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## Hip Muscle Strength and Protection Against Structural Worsening and Poor Function and Disability Outcomes in Knee Osteoarthritis

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### Abstract

**Objective:** Examine associations of hip abductor strength with i) cartilage damage worsening in the tibiofemoral and patellofemoral compartments 2 years later, and ii) poor function and disability outcomes 5 years later.

**Methods:** Participants had knee osteoarthritis (K/L 2) in at least one knee. Hip abductor strength was measured using Biodex Dynamometry. Participants underwent 3.0T MRI of both knees at baseline and 2 years later. Baseline-to-2-year cartilage damage progression, defined as any worsening of WOMS cartilage damage score, was assessed at each tibiofemoral and

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#### AUTHOR CONTRIBUTIONS

Each author participated in drafting the article or revising it critically for important intellectual content, and all authors approved the final version to be published. All authors have access to the data in the study and can take responsibility for the integrity of the data and the accuracy of the data analysis.

**Study conception and design.** Chang, Chmiel, Sharma

**Acquisition of data.** Chang, Moio, Prasad, Sharma, Szymaszek, Zhang

**Analysis and interpretation of data.** Almagor, Chang, Chmiel, Guermazi, Hayes, Moio, Sharma

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#### CONFLICT OF INTEREST:

Ali Guermazi is President of Boston Imaging Core Lab (BICL), LLC and Consultant to Pfizer, GE, AstraZeneca, TissueGene, Roche, Galapagos, MerckSerono. None of the other authors have declared any conflict of interest.

patellofemoral surface. LLFDI (Late-Life Function and Disability Instrument) and Chair-Stand-Rate were recorded at baseline and 5-year follow-up; outcomes analyzed using quintiles. Poor outcomes were defined as remaining in the same low-function quintiles or being in a worse quintile at 5-year follow-up. We analyzed associations of baseline hip abductor strength with cartilage damage worsening and function and disability outcomes using multivariable log-binomial models.

**Results:** 275 knees from 164 persons [age=63.7 (SD=9.8) years, 79.3% women] comprised the structural outcome sample, and 187 persons [age=64.2 (9.7), 78.6% women] the function and disability outcomes sample. Greater baseline hip abductor strength was associated with reduced risks of baseline-to-2-year medial patellofemoral and lateral tibiofemoral cartilage damage worsening [adjusted relative risks (RRs) range: 0.80–0.83] and with reduced risks of baseline-to-5-year poor outcomes for Chair-Stand-Rate and LLFDI Basic Lower-Extremity Function and Disability Limitation (adjusted RRs range: 0.91–0.94).

**Conclusion:** Findings support a beneficial role of hip abductor strength for disease modification and for function and disability outcomes, and as a potential therapeutic target in managing knee osteoarthritis.

### Keywords

Knee OA; Strength; MRI; Function; Disability

## INTRODUCTION

Functional impairments and disability are common among persons with knee osteoarthritis (OA)<sup>1,2</sup>. In the elderly, knee OA contributes to as much chronic disability as cardiovascular disease<sup>3</sup>. There is no disease-modifying therapy for OA; practice guidelines recommend strength training as an effective intervention to reduce symptoms and preserve function<sup>4,5</sup>. The quadriceps muscle has long been a focus, although any effect of quadriceps strengthening on delaying structural progression has not been confirmed<sup>6,7</sup>. In addition, observational studies have not consistently revealed an association between quadriceps strength and risk of subsequent progression<sup>8–10</sup>. Novel insights on alternative targets for disease modification and function preservation will help refine physical and rehabilitative therapy for knee OA.

Lower extremity muscle weakness has been proposed as a contributing factor to function decline and structural progression<sup>11</sup>. In daily activities, hip abductor activation is required to maintain balance and postural stability during walking and transfers<sup>12,13</sup>. Hip abductor weakness has been linked to poor function in persons with knee OA<sup>14</sup> and after knee arthroplasty<sup>15</sup>. Impaired hip abductor force generation may impact movement mechanics during weightbearing activities and potentially lead to altered joint loading and structural progression. Compared with age-matched healthy individuals, persons with knee OA had an approximately 20% hip abductor strength deficit<sup>16,17</sup>. Whether hip abductor weakness is a consequence of knee OA and/or a modifiable risk factor for disease progression remains debatable<sup>16</sup>. We reported that greater internal hip abduction moment during gait was associated with a reduced likelihood of subsequent medial tibiofemoral (TF) disease

worsening<sup>18</sup>. Although the internal hip abduction moment reflects dynamic activity of hip abductors during walking, it is a net joint moment representing the contribution of both hip abductors and adductors, and could be influenced by other variables such as limb inertia and body mass<sup>19,20</sup>.

