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A Biomechanical Perspective on Physical Therapy Management of Knee Osteoarthritis

Osteoarthritis (OA) is the most common cause of disability in the United States, affecting more than 1 in 5 adults.[25] Nearly half of individuals diagnosed with OA experience significant pain and disability that interfere with their performance of daily tasks.[25] The knee is the most commonly affected joint, with an approximately 45% lifetime risk of symptomatic OA in at least 1 knee.[142] Given the high prevalence of knee OA,[51,53,141] patients with symptomatic disease often seek physical therapy services to manage their symptoms and functional limitations. Traditionally, the focus of physical therapy management of knee OA has been to improve pain, mobility, and functional limitations by addressing impairments such as muscle weakness and deficits in joint flexibility.[32,33,54,56,63] However, as there are currently no effective long-term joint-protective treatment options, increased disease severity and symptoms often lead to the need for joint replacement surgery.[127] Therefore, along with strategies that provide symptomatic relief and improvements in functional capabilities, physical therapists also need to consider treatment options that are intended to limit the rate of structural disease progression for their patients.

SYNOPSIS: Altered knee joint biomechanics and excessive joint loading have long been considered as important contributors to the development and progression of knee osteoarthritis. Therefore, a better understanding of how various treatment options influence the loading environment of the knee joint could have practical implications for devising more effective physical therapy management strategies. The aim of this clinical commentary was to review the pertinent biomechanical evidence supporting the use of treatment options intended to provide protection against excessive joint loading while offering symptomatic relief and functional improvements for better long-term management of patients with knee osteoarthritis. The biomechanical and clinical evidence regarding the effectiveness of knee joint offloading strategies, including contralateral cane use, laterally wedged shoe insoles, variable-stiffness shoes, valgus knee bracing, and gait-modification strategies, within the context of effective disease management is discussed. In addition, the potential role of therapeutic exercise and neuromuscular training to improve the mechanical environment of the knee joint is considered. Management strategies for treatment of joint instability and patellofemoral compartment disease are also mentioned. Based on the evidence presented as part of this clinical commentary, it is argued that special considerations for the role of knee joint biomechanics and excessive joint loading are necessary in designing effective short- and long-term management strategies for treatment of patients with knee osteoarthritis.

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One potential reason for the lack of effective long-term physical therapy management strategies for knee OA is that the influence of altered joint biomechanics and excessive joint loading has not always been considered. Excessive loading of the knee joint can contribute to symptoms and disease progression by creating an unfavorable balance between breakdown and repair of joint tissues.[49,134] Although it is well accepted that genetics, inflammatory mediators, and age-related changes in joint biology play important roles in the structural progression of knee OA,[122] considering the influence of these systemic risk factors is beyond the scope of this commentary. However, evidence in support of the notion that excessive joint loading is linked to increased symp-

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toms[4,110,191] and progression of knee OA[134] suggests that joint-protective strategies may provide better symptomatic relief and enhanced long-term outcomes.[49] Therefore, the intent of this clinical commentary is to provide physical therapists with the current state of knowledge concerning the potential joint-protective capabilities of offloading interventions commonly utilized in the management of patients with knee OA.

KNEE JOINT LOADING AND OA

The Role of Knee Adduction Moment

Due to the difficulty of direct evaluation of in vivo joint loading, external knee adduction moment (KAM) has traditionally been used as the surrogate marker of medial compartment tibiofemoral joint loading. KAM is calculated as the product of ground reaction force (GRF) generated by the foot-ground interaction and the perpendicular distance of this force vector in the frontal plane from the knee center of rotation, also known as its lever arm. In a lower limb with neutral alignment, the GRF commonly passes medial to the knee joint's center of rotation, thus creating a KAM (**FIGURE 1A**). KAM creates a tendency for the tibia to rotate in a varus direction, such that a larger KAM concentrates higher compressive loads on the medial tibiofemoral compartment.[5] The uneven nature of the loads imparted on the tibiofemoral joint due to KAM is, in part, responsible for the higher prevalence of medial compartment knee OA.[34,113,130]

