics, pain, and function in 2 female runners with patellofemoral pain. J Orthop Sports Phys Ther. 2013; 43(12):864–74. [PubMed: 24175611]

29. Shull PB, Silder A, Shultz R, Dragoo JL, Besier TF, Delp SL, et al. Six-week gait retraining program reduces knee adduction moment, reduces pain, and improves function for individuals with medial compartment knee osteoarthritis. J Orthop Res. 2013; 31(7):1020–5. [PubMed: 23494804]
30. Hunt MA, Takacs J, Hart K, Massong E, Fuchko K, Biegler J. Comparison of mirror, raw video, and real-time visual biofeedback for training toe-out gait in individuals with knee osteoarthritis. Arch Phys Med Rehabil. 2014; 95(10):1912–7. [PubMed: 24910929]
31. Barrios JA, Crossley KM, Davis IS. Gait retraining to reduce the knee adduction moment through real-time visual feedback of dynamic knee alignment. J Biomech. 2010; 43(11):2208–13. [PubMed: 20452595]
32. Amin S, Luepongsak N, McGibbon CA, LaValley MP, Krebs DE, Felson DT. Knee adduction moment and development of chronic knee pain in elders. Arthritis Rheum. 2004; 51(3):371–6. [PubMed: 15188321]
33. Bennell KL, Creaby MW, Wrigley TV, Bowles KA, Hinman RS, Cicuttini F, et al. Bone marrow lesions are related to dynamic knee loading in medial knee osteoarthritis. Ann Rheum Dis. 2010; 69(6):1151–4. [PubMed: 19910299]
34. Mundermann A, Dyrby CO, Hurwitz DE, Sharma L, Andriacchi TP. Potential strategies to reduce medial compartment loading in patients with knee osteoarthritis of varying severity: reduced walking speed. Arthritis Rheum. 2004; 50(4):1172–8. [PubMed: 15077299]
35. Prodromos CC, Andriacchi TP, Galante JO. A relationship between gait and clinical changes following high tibial osteotomy. J Bone Joint Surg Am. 1985; 67(8):1188–94. [PubMed: 4055843]
36. Webster KE, Wittwer JE, Feller JA. Validity of the GAITRite walkway system for the measurement of averaged and individual step parameters of gait. Gait Posture. 2005; 22(4):317–21. [PubMed: 16274913]
37. Fransen M, Crosbie J, Edmonds J. Reliability of gait measurements in people with osteoarthritis of the knee. Phys Ther. 1997; 77(9):944–53. [PubMed: 9291951]
38. Youdas JW, Hollman JH, Aalbers MJ, Ahrenholz HN, Aten RA, Cremers JJ. Agreement between the GAITRite walkway system and a stopwatch-footfall count method for measurement of temporal and spatial gait parameters. Arch Phys Med Rehabil. 2006; 87(12):1648–52. [PubMed: 17141647]
39. Peterfy CG, Guermazi A, Zaim S, Tirman PF, Miaux Y, White D, et al. Whole-Organ Magnetic Resonance Imaging Score (WORMS) of the knee in osteoarthritis. Osteoarthritis Cartilage. 2004; 12(3):177–90. [PubMed: 14972335]
40. Zhang Y, Niu J, Felson DT, Choi HK, Nevitt M, Neogi T. Methodologic challenges in studying risk factors for progression of knee osteoarthritis. Arthritis Care Res (Hoboken). 2010; 62(11):1527–32. [PubMed: 20617531]
41. Zhang Y, Neogi T, Hunter D, Roemer F, Niu J. What effect is really being measured? An alternative explanation of paradoxical phenomena in studies of osteoarthritis progression. Arthritis Care Res (Hoboken). 2014; 66(5):658–61. [PubMed: 24877249]
42. de David AC, Carpes FP, Stefanyshyn D. Effects of changing speed on knee and ankle joint load during walking and running. J Sports Sci. 2015; 33(4):391–7. [PubMed: 25105739]
43. Studenski S, Perera S, Patel K, Rosano C, Faulkner K, Inzitari M, et al. Gait speed and survival in older adults. JAMA. 2011; 305(1):50–8. [PubMed: 21205966]
44. Cesari M, Kritchevsky SB, Penninx BW, Nicklas BJ, Simonsick EM, Newman AB, et al. Prognostic value of usual gait speed in well-functioning older people--results from the Health, Aging and Body Composition Study. J Am Geriatr Soc. 2005; 53(10):1675–80. [PubMed: 16181165]
45. Jerome GJ, Ko SU, Kauffman D, Studenski SA, Ferrucci L, Simonsick EM. Gait characteristics associated with walking speed decline in older adults: results from the Baltimore Longitudinal Study of Aging. Arch Gerontol Geriatr. 2015; 60(2):239–43. [PubMed: 25614178]
46. Balcarek P, Jung K, Ammon J, Walde TA, Frosch S, Schuttrumpf JP, et al. Anatomy of lateral patellar instability: trochlear dysplasia and tibial tubercle-trochlear groove distance is more pronounced in women who dislocate the patella. Am J Sports Med. 2010; 38(11):2320–7. [PubMed: 20713643]