Hip abductor strength, in contrast, is easily interpreted, clinically translatable, and enhanced by exercise. Hip strengthening exercise lessened pain and improved function in the short-term in persons with predominantly medial TF OA<sup>21–24</sup>, but its long-term effect on disease progression and function preservation is unclear. The role of hip abductor strength in patellofemoral (PF) OA is unknown. It is established that individuals with PF pain demonstrate weak hip abductors and hip strengthening is an integral component in managing PF pain<sup>25–27</sup>. Early MRI-detected change in patellar cartilage<sup>28</sup> and elevated PF joint stress<sup>29</sup> found in persons with PF pain suggest a disease continuum between PF pain and PF OA<sup>30,31</sup>. In theory, greater hip abductor strength may protect against OA progression in the PF compartment.

According to Nagi's disablement model<sup>32</sup> and the World Health Organization's International Classification of Functioning, Disability, and Health (ICF)<sup>33</sup>, function limitation pertains to the inability or limitation to perform discrete physical tasks, such as ambulation, climbing stairs, or reaching; disability refers to the inability or limitation in major life tasks or social roles within a typical sociocultural and physical environment, such as personal care, household management, job, or hobbies. Ideally, both function and disability should be considered.

The central role of hip abductors in activities and the potential for strong hip muscles to prevent function decline, disability progression, *and* structural worsening make hip abductors an attractive target in the management of knee OA. We tested the hypotheses that greater baseline hip abductor strength is associated with i) a reduced risk of cartilage damage worsening in the TF and PF compartments 2 years later, and ii) a reduced risk of poor function and disability outcomes 5 years later.

## METHODS

### Participants.

Study participants were from a prospective, longitudinal, observational cohort study of knee OA, the MAK-3 Study (Mechanical Factors in Arthritis of the Knee-Study 3)<sup>34</sup>. They were recruited from the community using advertising in periodicals targeting older persons, neighborhood organizations, letters to members of the registry of the Buehler Center on Aging, Health, and Society at Northwestern University, and via medical center referrals. Inclusion criteria were: definite TF osteophyte presence [Kellgren/Lawrence (K/L) radiographic grade = 2] in one or both knees; and Likert category of at least "a little difficulty" for 2 or more items in the WOMAC (Western Ontario and McMaster Universities Osteoarthritis Index) physical function scale. Exclusion criteria were: corticosteroid injection within the previous 3 months; history of avascular necrosis, rheumatoid or other inflammatory arthritis, periarticular fracture, Paget's disease, villonodular synovitis, joint infection, ochronosis, neuropathic arthropathy, acromegaly, hemochromatosis, gout,

pseudogout, osteopetrosis, or meniscectomy; or exclusion criteria for MRI. Approval was obtained from the Institutional Review Boards of Northwestern University and NorthShore University HealthSystem Evanston Hospital. All participants provided written consent.

### **Baseline hip abductor and knee extensor strength.**

We used a computer-driven Biodex System 3 PRO dynamometer (Biodex Medical, Shirley, NY, USA) to measure bilateral baseline isometric hip abductor strength, quantified as torque in the unit of Newton-meter. The Biodex System is widely used for measuring strength and has good reliability and validity<sup>35</sup>. After calibration, participants stood in a padded height-and-weight-adjustable standing frame with forearm supports and handgrips. The thigh resistance pad was placed on the lateral thigh, proximal to the knee. The axis of rotation was aligned at the ipsilateral anterior superior iliac spine, with the hip joint in a neutral position. Participants practiced pushing against the pad at submaximal effort 2 times, then performed 3 repetitions of maximal isometric hip abduction, holding for 5 seconds with 60-second rest between repetitions. We tested right and left hip strength sequentially. To investigate the additional impact of knee extensor strength in the relationship between hip abductor strength and poor outcomes, we measured bilateral knee extensor isometric strength in a seated position, at 60-degree knee flexion. An experienced examiner conducted all testing. Test-retest reliability was excellent [intraclass correlation coefficient (ICC) = 0.91]. For analysis, we averaged peak hip abductor and knee extensor torque from 3 repetitions and normalized to body weight.