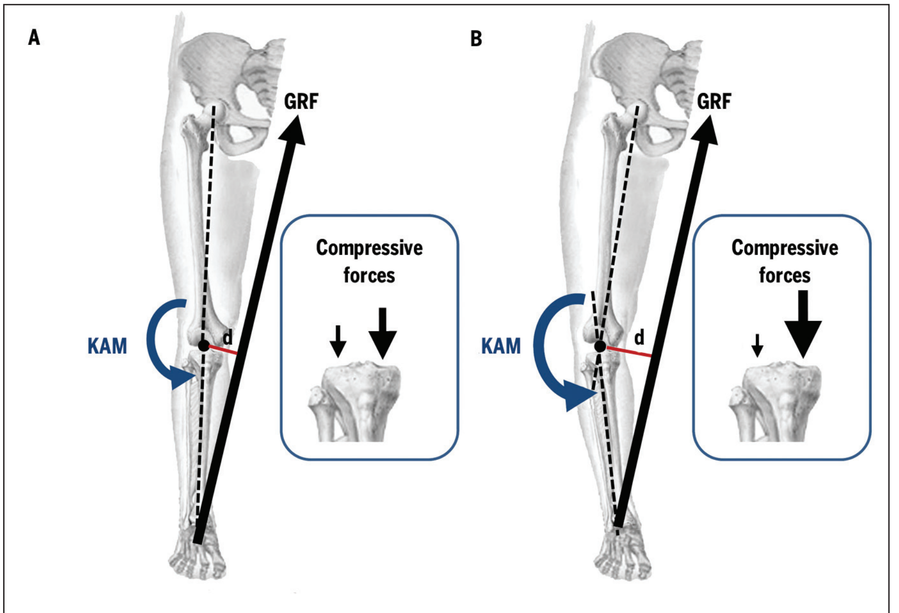

FIGURE 1. (A) In a lower limb with neutral alignment, the GRF passing medial to the knee center of rotation creates a small KAM that concentrates higher compressive loads on the medial tibiofemoral compartment. A lower limb is considered neutral when the angle formed between the intersection of the mechanical axis of the femur (the dotted line from femoral head center to femoral intercondylar notch center) and the mechanical axis of the tibia (the dotted line from ankle talus center to the center of the tibial spine) is 0°. (B) In a lower limb with varus alignment, the increase in the perpendicular distance between the GRF and the center of rotation of the knee (d) increases both KAM and compressive loads on the medial tibiofemoral compartment. A lower limb is considered to be in varus when the angle formed between the intersection of the mechanical axes of the femur and the tibia (dotted lines) is greater than 0° in the varus direction. The vertically aligned black arrows signify the relative magnitude of the medial and lateral joint compressive loads created by the KAM. Cocontraction of the muscles crossing the knee joint and higher external knee flexion moments may also provide additional joint compressive loads, which are not depicted in the figure. Abbreviations: GRF, ground reaction force; KAM, knee adduction moment.

KAM typically exhibits 2 peaks during the stance phase of gait that correspond to the peaks in the vertical GRF. The larger initial peak occurs during the load-acceptance phase of gait, and the second peak occurs in late stance (**FIGURE 2**).[87] A higher first peak in KAM has been previously reported in patients with medial compartment knee OA,[94,138] and a larger KAM has been associated with greater radiographic disease severity[9,173] and pain.[4,191] Additionally, a 1-unit increase in KAM at baseline has been associated with a 6-fold increase in the likelihood of medial compartment disease progression over 6 years.[134] Given that KAM is often used as an outcome measure in research studies that assess the effectiveness of interventions used in management of patients with knee OA,[16,61,118,131,181] it is essential for physical therapists to have a thorough understanding of the factors that could influence KAM, along with the limitations of its use.

Offloading Intervention Strategies and KAM

Current clinical approaches for reducing KAM are primarily designed around the premise that GRF and its frontal plane lever arm are independent variables that could be manipulated through various interventions. GRF is the equal and opposite reaction force exerted by the ground on the body during weight bearing (Newton's third law of motion). The magnitude of this GRF, as described by Newton's second law of motion, is determined by the product of the patient's body mass and the acceleration of the patient's center of mass (force = mass × acceleration). Therefore, strategies that could either limit the influence of the patient's body mass on the magnitude of GRF (eg, using a cane for offloading of the stance limb[107,125]) or decrease the acceleration of the patient's center of mass (eg, reduced gait speed[139]) could be effectively used to decrease KAM.

Additionally, strategies to decrease the length of the frontal plane KAM lever arm through lower-limb realignment or lateral displacement of the center of pressure could also reduce KAM. For example, a static varus lower-limb malalignment, which is a common finding in patients with medial compartment knee OA, has been suggested to lead to elevations in KAM.[174] As the GRF vector typically runs from the center of pressure under the foot toward the body's center of mass, a more laterally positioned center of rotation in knees with varus malalignment lengthens the GRF lever arm in the frontal plane, thus increasing KAM (**FIGURE 1B**).[87,202] Theoretically, interventions aimed at decreasing lower-limb varus malalignment, such as valgus bracing[45,46,104,149] or a medial thrust gait pattern,[11,66,165] can bring the knee center of rotation closer to the line of action of the GRF and thus decrease KAM by reducing its frontal plane lever arm. Similarly, moving the GRF vector closer to the knee center of rotation by moving the center of pressure laterally through a lateral trunk lean[89,137] or a toe-out gait pattern[67,100,124] could also be effective in reducing KAM by shortening its frontal plane lever arm.