47. Shabshin N, Schweitzer ME, Morrison WB, Parker L. MRI criteria for patella alta and baja. Skeletal Radiol. 2004; 33(8):445–50. [PubMed: 15221214]

48. Livingston LA. The quadriceps angle: a review of the literature. J Orthop Sports Phys Ther. 1998; 28(2):105–9. [PubMed: 9699160]

49. Conley S, Rosenberg A, Crowninshield R. The female knee: anatomic variations. J Am Acad Orthop Surg. 2007; 15(Suppl 1):S31–6. [PubMed: 17766787]

Significance and Innovation

- Gait retraining is a potential rehabilitative intervention for individuals with or at risk of knee osteoarthritis
- Step length is an easily modifiable gait characteristic and changes in step length have previously been associated with changes in PFJ stress
- In women, but not men, we found a longer step length was associated with decreased prevalence of PFJ structural damage; no relationship was found between step length and worsening PFJ damage in either sex
- Women with PFJ structural damage may adapt their gait by shortening their step length, but this may not be sufficient to reduce risk of worsening damage over time

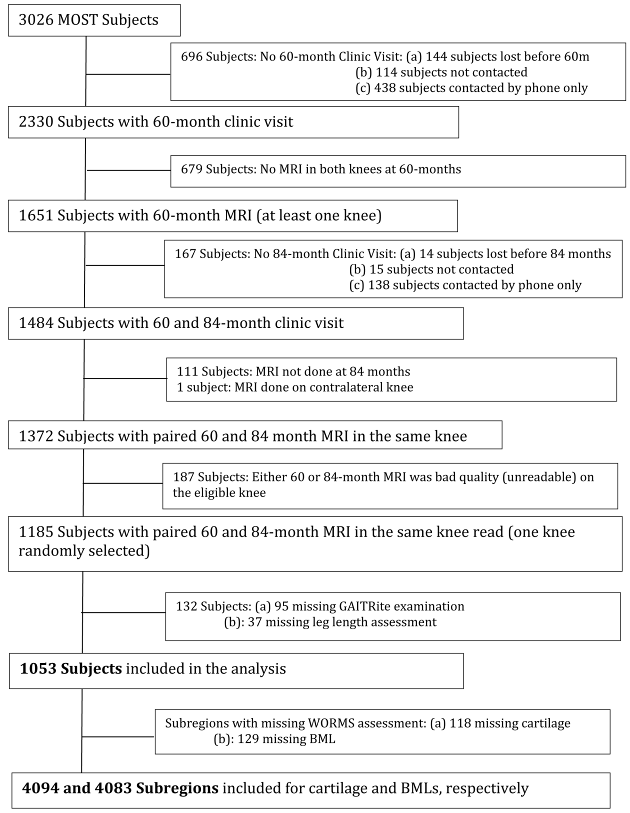

Figure 1.