### **MRI acquisition and assessment of cartilage damage worsening.**

At baseline and 2-year follow-up, MRIs of both knees were obtained using a commercial knee coil and 1 of 2 whole-body scanners, a 3T Verio (Siemens Healthcare, Erlangen, Germany) or a 1.5T Avanto (Siemens Healthcare, Erlangen, Germany); the same scanner was used at both evaluations. The protocol included coronal T1-weighted spin-echo [TR/TE/FOV/Matrix/Slice thickness = 3 s/20 ms/14 cm, 256×256, 3 mm at 3T; TR/TE/FOV/Matrix/Slice thickness = 3 s/18 ms/14 cm, 256×256, 3 mm at 1.5T], and sagittal axial, and coronal fat-suppressed proton density-weighted turbo spin echo sequences [TR/TE/Turbo Factor/FOV/Matrix/Slice thickness = 500 ms/11 ms/7/12 cm, 320×320, 3 mm at 3T; TR/TE/Turbo Factor/FOV/Matrix/Slice thickness = 600 ms/11 ms/7/12 cm, 320×320, 3 mm at 1.5T]. Each knee was scored using the Whole-Organ MRI Score (WORMS) method<sup>36</sup>, by 1 of 2 expert musculoskeletal radiologists (inter-rater ICC = 0.98 for medial cartilage morphology)<sup>36</sup>. Baseline and 2-year scans were evaluated as pairs, with known chronology as suggested for longitudinal studies in knee OA<sup>37</sup>, but blinded to all other data. Three subregions (anterior, central, and posterior) of the medial and lateral femoral condyles and tibial plateaus were each scored separately for cartilage damage (0–6 scale), where 0 = normal cartilage thickness and signal, 1 = increased intrasubstance signal intensity without morphologic defect, 2 = solitary focal partial thickness defect, 2.5 = solitary full thickness defect, 3 = multiple partial-thickness loss, 4 = diffuse partial thickness loss, 5 = multiple areas of full-thickness loss, and 6 = diffuse full-thickness loss. The medial and lateral patellar surfaces were each scored separately on the same 0–6 scale.

We assessed cartilage damage worsening as medial TF, lateral TF, and any TF and medial PF, lateral PF, and any PF. Baseline-to-2-year cartilage damage worsening in the medial TF compartment was defined as WORMS score worsening in any of the 5 medial TF subregions (central and posterior medial femoral; and anterior, central, and posterior medial tibial); lateral TF worsening as worsening in any of the 5 lateral TF subregions (central and posterior lateral femoral; and anterior, central, and posterior lateral tibial); any TF worsening as any worsening in medial or lateral TF compartments. Medial PF cartilage damage worsening was defined as WORMS score worsening in either the medial anterior (trochlear) femoral or medial patellar subregion, lateral PF worsening as worsening in either the lateral anterior (trochlear) femoral or lateral patellar, and any PF worsening as worsening in either medial or lateral PF<sup>38–40</sup>.

### **Baseline-to-5-year function and disability outcomes.**

At baseline and 5-year follow-up, participants completed the Late-Life Function and Disability Instrument (LLFDI)<sup>41,42</sup>, a self-reported measure that assesses functional limitations and disability. The LLFDI Function component consists of 32 items that rate task difficulty. We examined 3 relevant domains: Total Function, Basic Lower Extremity Function, and Advanced Lower Extremity Function. These 3 distinct measures separately capture physical function as a whole and in basic and advanced tasks involving the lower extremity, which are often compromised in persons with chronic knee symptoms. Sample questions in the Basic Lower Extremity Function include walking around one floor of home and stepping up and down from a curb; in the Advanced Lower Extremity Function questions include taking a 1-mile brisk walk without stopping or going up and down 3 flights of stairs with handrail. The LLFDI Disability component consists of 16 items that rate both task difficulty and frequency of participation. We examined 3 distinct disability domains; Frequency of Participation (i.e., how often does one do a particular activity), Limitation (i.e., to what extent does one feel limited in doing a particular activity), and Instrumental Role Limitation (i.e., to what extent does one feel limited in the ability to move around the home and the community). Scores in each domain are scaled as 0–100; higher scores indicate better function and less disability. The LLFDI was constructed using factor analysis and Rasch analytic techniques, and its validity and test–retest reliability have been evaluated in ethnically and racially diverse older adults with a range of functional limitations and chronic health conditions<sup>41,42</sup>. We also assessed Chair-Stand-Rate, a performance-based function measure, at baseline and 5-year follow-up. Time required for 5 repetitions of rising from a chair and sitting down was converted to a rate (number of stands per minute); higher rate indicates better function. The use of rate allows the inclusion of individuals who could not complete the test (i.e., those with a rate of 0).

To determine baseline-to-5-year poor outcome in each of the 6 LLFDI domains and in Chair-Stand-Rate, participants were categorized by baseline quintile, ranging from worst to best scores. Poor outcome was defined as remaining within the same low-function group (the worst two quintiles) or moving into a worse function quintile at 5-year follow-up<sup>43–46</sup>.