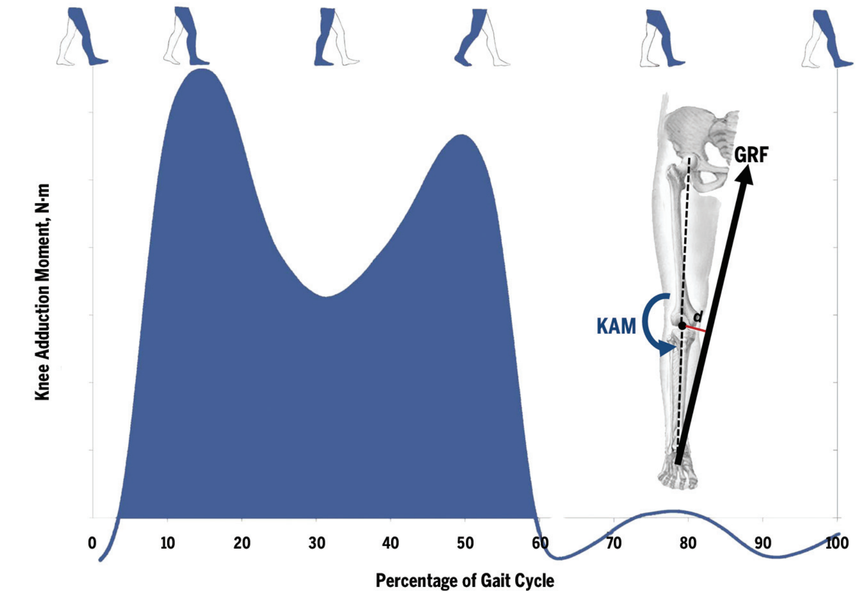

FIGURE 2. Schematic representation of the KAM during gait. The KAM typically exhibits 2 peaks during the stance phase of gait. Each peak corresponds to the peak in the vertical GRF. The larger first peak occurs during the load-acceptance phase of gait (0%-12% of gait cycle), with the second, smaller peak occurring in late stance (50%-62% of gait cycle). The KAM is negligible during the swing phase of gait (62%-100% of gait cycle). Abbreviations: GRF, ground reaction force; KAM, knee adduction moment.

Limitations of KAM in Studies of Knee OA

Although KAM is an easily measured and commonly used marker of tibiofemoral joint loading, its application as the sole marker of knee joint loading is associated with a number of limitations. First, the cocontraction of knee-spanning muscles (eg, quadriceps, hamstrings, and gastrocnemius), which can substantially contribute to the medial compartment compressive loads, is not accounted for when calculating KAM.[121,203] Given that increased muscular cocontraction is often reported in patients with knee OA,[71,117,204] reports of KAM that ignore muscle activation contributions to joint loading may underestimate the actual compressive loads experienced by patients with knee OA. Second, an increased external knee flexion moment in the sagittal plane has also been suggested to significantly contribute to tibiofemoral joint contact forces during weight bearing in the absence of a change in KAM.[201] To counterbalance the increase in externally generated knee flexion moments (eg, during the loading phase of gait), an equal and opposite internal knee extension moment is needed, which is primarily produced by increases in quadriceps muscle force and an elevation in knee joint contact forces. Therefore, neglecting the potential compressive forces created by greater sagittal plane knee flexion moments could represent an incomplete picture of the dynamic loading environment of the knee joint during weight bearing. Further, KAM may be a poor surrogate for the complex interaction of the tibial plateau and the femoral condyle contact forces, which may be dictated by joint geometry, meniscus function, and cartilage responses, which are not considered in calculations of KAM.

Despite its limitations, KAM remains a convenient measure of the gross loading environment of the medial tibiofemoral compartment. For example, assuming that the level of cocontraction and the magnitude of the external knee flexion moment remain constant, interventions that decrease KAM most likely lead to lower loads placed on the medial tibiofemoral compartment. Additionally, KAM still has value as a screening tool to identify individuals at risk for knee OA, because peak KAM during the early stance phase of gait in subjects with knee OA is greater than that of asymptomatic subjects,[94] and larger peak KAM has been linked to increased pain[4,191] and higher rates of disease progression.[134]

MEDIAL COMPARTMENT OFFLOADING STRATEGIES

Treatment strategies with potential for tibiofemoral compartment offloading may provide a unique opportunity for both symptomatic relief and reducing structural disease progression in patients with knee OA. Given the higher prevalence of medial knee OA,[34,113,130] offloading strategies of the medial compartment are of great interest. To this end, a whole host of conservative medial compartment offloading strategies have been recommended, with great potential for clinical utilization.

TABLE 1 Immediate Influence of Cane Use on Knee Adduction Moment

Study	Cane Use	Comparison Condition	KAM Change, %: First Peak	KAM Change, %: Second Peak
Chan et al[22]	Ipsilateral	Unaided	+40	NR
	Contralateral		–7	NR
Kemp et al[107]	Contralateral	Unaided	–10	NR
Simic et al[177]	Contralateral (10% body-weight support)	Unaided	–6	–17
	Contralateral (15% body-weight support)		–12	–29
	Contralateral (20% body-weight support)		–17	–46

Abbreviations: KAM, knee adduction moment; NR, not reported.

TABLE 2 Immediate Influence of Laterally Wedged Shoe Insoles on Knee Adduction Moment