Flow chart of subjects/subregions included in analysis

Table 1

Relation of step length quintiles to **prevalent** MRI-detected structural damage in subregions of the PFJ among **females**

Step Length (Range)	**Prevalence**	**Crude OR**	**Adjusted OR***	**Adjusted OR* in knees without pain**
Any cartilage damage				
Quintile 5	229/518	0.60	0.62	0.50
(68.78-83.30)	(44.2)	(0.45, 0.82)	(043, 0.88)	(0.32, 0.77)
Quintile 4	259/518	0.76	0.77	0.66
(64.72-68.77)	(50.0)	(0.56, 1.0)	(0.56, 1.1)	(0.44, 1.0)
Quintile 3	271/520	0.83	0.85	0.71
(61.44-64.71)	(52.1)	(0.61, 1.1)	(0.62. 1.2)	(0.48, 1.1)
Quintile 2	275/522	0.85	0.80	0.59
(57.41-61.43)	(52.7)	(0.62, 1.2)	(0.58, 1.1)	(0.38, 0.91)
Quintile 1	293/516	1.0	1.0	1.0
(35.45-57.40)	(56.8)	(Reference)	(Reference)	(Reference)
		p trend=0.001	p trend=0.01	p trend=0.007
Full-thickness cartilage damage				
Quintile 5	73/518	0.57	0.76	0.58
(68.78-83.30)	(14.1)	(0.37, 0.87)	(0.47, 1.2)	(0.32, 1.1)
Quintile 4	65/518	0.49	0.55	0.50
(64.72-68.77)	(12.6)	(0.32, 0.75)	(0.36, 0.86)	(0.28, 0.89)
Quintile 3	74/520	0.57	0.66	0.66
(61.44-64.71)	(14.2)	(0.38, 0.87)	(0.43, 1.0)	(0.38, 1.2)
Quintile 2	79/522	0.61	0.65	0.55
(57.41-61.43)	(15.1)	(0.41, 0.93)	(0.42, 1.0)	(0.31, 0.98)
Quintile 1	116/516	1.0	1.0	1.0
(35.45-57.40)	(22.5)	(Reference)	(Reference)	(Reference)
		p trend= 0.006	p trend=0.14	p trend=0.07
Any BML				
Quintile 5	117/515	0.61	0.59	0.50
(68.78-83.30)	(22.7)	(0.44, 0.86)	(0.40, 0.87)	(0.32, 0.80)
Quintile 4	140/520	0.77	0.70	0.60
(64.72-68.77)	(26.9)	(0.55, 1.1)	(0.50, 0.99)	(0.39, 0.93)
Quintile 3	163/520	0.95	0.93	0.77
(61.44-64.71)	(31.4)	(0.70, 1.3)	(0.68, 1.3)	(0.51, 1.2)
Quintile 2	156/524	0.88	0.85	0.78
(57.41-61.43)	(29.8)	(0.64, 1.2)	(0.61, 1.2)	(0.51, 1.2)
Quintile 1	168/518	1.0	1.0	1.0
(35.45-57.40)	(32.4)	(Reference)	(Reference)	(Reference)

Any cartilage damage				
Step Length (Range)	**Prevalence**	**Crude OR**	**Adjusted OR***	**Adjusted OR* in knees without pain**
		p trend=0.007	p trend= 0.01	p trend= 0.01
BMLs >1				
Quintile 5	36/515	0.83	0.83	0.49
(68.78-83.30)	(7.0)	(0.49, 1.4)	(0.48, 1.5)	(0.25, 0.97)
Quintile 4	37/520	0.85	0.77	0.48
(64.72-68.77)	(7.1)	(0.50, 1.4)	(0.45, 1.3)	(0.24, 0.94)
Quintile 3	51/520	1.2	1.2	1.0
(61.44-64.71)	(9.8)	(0.74, 1.9)	(0.73, 2.0)	(0.55, 1.8)
Quintile 2	38/524	0.86	0.84	0.63
(57.41-61.43)	(7.3)	(0.52, 1.4)	(0.49, 1.4)	(0.33, 1.2)
Quintile 1	43/518	1.0	1.0	1.0
(35.45-57.40)	(8.3)	(Reference)	(Reference)	(Reference)
		p trend=0.4	p trend=0.4	p trend=0.12