### Baseline assessment of covariates, radiographic disease severity and pain.

All participants underwent bilateral, antero-posterior, weightbearing knee radiographs at baseline in the semi-flexed position with fluoroscopic confirmation of superimposition of the anterior and posterior tibial plateau lines and centering of the tibial spines within the femoral notch<sup>47</sup>. TF disease severity was assessed using the K/L system, 0 = normal, 1 = possible osteophytes, 2 = definite osteophytes, possible joint space narrowing, 3 = moderate osteophytes, definite joint space narrowing, some sclerosis, possible attrition, and 4 = large osteophytes, marked joint space narrowing, severe sclerosis, definite attrition<sup>48</sup>. To visualize the PF compartment, weight-bearing, 30° flexion, axial (skyline) views were obtained according to a protocol that specified participant positioning and technical acquisition parameters<sup>47</sup>. Medial and lateral PF compartments were graded separately using the OARSI (Osteoarthritis Research Society International) atlas-based scales<sup>49</sup>, with 0 = no joint space narrowing, 1 = possible narrowing, 2 = definite narrowing, 3 = severe narrowing. Radiographs were obtained in a single unit by 2 trained technicians. The reliability of the radiographic grading for the single x-ray reader was high with a Kappa coefficient of 0.86.

Pain was assessed by self-report using the WOMAC pain subscale (Likert format; range 0–20, higher worse). The reliability, validity, and responsiveness of WOMAC scores have been well established in studies of knee OA<sup>50,51</sup>. Pain during hip strength testing was recorded as none, mild, moderate, or severe.

### Statistical analyses.

The relationships between baseline hip abductor strength and baseline-to-2-year TF and PF cartilage damage worsening were examined using log-binomial models<sup>52</sup> with generalized estimating equations to account for correlations between the 2 limbs of each individual. The relationships between baseline hip abductor strength (worse limb) and poor baseline-to-5-year function and disability outcomes were examined using person-level log-binomial models. Unadjusted and adjusted (adjusting for baseline age, sex, pain, and disease severity by K/L grade) relative risks (RRs) and associated 95% confidence intervals (CIs) were calculated; a 95% CI that excludes 1.0 was considered to be statistically significant. We chose adjustment variables (e.g., age, sex, pain, and radiographic disease severity) based on our understanding of the disease course and previous cohort studies in knee OA and guided by underlying plausible interrelationships of the predictor, outcome, and covariates for each of the strength-structure and strength-function associations. Body mass index (BMI) was not included in the models because hip abductor strength was normalized to body weight. We performed sensitivity analyses adjusting for baseline PF joint space narrowing score (instead of K/L grade) for cartilage damage worsening outcomes in the respective compartment of any PF, medial PF, and lateral PF. To investigate the influence of knee extensor strength in these relationships, we examined these associations stratified by baseline median knee extensor strength.

## RESULTS

### Hip abductor strength and cartilage damage worsening 2 years later.

The derivation of the analysis sample (275 knees from 164 persons) for this 2-year outcome is shown in Figure 1A. Table 1 summarizes baseline characteristics of the sample. Table 2 shows the number of knees that had a poor outcome (baseline-to-2-year cartilage damage worsening) in the TF and PF compartments. As shown in Table 2, greater baseline hip abductor strength was significantly associated with reduced risks of medial PF (adjusted RR = 0.80, 95% CI: 0.67, 0.95) and lateral TF (adjusted RR = 0.83, 95% CI: 0.71, 0.98) cartilage damage worsening 2 years later. For every 0.1 Nm/kg increase in body-weight-normalized hip abductor strength, there was a 17–20% reduction in risk of medial PF and lateral TF cartilage damage worsening. Adjusted RRs for each compartment were in the protective range (i.e., each RR < 1.0), but most were not statistically significant (Table 2). Sensitivity analyses where pain and K/L grade were removed as covariates minimally altered the effect estimates. Sensitivity analyses that adjusted for baseline PF joint space narrowing score (instead of K/L grade) for cartilage damage worsening outcomes in the respective compartment of any PF, medial PF, and lateral PF yielded minimally different RRs and 95% CIs (data not shown). Similar trends were noted when only women were included in the models (Supplemental Table A). The number of men (n=34) was insufficient for a separate men-only analysis.

We further examined these relationships stratified by baseline knee extensor strength. In knees with better baseline extensor strength, baseline hip abductor strength was generally associated with a reduced likelihood of TF cartilage damage worsening. Women-only analyses had similar results (Supplemental Table B).

### Hip abductor strength and poor function and disability outcomes 5 years later.

The derivation of the analysis sample (187 persons) is shown in Figure 1B. Table 3 illustrates LLFDI Total Function baseline cutpoints for each quintile and quintile movement between baseline and 5-year follow-up. Poor outcome was defined as remaining within the same low-function group (the worst two quintiles) or moving into a worse function quintile at 5-year follow-up. Similar methods were used to define poor outcomes in the other 5 LLFDI domains and for Chair-Stand-Rate. Table 4 summarizes the baseline characteristics of this sample. Of the 187 persons, 12 did not complete the Chair-Stand test at 5-year follow-up. Table 5 shows the number of persons with a poor outcome for each function or disability scale. As shown in Table 5, greater baseline hip abductor strength was significantly associated with reduced risks of poor outcomes for Chair-Stand-Rate (adjusted RR = 0.91, 95% CI: 0.83, 0.99), LLFDI Basic Lower Extremity Function (adjusted RR = 0.94, 95% CI: 0.88, 0.99), and LLFDI Disability Limitation (adjusted RR = 0.92, 95% CI: 0.85, 0.99) over the baseline-to-5-year follow-up interval. Every 0.1 Nm/kg increase in baseline body-weight-normalized hip abductor strength was associated with a 6–9% reduction in risk of poor outcomes. Sensitivity analyses where pain and K/L grade were removed as covariates minimally altered the effect estimates. Similar trends were noted in women-only models (Supplemental Table C).