Study	Shoe Insole Design	Comparison Condition	KAM Change, %: First Peak	KAM Change, %: Second Peak
Abdallah and Radwan[1]	6° full-length lateral wedge	Flat insoles	–9	NR
	11° full-length lateral wedge		–5	NR
Butler et al[21]	9.6° full-length lateral wedge	Flat insoles	–9	–2
Fantini Pagani et al[45]	4° full-length lateral wedge	Normal walking shoe	–7	–8
Hinman et al[76]	5° full-length lateral wedge	Normal walking shoe	–5	–5
Hinman et al[77]	5° full-length lateral wedge	Normal walking shoe	–6	NR
Hinman et al[78]	5° full-length lateral wedge	Normal walking shoe	–12	–14
	5° lateral heel wedge		–7	–7
Jones et al[104]	5° lateral heel wedge	Normal walking shoe	–13	–15
Kerrigan et al[108]	5° lateral heel wedge	Normal walking shoe	–5	–6
	10° lateral heel wedge		–8	–8
Leitch et al[115]	4° lateral heel wedge	Normal walking shoe	–2	NR
	8° lateral heel wedge		–3	NR
Maly et al[126]	5° lateral heel wedge	Normal walking shoe	–2	NR
	Off-the-shelf orthosis modified to maintain rearfoot in 5° of valgus	Normal walking shoe	+4	NR
Shimada et al[176]	10-mm elevation lateral heel wedge (grade I OA)	Normal walking shoe	–5	NR
	10-mm elevation lateral heel wedge (grade II OA)		–7	NR
	10-mm elevation lateral heel wedge (grade III OA)		–3	NR
	10-mm elevation lateral heel wedge (grade IV OA)		–5	NR

Abbreviations: KAM, knee adduction moment; NR, not reported; OA, osteoarthritis.

The basic premise behind these offloading strategies is that manipulating the magnitude of the GRF and/or reducing its external lever arm leads to substantial reductions in KAM and the medial compartment compressive loads.

Contralateral Cane Use

Prescription of an assistive walking device, such as a cane, is recommended by most clinical guidelines as an integral component of conservative medical care for patients with knee OA.[84,145,205,206] Using a cane opposite the side of the symptomatic knee has been previously shown to reduce KAM by an average of 7% to 10% compared to walking unaided (**TABLE 1**). Additionally, contralateral cane usage can reduce the cumulative loading of the knee joint over a given gait distance through adaptive increases in stride length and an associated decrease in cadence.[107,177] The immediate offloading effects of contralateral cane use could be attributed to shifting a portion of the body weight off the symptomatic knee joint (ie, a reduction in GRF) and/or to the reduction of the external KAM lever arm. Kemp and colleagues[107] reported that reductions in KAM during contralateral cane use were partially explained by a 6% decrease in the GRF magnitude created by upper-limb support through the cane. It is also reported that when the tip of the cane and the foot touch the ground simultaneously, the cane could share as much as 34% of the force at heel strike, 25% at midstance, and 30% at toe-off during the stance phase of gait.[125] Additional reductions in KAM due to a decrease in the length of the KAM lever arm can also arise due to changes in the position of the trunk or a change in position of the knee relative to the line of action of the GRF.[22]

Contralateral cane use can also effectively diminish pain and improve function and some aspects of quality of life in patients with knee OA.[103] Recent randomized clinical trials of patients with knee OA demonstrated significantly diminished pain and improved physical function after 2 months of daily cane use.[103,135] For optimal efficacy, patients with knee OA should be instructed to use a cane on the contralateral side and as far laterally as possible to optimize reductions in knee loads. Placing the cane at a longer lateral distance can create neutralizing knee abduction moments to further counteract and decrease KAM during gait.[177] Inappropriate cane placement, however, is not a trivial issue, as increases of up to 40% in KAM have been previously reported with ipsilateral cane use (**TABLE 1**).[22] Therefore,

TABLE 3 — Immediate Influence of Variable-Stiffness Shoes on Knee Adduction Moment

Study	Treatment	Comparison Condition	KAM Change, %: First Peak	KAM Change, %: Second Peak
Erhart-Hledik et al[44]	Variable-stiffness shoe	Constant-stiffness control shoe	–6	NR
Erhart et al[41]	Variable-stiffness shoe	Constant-stiffness personal shoe	–13	–22
Erhart et al[42]	Variable-stiffness shoe	Constant-stiffness control shoe	–7	NR
Erhart et al[43]	Variable-stiffness shoe (slow gait)	Constant-stiffness control shoe	–2	NR
	Variable-stiffness shoe (normal gait)		–5	NR
	Variable-stiffness shoe (fast gait)		–6	NR
Jenkyn et al[99]	Variable-stiffness shoe	Constant-stiffness control shoe	–7	NR

Abbreviations: KAM, knee adduction moment; NR, not reported.

no cane use would be preferred to ipsilateral cane use in patients with medial compartment knee OA.

Patients with knee OA should also be urged to maintain greater overall body-weight support through the cane across the stance phase of gait, which can result in additional reductions in KAM (**TABLE 1**).[177] Moreover, patients should be encouraged to achieve earlier peak body-weight support through the cane during the load-acceptance phase of gait, which coincides with the largest peak in KAM. The prescription of cane use for novice users should take into account the substantial increase in energy expenditure at the onset of cane use,[102] which decreases over time through an ongoing process of adaptation to using an assistive device.[103] Clinicians should also be reminded that, although cane use appears to be an effective offloading strategy, lack of patient compliance is a significant clinical obstacle, due to a common patient perception that canes are for frail, elderly people and imply aging.