*Adjusted for age, BMI, leg length and tibiofemoral joint structural damage

Table 2

Relation of step length quintiles to **prevalent** MRI-detected structural damage in subregions of the PFJ among **males**

Step Length (Range)	Prevalence	Crude OR	Adjusted OR*	Adjusted OR* in knees without pain
Any cartilage damage				
Quintile 5	126/304	0.87	0.92	0.88
(75.99-93.59)	(41.5)	(0.56, 1.4)	(0.56, 1.5)	(0.51, 1.6)
Quintile 4	124/298	0.88	0.97	0.95
(72.25-75.98)	(41.6)	(0.57, 1.4)	(0.62, 1.5)	(0.58, 1.6)
Quintile 3	125/296	0.90	0.91	0.88
(67.86-72.24)	(42.2)	(0.59, 1.4)	(0.59, 1.4)	(0.53, 1.5)
Quintile 2	126/298	0.90	0.95	0.88
(62.87-67.85)	(42.3)	(0.58, 1.4)	(0.60, 1.5)	(0.51, 1.5)
Quintile 1	136/304	1.0	1.0	1.0
(44.08-62.86)	(44.7)	(Reference)	(Reference)	(Reference)
		p trend=0.5	p trend=0.8	p trend=0.8
Full-thickness cartilage damage				
Quintile 5	36/304	1.2	1.4	1.2
(75.99-93.59)	(11.4)	(0.62, 2.3)	(0.70, 2.8)	(0.54, 2.9)
Quintile 4	37/298	1.2	1.5	1.5
(72.25-75.98)	(12.2)	(0.66, 2.4)	(0.75, 2.8)	(0.69, 3.3)
Quintile 3	31/296	1.0	1.1	1.2
(67.86-72.24)	(8.5)	(0.56, 1.9)	(0.60, 2.0)	(0.57, 2.4)
Quintile 2	39/298	1.3	1.5	1.3
(62.87-67.85)	(12.8)	(0.72, 2.4)	(0.80, 2.7)	(0.59, 2.8)
Quintile 1	31/304	1.0	1.0	1.0
(44.08-62.86)	(9.8)	(Reference)	(Reference)	(Reference)
		p trend= 0.7	p trend=0.4	p trend=0.5
Any BML				
Quintile 5	65/304	0.85	0.84	0.71
(75.99-93.59)	(21.4)	(0.53, 1.3)	(0.51, 1.4)	(0.39, 1.3)
Quintile 4	70/292	0.98	0.96	0.89
(72.25-75.98)	(24.0)	(0.62, 1.5)	(0.60, 1.5)	(0.52, 1.5)
Quintile 3	63/286	0.88	0.83	0.77
(67.86-72.24)	(22.0)	(0.57, 1.3)	(0.53, 1.3)	(0.45, 1.3)
Quintile 2	76/304	1.0	1.0	0.74
(62.87-67.85)	(25.0)	(0.67, 1.6)	(0.65, 1.7)	(0.40, 1.4)
Quintile 1	73/300	1.0	1.0	1.0
(44.08-62.86)	(24.3)	(Reference)	(Reference)	(Reference)

Any cartilage damage				
Step Length (Range)	**Prevalence**	**Crude OR**	**Adjusted OR***	**Adjusted OR* in knees without pain**
		p trend=0.5	p trend= 0.5	p trend= 0.5
BML > 1				
Quintile 5	22/304	1.3	0.97	0.59
(75.99-93.59)	(7.2)	(0.56, 3.0)	(0.40, 2.3)	(0.20, 1.7)
Quintile 4	26/292	1.6	1.3	1.1
(72.25-75.98)	(8.9)	(0.79, 3.4)	(0.57, 2.9)	(0.43, 2.9)
Quintile 3	16/286	0.99	0.84	0.72
(67.86-72.24)	(5.6)	(0.45, 2.2)	(0.37, 1.9)	(0.26, 2.0)
Quintile 2	21/304	1.2	1.1	0.68
(62.87-67.85)	(6.9)	(0.57, 2.7)	(0.49, 2.5)	(0.24, 1.9)
Quintile 1	17/300	1.0	1.0	1.0
(44.08-62.86)	(5.7)	(Reference)	(Reference)	(Reference)
		p trend=0.3	p trend= 0.7	p trend= 0.9