We further examined these relationships stratified by baseline knee extensor strength. In persons with better baseline knee extensor strength, hip abductor strength had additional protective effects on function decline and disability, especially in Chair-Stand-Rate and LLFDI Disability Frequency of Participation. Women-only analyses yielded similar findings (Supplemental Table D).

## DISCUSSION

In persons with knee OA, these findings suggest an association of greater baseline hip abductor strength and reduced risks of both baseline-to-2-year knee MRI-detected structural worsening and poor baseline-to-5-year function and disability outcomes. For every 0.1 Nm/kg increase in baseline body-weight-normalized hip abductor strength, there was a 17–20% reduced risk of 2-year medial PF and lateral TF compartment cartilage damage worsening and a 6–9% reduced risk of poor 5-year function and disability outcomes. Prior clinical trials of hip strengthening in the setting of knee OA have shown abductor strength improvements ranging from 0.14 to 0.25 Nm/kg<sup>21,22</sup>. An increase of 0.1 Nm/kg is reasonably attainable for individuals with knee OA. These findings support a beneficial role of hip abductor strength for disease modification and function preservation and as a therapeutic target to be incorporated in conservative management of knee OA.

Individuals with knee OA have hip abductor strength deficits when compared with healthy older adults<sup>14–17</sup>. These studies were cross-sectional, and unable to determine whether hip abductor weakness is a risk factor for disease worsening. To our knowledge, the current study, a prospective cohort study, is the first to report a potential benefit of hip abductor strength on subsequent cartilage damage worsening. The mean isometric hip abductor strength in our participants was 0.84 (SD 0.24) Nm/kg, comparable to published reports of 0.86 (SD 0.29) Nm/kg among 89 persons<sup>16</sup> and 0.83 (SD 0.16) Nm/kg among 99 persons<sup>53</sup> with knee OA.

The mechanisms by which greater hip abductor strength protects against progression are unclear and warrant further investigation. Trials<sup>21–23,54</sup> have consistently found short-term clinical improvements in pain and function after hip-focused strengthening programs, of 4 to 12 weeks duration. The structural effects of such interventions have not been examined. Excessive knee load during walking has been shown to accelerate disease progression<sup>55,56</sup>, but it remains unclear whether hip strengthening alters knee loading. A 4-week hip abductor strength training program<sup>23</sup> resulted in a reduction in the external knee adduction moment (KAM), a determinant of medial knee load during gait, in persons with knee OA. Hip abductor and external rotator strengthening for 6 weeks<sup>57</sup> reduced KAM during running in healthy women. In contrast, despite improved symptoms, function, and strength, KAM change was not observed following 8 or 12 weeks of a supervised home hip-focused exercise program<sup>21,22</sup>. KAM, although a commonly used marker for knee load, may not fully capture the overall loading condition at the knee<sup>58</sup>. A probabilistic approach in musculoskeletal modeling revealed that weakening hip abductor force-generating capacity during gait elevated first and second peak knee contact force by 0.2 and 0.5 times body weight, respectively<sup>59</sup>, supporting the idea that diminished hip abductor strength could increase knee load.



In previous studies of persons with PF pain, hip abductor strengthening has resulted in symptom relief and normalized lower limb movement patterns and PF joint mechanics<sup>60–62</sup>. In theory, greater hip abductor strength may contribute to better local mechanical environment for the PF compartment. As a stabilizing muscle in the frontal plane, greater hip abductor strength may help normalize load distribution between the medial and lateral TF compartment, preventing TF cartilage deterioration. It is also plausible that the beneficial effect of hip strength operates through a combination of load moderation and other unidentified mechanisms.

To our knowledge, our study is the first long-term study reporting a protective effect of hip abductor strength on poor lower extremity function and disability outcomes in persons with knee OA. Our definition of poor outcome did not rely on change. In OA, change in function or disability measures may require several years. A focus on change ignores those with persistently high or low function, effectively lumping these individuals together in the same group. In a chronic disease that is slow to evolve, factors related to persistent low- or high-function states are of particular importance to the development of prevention or intervention programs. While clinical trials<sup>21–23,54</sup> of hip-focused strengthening have consistently demonstrated short-term benefits, long-term associations have not been examined. Considering the critical role of the hip musculature in maintaining balance and postural stability during walking and transfers, our findings are not surprising. A recent study also demonstrated the benefit of adding hip abductor strengthening to a standard rehabilitation program in performance-based function measures 1 year after total knee arthroplasty<sup>63</sup>.