Laterally Wedged Shoe Insoles

Shoe insoles with a wedged incline along the outside of the heel have been shown to be effective in reducing the first and second peaks in KAM by as much as 13% and 15%, respectively (**TABLE 2**). Theoretically, KAM reductions of this magnitude accumulated over thousands of steps per day can be clinically meaningful in terms of mitigating symptoms and reducing the risk of structural disease progression. The primary mechanism responsible for KAM reduction with a laterally wedged insole is attributed to a lateral shift of the center of pressure and a reduction of the external KAM lever arm. Extension of the lateral wedge along the entire length of the foot seems to further reduce KAM compared to a laterally wedged insole covering just the heel region.[45,76-78] To encourage better compliance, patient-specific prescription of a full-length lateral wedge angle that provides the maximum amount of pain reduction while limiting foot discomfort during a functional task is clinically recommended.[21] Conversely, wearing down the lateral shoe sole or use of medial arch supports could have the opposite effect by moving the center of pressure medially and increasing KAM, which should be avoided.[65]

Although evidence in support of the immediate reduction of KAM with laterally wedged insoles is promising, their long-term impact on improving pain and limiting structural disease progression is less convincing. Numerous studies have reported reductions in pain scores in the short term (12 months or less) with the use of laterally wedged insoles.[10,83,104,106,160,168] Adding elastic strapping of the subtalar joint to the lateral wedge intervention seems to further decrease pain compared to the traditional wedged insoles at both 2 and 6 months.[195,196] However, 2 recent randomized clinical trials of patients with knee OA reported that laterally wedged insoles provide no long-term symptomatic or structural benefits.[7,14] Furthermore, a systematic review concluded that, based on current evidence, there are no major long-term clinical effects with the use of laterally wedged insoles.[158]

It is plausible that the long-term effectiveness of laterally wedged insoles may depend on factors such as disease severity and patient-specific prescription of the device. For example, the effectiveness of a laterally wedged insole in reducing KAM has been shown to be significant in individuals with early to mild knee OA but not in the presence of more severe disease.[176] Interestingly, the average degree of wedging necessary to produce the maximum amount of pain relief has been reported to increase with radiographic disease severity, suggesting that greater wedging is needed for more advanced knee OA.[21] However, insoles with greater than a 7° wedge have been associated with increased reports of foot and ankle discomfort.[21,108] If greater wedging is necessary, an individually contoured arch profile, along with a gradual reduction in heel wedge inclination to 0° at the fifth metatarsal head, may reduce the reported foot and ankle discomfort and improve patient satisfaction.[104] It is also suggested that insoles with subtalar strapping are more efficacious for younger patients and those with greater lower-limb lean body mass, and less efficacious for older patients with sarcopenia.[194] It appears that proper patient selection criteria and individualized prescription of laterally wedged insoles are necessary to improve outcomes and encourage better compliance.

Variable-Stiffness Shoes

Evidence suggests that, compared with barefoot walking, wearing shoes significantly increases knee loading.[107,171] However, because it is potentially dangerous, as well as impractical, to advise patients with knee OA to walk barefoot, selection of more appropriate types of shoes may provide a logical alternative. Variable-stiffness shoes, in which the stiffness of the lateral sole is greater than the medial portion, could be a viable option for patients with medial compartment knee OA. Variable-stiffness shoes have been shown to significantly reduce the first peak in KAM by as much as 13% compared to constant-stiffness control shoes (**TABLE 3**).[41-44,99] Given that the magnitude of the GRF remains relatively unchanged when wearing variable-stiffness shoes, it has been suggested that reductions in KAM are related to a lateral shift in the center of pressure at the foot, which reduces the external KAM lever arm.[99] An instrumented knee replacement prosthesis that directly measured knee loading in a single patient found reductions of 13% in the first peak in KAM, 22% in the second peak in KAM, and 12% in the medial compartment joint contact force when walking with variable-stiffness shoes compared to personal shoes.[41] Clinical evidence also supports the effectiveness of variable-stiffness shoes in reducing knee pain and improving function after 6 and 12 months of continuous use.[42,44] Therefore, the use of variable-stiffness shoes seems to be an effective treatment strategy for reducing symptoms and medial compartment loading for patients with knee OA during gait.

TABLE 4 IMMEDIATE INFLUENCE OF A VALGUS KNEE BRACE ON KNEE ADDUCTION MOMENT

			KAM Change, %	
Study	**Knee-Brace Design**	**Comparison Condition**	**First Peak**	**Second Peak**
Draganich et al[35]	Neutral valgus brace	No brace	–9	NR
	1.5° valgus brace		–25	NR
Fantini Pagani et al[45]	4° valgus brace	No brace	–2	–18
	8° valgus brace		–7	–21
Fantini Pagani et al[46]	Neutral valgus brace	No brace	–6	–14
	4° valgus brace		–13	–22
	8° valgus brace		–19	–34
Jones et al[104]	6° valgus brace	No brace	–7	–13
Lindenfeld et al[120]	Adjustable valgus brace	No brace	–10	NR
Pollo et al[149]	4° valgus brace	No brace	–13	NR
Toriyama et al[197]	Adjustable valgus brace	No brace	–11	0

Abbreviations: KAM, knee adduction moment; NR, not reported.

Valgus Knee Bracing

The aim of valgus bracing is to change the way the forces are distributed at the knee, by transferring joint loading away from the painful medial compartment. Valgus braces are designed to apply an external counteracting valgus moment to the knee, thereby reducing KAM and the compressive loads of the medial compartment. Valgus knee braces with variable amounts of valgus correction have been reported to reduce the first peak in KAM by as much as 25% and the second peak in KAM by as much as 34% during gait (**TABLE 4**). The variability in the reported effectiveness of valgus bracing may be due to the fact that each study examined a brace made by a different manufacturer, with varying degrees of valgus correction. Misalignment of the brace hinge because of poor fit may also affect its usefulness in reducing KAM and could lead to increased patient discomfort.[180] Therefore, it is probable that the effectiveness of the brace is dependent on its mechanical design and how well it fits the patient.