*Adjusted for age, BMI, leg length and tibiofemoral joint structural damage

Table 3

Relation of step length quintiles to **worsening** of cartilage damage and any BMLs from 60 to 84 months in subregions of the PFJ among **females**

	Worsening Cartilage Damage (n= 1662 subregions)			Worsening BMLs (n=2582 subregions)		
Step Length	**Prevalence**	**Crude OR**	**Adjusted OR***	**Prevalence**	**Crude OR**	**Adjusted OR***
Quintile 5	25/332	1.0	0.85	62/511	1.2	1.2
(69.30-83.29)	(7.5%)	(0.55, 2.0)	(0.41, 1.7)	(12.1%)	(0.78, 1.8)	(0.74, 1.8)
Quintile 4	10/330	0.40	0.36	44/518	0.80	0.76
(65.16-69.29)	(3.0%)	(0.17, 0.95)	(0.15, 0.87)	(8.5%)	(0.51, 1.2)	(0.49, 1.2)
Quintile 3	26/333	1.1	1.0	58/520	1.1	1.1
(61.87-65.15)	(7.8%)	(0.57, 2.1)	(0.52, 2.0)	(11.2%)	(0.70, 1.6)	(0.70, 1.7)
Quintile 2	33/337	1.4	1.2	59/517	1.1	1.1
(58.03-61.86)	(9.8%)	(0.75, 2.6)	(0.67, 2.3)	(11.4%)	(0.71, 1.7)	(0.70, 1.7)
Quintile 1	24/330	1.0	1.0	54/516	1.0	1.0
(41.51-58.02)	(7.3%)	(Reference)	(Reference)	(10.5%)	(Reference)	(Reference)
		p trend=0.3	p trend=0.1		p trend=0.9	p trend= 0.7

*Adjusted for age, BMI, leg length and tibiofemoral joint structural damage

Table 4

Relation of step length quintiles to **worsening** of cartilage damage and any BMLs from 60 to 84 months in subregions of the PFJ among **males**

	Worsening Cartilage Damage (n= 1101 subregions)			Worsening BMLs (n=1468 subregions)		
Step Length (Range)	**Prevalence**	**Crude OR**	**Adjusted OR***	**Prevalence**	**Crude OR**	**Adjusted OR***
Quintile 5	17/227	1.1	1.1	29/300	1.0	1.3
(76.02-89.38)	(7.5%)	(0.47, 2.6)	(0.43, 2.8)	(9.7%)	(0.51, 2.0)	(0.63, 2.6)
Quintile 4	12/220	0.79	0.79	26/290	0.94	1.1
(72.35-76.01)	(5.5%)	(0.29, 2.2)	(0.29, 2.1)	(9.0%)	(0.50, 1.8)	(0.57, 2.2)
Quintile 3	15/214	1.0	1.0	22/286	0.79	0.85
(67.96-72.34)	(7.0%)	(0.42, 2.5)	(0.41, 2.5)	(7.7%)	(0.41, 1.5)	(0.43, 1.7)
Quintile 2	12/220	0.79	0.84	22/298	0.76	0.85
(62.39-67.95)	(5.5%)	(0.32, 2.0)	(0.33, 2.1)	(7.4%)	(0.40, 1.4)	(0.44, 1.6)
Quintile 1	15/220	1.0	1.0	28/294	1.0	1.0
(44.08-62.38)	(6.8%)	(Reference)	(Reference)	(9.5%)	(Reference)	(Reference)
		p trend=0.8	p trend=0.8		p trend=0.6	p trend= 0.2

*Adjusted for age, BMI, leg length and tibiofemoral joint structural damage