Interestingly, in the setting of better knee extensor strength, greater hip abductor strength appeared to confer additional beneficial effects on both joint health and long-term function and disability, suggesting that stronger hip abductors could further protect against poor structural and function outcomes compared to strong knee extensors alone. Our findings align with the conclusion of a recent meta-analysis<sup>64</sup> suggesting that combined hip and knee strengthening over an average of 6 weeks resulted in greater pain relief and self-reported activity when compared with knee strengthening alone in individuals with PF pain. The improvements of combined hip and knee strengthening were maintained beyond the intervention period, with moderate-to-large effect sizes, suggesting possible long-term effects<sup>64</sup>.

The current study has limitations. Knee structural worsening was assessed between baseline and 2-year follow-up. A longer follow-up time may further elucidate the role of hip abductor strength in protecting against cartilage deterioration. Nearly 80% of our study participants were women, limiting the ability to perform analyses in men only. It is unclear whether these results can be generalized to men. The functional threshold for knee extensor strength in persons with knee OA has not been established. Therefore, we used median values as cutpoints to dichotomize knee strength in subgroup analyses. Although clinically relevant and important, subgroup analyses by knee extensor strength and by sex are likely to have limited power for many comparisons of interest.

In summary, greater baseline hip abductor strength was associated with a reduced risk of knee cartilage damage worsening, particularly in the medial PF and lateral TF

compartments, and poor function and disability outcomes. Stronger hip abductors may confer additional structural and functional benefits in the presence of strong knee extensors. Incorporating hip abductor strengthening into nonpharmacological management of knee OA may help to optimize patient outcomes and slow structural progression. Our findings highlight the need for future clinical trials to assess the effects of hip-focused strengthening on long-term pain, function and disability outcomes as well as on structural preservation, and to determine the optimal exercise prescription of strengthening frequency, intensity, and duration.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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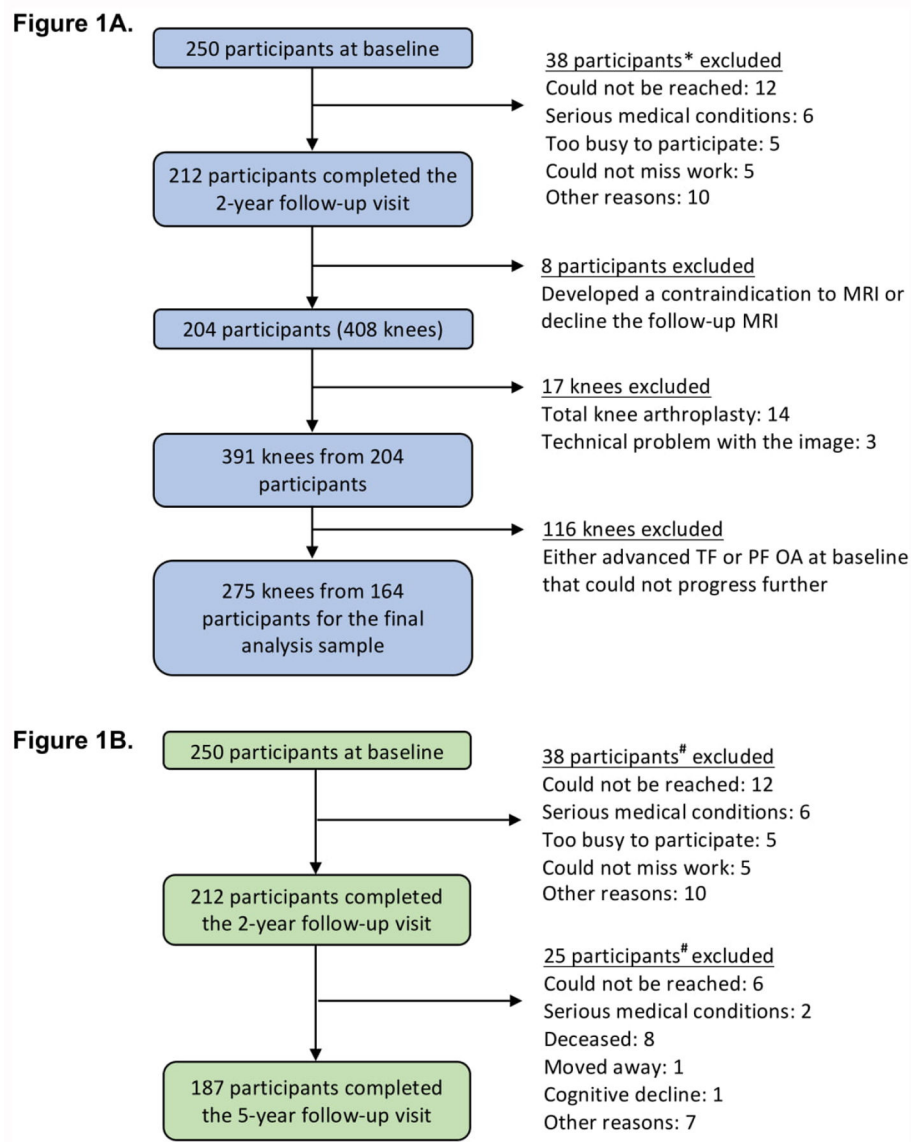
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**Figure 1. Derivation of Analysis Samples for the 2-year cartilage damage worsening (1A) and 5-year poor function and disability outcomes (1B).**