Valgus knee braces have also been shown to significantly reduce knee pain in the short term (0-12 months).[69,73,109,120,129,149] In a randomized controlled trial of 117 patients with medial knee OA, valgus bracing resulted in better knee function and walking distance compared with no brace in patients with varus malalignment.[19] However, many patients in that study did not adhere to the brace treatment, mainly because of skin irritation and poor fit. Therefore, lack of treatment adherence may be the biggest factor in limiting good outcomes in the long-term use of valgus knee braces. Custom-fitted valgus bracing may offer better compliance by providing more comfort and leading to more desirable changes in joint loading, with better subjective relief of knee pain.[35,112] In a prospective, parallel-group, randomized clinical trial of 119 patients with knee OA and varus malalignment, custom-made unloader bracing resulted in significant improvement in the disease-specific quality of life and function at 6 months.[109] Although the patients in that study found the custom-fitted brace to be reasonably comfortable, it was more common for them to wear the brace for specific activities rather than for the entire day. This may limit the usefulness of the brace for people who regularly engage in activities that may not be amenable to wearing a brace. Additionally, individuals who are obese may have particular difficulty with generically sized braces. Valgus knee braces are also expensive and may be financially impractical for many patients with knee OA. Finally, valgus knee braces may only be effective for individuals with isolated medial knee OA and in the absence of a major fixed knee joint deformity. It is currently unknown which patients are ideal candidates for valgus bracing, and additional studies are needed to identify important predictive variables for its successful use.

Gait Modification

Training patients with knee OA to modify their gait pattern may also be beneficial in reducing knee loads, with or without a need for an external device. A systematic review of gait-modification strategies for reducing KAM recently concluded that modification strategies such as ipsilateral trunk lean and toe-out gait indeed have the ability to reduce medial compartment joint loading.[178] An ipsilateral trunk lean is a compensatory mechanism naturally adopted by many patients with medial knee OA for symptomatic relief during gait, with greater trunk leans being associated with greater disease severity.[89,137] Transfer of the body's center of mass and, therefore, the center of pressure laterally through an ipsilateral trunk lean can shift the GRF vector closer to the knee joint center and thereby reduce the external KAM lever arm. A self-induced lateral trunk lean toward the stance limb in healthy subjects has been shown to effectively reduce the first peak in KAM by as much as 65% (**TABLE 5**).[137] Additionally, greater amounts of naturally adopted lateral trunk lean have been shown to lead to greater reductions in KAM in patients with medial compartment knee OA.[88,179] Although lateral trunk lean may substantially reduce medial compartment loading, the training of this movement strategy as a long-term solution should be considered in light of increases in body sway and the risk of falls, increased probability of injury to other body regions, such as the hip and the lumbar spine, and the potential for excessive loading of the lateral tibiofemoral compartment.

TABLE 5 — Immediate Influence of Gait Modification on Knee Adduction Moment

Study	Gait-Modification Strategy	Comparison Condition	KAM Change, % First Peak	KAM Change, % Second Peak
Hunt et al[88]	4° lateral trunk lean	Natural gait	–6	–13
	8° lateral trunk lean		–17	–13
	12° lateral trunk lean		–20	–15
Mündermann et al[137]	Increased mediolateral trunk lean	Natural gait	–65	NR
Mündermann et al[140]	10° lateral trunk lean	Natural gait	–55	NR
Simic et al[179]	6° lateral trunk lean	Natural gait	–9	–17
	9° lateral trunk lean		–11	–18
	12° lateral trunk lean		–15	–24
Fregly et al[66]	15.0° toe-out gait	Natural gait	0	–38
Guo et al[70]	18.6° toe-out gait	Natural gait	+1	–40
Jenkyn et al[100]	11.4° toe-out gait	Natural gait	–11	–35
Lynn and Costigan[123]	17.1° toe-out gait	Natural gait	+2	–23
Lynn et al[124]	40.2° toe-out gait	Natural gait	+13	–93
Schache et al[165]	11° toe-out gait	Natural gait	0	–23
	Medial knee thrust		–44	–17
Barrios et al[11]	Increased hip internal rotation/adduction	Natural gait	–20	NR
Fregly et al[67]	Medial knee thrust	Natural gait	–50	–55
Walter et al[201]	Medial knee thrust	Natural gait	–32	–15

Abbreviations: KAM, knee adduction moment; NR, not reported.