\* Compared to those who completed the 2-year visit ( $n=212$ ), those ( $n=38$ ) not completing the 2-year visit did not differ statistically with respect to sex distribution (71.7% female in non completers versus 76.5% in completers), BMI (mean  $28.9 \text{ kg/m}^2$ , SD 5.1 versus 28.5, 5.7, respectively), or disease severity by K/L grade (38.1% had K/L grade 3 or 4 versus 31.4%), but were statistically slightly older (mean 68.1 years, SD 11.1 versus 64.2, 10.0).

# Compared to those who completed the 5-year visit ( $n=187$ ), those ( $n=63$ ) not completing the 5-year visit did not differ statistically with respect to sex distribution (66.7% female in noncompleters versus 78.6% in completers), BMI (mean  $28.3 \text{ kg/m}^2$ , SD 4.9 versus 28.6, 5.8), or disease severity by K/L grade (39.7% had K/L grade 3 or 4 versus 29.9%), but were statistically slightly older (mean 67.4 years, SD 11.6 versus 64.2, 9.7).

**Table 1.**

Baseline characteristics of the baseline-to-2-year cartilage damage worsening analysis sample (n = 275 knees from 164 persons)

<i>Person-based characteristics (n = 164):</i>	<b>Mean (SD) or number (%)</b>
Age (years)	63.7 (9.8)
Female	130 (79.3%)
BMI (kg/m <sup>2</sup> )	28.0 (5.3)
WOMAC pain (0–20), higher indicating more severe pain	4.5 (3.5)
WOMAC function (0–68), higher indicating worse function	12.9 (11.1)
<b>Knee-based characteristics (n = 275):</b>	
K/L grade	
0	16 (5.8%)
1	72 (26.2%)
2	143 (52.0%)
3	44 (16.0%)
PF joint space narrowing score	
0	101 (36.7%)
1	103 (37.5%)
2	71 (25.8%)
Hip abductor strength (Nm/kg)	0.84 (0.24)
Knee extensor strength (Nm/kg)	1.01 (0.29)

Abbreviations: SD, Standard Deviation; BMI, Body Mass Index; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index; K/L, Kellgren/Lawrence; PF, patellofemoral



**Table 2.**

Associations of baseline BW-normalized hip abductor strength (per 0.1 Nm/kg) with baseline-to-2-year tibiofemoral and patellofemoral cartilage damage worsening outcomes [Relative Risk (95% CI)] (n = 275 knees from 164 persons)

<b>Baseline Hip Abductor Strength (Nm/kg)</b>	<b>Any TF</b>	<b>Medial TF</b>	<b>Lateral TF</b>	<b>Any PF</b>	<b>Medial PF</b>	<b>Lateral PF</b>
Number of knees (%) with poor outcome	65 (23.6)	38 (13.8)	30 (10.9)	46 (16.7)	27 (9.8)	23 (8.4)
Unadjusted	0.92 (0.84, 1.01)	0.95 (0.84, 1.08)	<b>0.84<sup>*</sup> (0.73, 0.97)</b>	0.90 (0.78, 1.04)	<b>0.83<sup>*</sup> (0.70, 0.99)</b>	0.94 (0.78, 1.13)
Adjusted <sup>a</sup>	0.94 (0.86, 1.04)	0.95 <sup>b</sup> (0.84, 1.08)	<b>0.83<sup>ab</sup> (0.71, 0.98)</b>	0.88 (0.75, 1.02)	<b>0.80<sup>*</sup> (0.67, 0.95)</b>	0.92 (0.75, 1.13)

Abbreviations: BW, body weight; CI, confidence interval; TF, tibiofemoral; PF, patellofemoral; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index; K/L, Kellgren/Lawrence

\* Relative risk (RR) with associated 95% CI that excludes 1.0 was considered to be statistically significant

<sup>a</sup> Adjusted for age, sex, WOMAC pain, and K/L grade

<sup>b</sup> Adjusted for age and sex. Models became unstable when adjusting for age, sex, WOMAC pain, and K/L grade