Walking with a toe-out gait (ie, externally rotated lower limb) has also been proposed to reduce medial compartment joint loads by converting a portion of the external KAM into an external knee flexion moment.[100] The external rotation of the lower limb reduces KAM by shifting the GRF vector closer to the knee center of rotation, thus shortening the external KAM lever arm by 7% and reducing the first peak in KAM by as much as 11% (**TABLE 5**). However, biomechanical evaluations of toe-out gait in patients with medial compartment knee OA have, for the most part, reported larger reductions in the second peak of KAM during the late stance phase of gait, due to a lateral shift in the path of the center of pressure. In support of the potential long-term benefits of toe-out gait, a longitudinal observational study of 56 patients with medial knee OA demonstrated that a greater naturally adopted toe-out angle during gait was associated with reduced likelihood of structural disease progression over 18 months.[24] However, issues with compliance may render long-term outcomes less effective, as implementation of toe-out gait modification requires a permanent adoption of an altered gait strategy by the patient. The externally rotated lower limb also causes the GRF vector to pass more posterior to the knee center of rotation in the sagittal plane, and therefore may lead to an undesirable increase in the external knee flexion moment and greater loading of the knee joint.[100]

Gait-modification strategies targeting the hip and ankle joint may also provide unique opportunities for reducing medial knee compartment loading in patients with knee OA. For instance, the "medial knee thrust" gait pattern, which involves a conscious movement of the knee joint in a medial direction, has been proposed as an effective strategy for decreasing KAM. Medial movement of the knee joint, by changing the orientation of the femur at the hip joint and/or the tibia at the ankle joint, repositions the knee joint center closer to the GRF vector and thus reduces the external KAM lever arm. In a single-subject study, modeling simulations of the medial-thrust gait pattern in a patient with knee OA predicted reductions of as high as 50% for the first peak and 55% for the second peak in KAM (**TABLE 5**).[67] A recent study of systematic training of medial-thrust gait pattern using real-time knee alignment feedback also reported a 19% decrease in KAM after only 8 training sessions in 8 asymptomatic but varus-aligned individuals.[11] Although seemingly effective, training of this movement modification may pose several clinical challenges, given the complexity of the movement and the requirement for special training and biofeedback equipment.[178] Implementing this strategy for patients with multicompartmental knee OA, end-stage disease, or an associated fixed knee joint deformity may also lead to suboptimal treatment outcomes. Larger randomized trials with long-term follow-up surveillance are currently needed to establish the clinical applicability and joint-protective abilities of medial-thrust gait-modification strategies for treatment of individuals with knee OA.

EXERCISE THERAPY TO REDUCE JOINT LOADING IN KNEE OA

Lower extremity muscle weakness is a hallmark impairment of knee OA. Muscular strength is critical to maintaining proper dynamic joint function, as muscles aid in shock absorption and proper force transfer across the joint.[93] Although large randomized clinical trials of knee OA management have substantiated the effectiveness of exercise therapy in reducing pain, improving function, and limiting disability, there are currently no recommendations for exercise therapy to promote better joint protection for prevention of further joint damage.[64]

Quadriceps Strengthening

Quadriceps muscle weakness is suggested as a strong risk factor for knee OA[50,182,183] and a good predictor of pain and impaired physical function in those with symptomatic disease.[3,55,182] To this end, evidence from several studies suggests that quadriceps weakness is associated with higher rates of joint loading during the early stance phase of gait and higher average KAM during the entire stance phase of gait.[133,155,186] Accordingly, several mechanical explanations have been suggested for the potential relationship between quadriceps strength and prevention of structural disease progression in knee OA. For instance, the quadriceps may have a joint-protective role as shock absorbers to help dampen the rate of knee joint loading, such as the potentially harmful loads occurring at heel strike during gait.[97] Due to the laterally positioned patellar tendon line of pull with respect to the knee center of rotation, contraction of the quadriceps has also been suggested to provide abduction moments that help to stabilize the knee joint in the frontal plane and contribute to balancing the KAM during the early stance phase of gait.[121,175] Additionally, coactivation of the quadriceps and hamstrings can counteract a major portion of the passive KAM generated during gait.[121] However, muscle cocontractions could also significantly increase the overall compressive loads imparted on the knee joint and may not be desirable.[185]

Conversely, Lim and colleagues[119] recently reported no significant association between quadriceps strength and peak KAM during gait in 184 community volunteers with medial knee OA. Furthermore, randomized controlled trials of quadriceps strengthening in patients with medial compartment knee OA, with or without a static varus malalignment, reported no posttreatment changes in KAM during gait or a step-down task, even though increases in quadriceps strength and improvements in pain and function were observed.[61,118,131] Despite the lack of evidence in support of the effectiveness of quadriceps strengthening in reducing KAM, the potential unloading benefits of this intervention in patients with knee OA should not be completely ruled out. Walter and colleagues[201] recently suggested that a reduction in peak KAM may not be the only mechanism by which the peak medial compartment compressive forces could be reduced. This conclusion was reached based on the finding that an expected reduction in the medial compartment compressive loads due to a decrease in KAM may be attenuated by an increase in the absolute value of the external knee flexion moment. To this end, better control of the knee flexion motion provided by stronger quadriceps could lead to reductions in the knee flexion moment and a decrease in compressive loading of the medial tibiofemoral compartment. Therefore, in investigations of quadriceps strengthening programs where improved clinical outcomes in pain and function were not associated with a reduction in KAM,[61,118,131] lack of consideration for potential changes in the knee flexion moment may have contributed to an incomplete picture of the posttreatment unloading of the medial knee compartment.