**Table 3.**

LLFDI Total Function baseline quintiles and quintile movements between baseline and 5-year follow-up

LLFDI Total Function quintile group at <i>baseline</i> (n = 187)	LLFDI Total Function quintile group at <i>5-year follow-up</i> (n = 187)					
	Q1 (worst)	Q2	Q3	Q4	Q5 (best)	
Q1 (worst) ( < 54.14)	30	8	2	0	1	41
Q2 (> 54.14, < 59.92)	15	17	3	1	0	36
Q3 (> 59.92, < 65.02)	3	16	11	8	4	42
Q4 (> 65.02, < 69.6)	1	5	10	11	9	36
Q5 (best) (> 69.6)	0	1	7	6	18	32
	49	47	33	26	32	187

Abbreviations: LLFDI, Late-Life Function and Disability Instrument; Q1 to Q5 define quintile ranges used for the analysis. Shaded cells are numbers of participants with poor baseline-to-5-year outcome, defined as remaining within the same low-function group (the worse two groups) or moving into a worse function group at the 5-year follow-up.

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**Table 4.**

Baseline characteristics of the baseline-to-5-year poor function and disability outcomes analysis sample (n = 187 persons)

<i>Person-based (n = 187):</i>	<b>Mean (SD) or number (%)</b>
Age (years)	64.2 (9.7)
Female	147 (78.6%)
BMI (kg/m <sup>2</sup> )	28.6 (5.8)
K/L grade of the knee with <i>worse</i> baseline hip abductor strength	
0	12 (6.4%)
1	30 (16.0%)
2	89 (47.6%)
3	27 (14.4%)
4	29 (15.5%)
PF joint space narrowing score of the knee with <i>worse</i> baseline hip abductor strength	
0	52 (27.8%)
1	61 (32.6%)
2	41 (21.9%)
3	33 (17.6%)
WOMAC pain (0–20), higher indicating more severe pain	4.5 (3.5)
WOMAC function (0–68), higher indicating worse function	13.3 (11.3)
Hip abductor strength (worse of the two limbs) (Nm/kg)	0.77 (0.22)
Knee extensor strength (worse of the two limbs) (Nm/kg)	0.82 (0.28)
Chair-Stand-Rate (#/min)	20.40 (6.58)
LLFDI Total Function (0–100), higher indicating better function	61.88 (9.35)
LLFDI Basic LE Function (0–100)	71.56 (13.25)
LLFDI Advanced LE Function (0–100)	54.80 (12.94)
LLFDI Disability Frequency of Participation (0–100), higher indicating less disability	55.46 (6.69)
LLFDI Disability Limitation (0–100)	74.03 (12.84)
LLFDI Disability Instrumental Role Limitation (0–100)	73.28 (13.41)

Abbreviations: SD, Standard Deviation; BMI, Body Mass Index; K/L, Kellgren/Lawrence; PF, patellofemoral; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index; LLFDI, Late Life Function Disability Instrument

**Table 5.** Associations of baseline BW-normalized hip abductor strength (per 0.1 Nm/kg) with baseline-to-5-year poor outcomes by Chair-Stand-Rate and LLFDI function and disability scores [Relative Risk (95% CI)] (n = 187 persons)

Baseline Hip Abductor Strength (Nm/kg)	Chair-Stand-Rate	LLFDI Total Function	LLFDI Basic Lower Extremity Function	LLFDI Advanced Lower Extremity Function	LLFDI Disability Frequency of Participation	LLFDI Disability Limitation	LLFDI Disability Instrumental Role Limitation
Number of persons (%) with poor outcome	71 (40.6)	111 (59.4)	107 (57.2)	122 (65.2)	91 (48.7)	85 (45.5)	86 (46.0)
Unadjusted	<b>0.90</b> * ( <b>0.83, 0.98</b> )	0.95 (0.90, 1.00)	<b>0.93</b> * ( <b>0.88, 0.99</b> )	<b>0.95</b> * ( <b>0.90, 0.99</b> )	0.94 (0.88, 1.01)	0.94 (0.87, 1.01)	0.96 (0.90, 1.03)
Adjusted <sup>a</sup>	<b>0.91</b> * ( <b>0.83, 0.99</b> )	0.99 (0.95, 1.02)	<b>0.94</b> * ( <b>0.88, 0.99</b> )	0.98 (0.95, 1.02)	0.94 (0.88, 1.00)	<b>0.92</b> * ( <b>0.85, 0.999</b> )	0.95 (0.88, 1.02)

Abbreviations: BW, body weight; LLFDI, Late Life Function Disability Instrument; CI, confidence interval; K/L, Kellgren/Lawrence

\* Relative risk (RR) with associated 95% CI that excludes 1.0 was considered to be statistically significant

<sup>a</sup> Adjusted for age, sex, hip pain during strength testing, and K/L grade of the knee with worse baseline hip abductor strength