The role of quadriceps strength in preventing structural progression of knee OA is also controversial. Large prospective cohort studies have suggested that quadriceps weakness is a risk factor for developing knee OA in women[183] and that quadriceps weakness can predict incident symptomatic knee OA over 2.5 years.[169] On the other hand, a prospective study of the natural history of knee OA in 265 individuals failed to show any association between quadriceps weakness and tibiofemoral joint cartilage loss over 2.5 years.[3] Quadriceps weakness among women with established knee OA was also reported not to be associated with increased risk of radiographic disease progression over 2.5 years.[18] Similarly, a randomized clinical trial of lower extremity strength training versus range-of-motion exercise in 221 older adults failed to demonstrate that a better retention of quadriceps strength had a protective effect on progression of joint space narrowing over 30 months.[132]

Although quadriceps strengthening has proven to be effective in reducing pain and improving function in patients with knee OA,[98,118,147] benefits may be more evident in patients without knee malalignment and with less severe disease.[118] Overall, despite its beneficial effects on reducing pain and improving function, whether quadriceps strengthening can influence loading of the knee joint or prevent structural disease progression in patients with knee OA remains unclear. These findings have potential clinical implications, as conventional exercise regimens recommended for treatment of

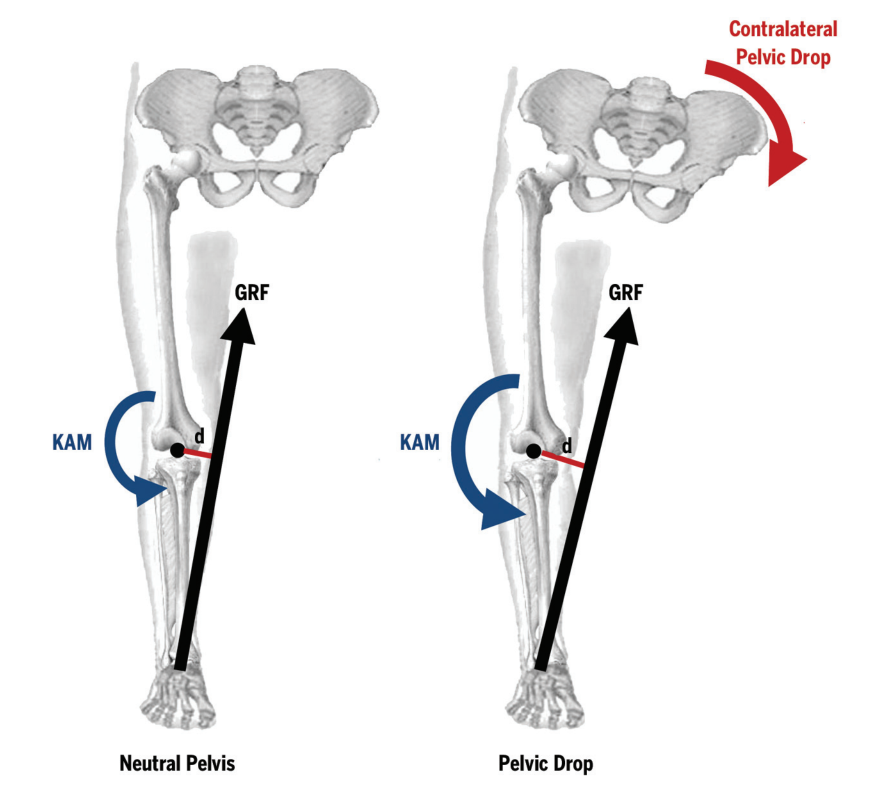

FIGURE 3. Weakness of the stance-limb hip abductor muscles can result in a contralateral pelvic drop, shifting the body's center of mass away from the stance limb and toward the swing limb. The medial shift of the center of mass away from the stance limb consequently increases the perpendicular distance between the GRF and the center of rotation of the knee (d), which leads to an increase in the KAM and compressive loads on the medial tibiofemoral compartment. Abbreviations: GRF, ground reaction force; KAM, knee adduction moment.

knee OA are heavily focused on isolated quadriceps strengthening, despite lack of strong evidence that quadriceps can influence KAM or prevent structural disease progression.

Hip Abductor Strengthening

More recently, a new body of evidence has emerged to support the premise that impairments of the hip abductor musculature may also be linked to the pathomechanics of knee OA.[23,81] In a prospective cohort study of 57 patients with knee OA, hip abductor weakness was associated with a greater likelihood of medial knee OA progression over 18 months.[23] Evidence also suggests that significant strength deficits of the hip abductors are common in patients with knee OA.[2,16,81] Weakness of the stance-limb hip abductors can result in a drop of the contralateral pelvis, shifting the body's center of mass away from the stance limb and toward the swing limb.[23] This shift of the center of mass will theoretically increase the external KAM lever arm, thereby increasing the loading of the medial tibiofemoral compartment (**FIGURE 3**).[189]

The evidence related to the influence of hip abductor muscle weakness in altering medial compartment knee loads, however, remains inconclusive across the literature. In a small pilot study of 6 individuals with medial knee OA, a 4-week exercise program specifically targeting the hip abductor musculature resulted in small decreases in KAM but significant improvements in knee pain scores.[192] Conversely, a 6-month randomized clinical trial of progressive resistance training targeting the hip abductors failed to show any improvements in KAM despite significant increases in hip abductor strength.[62] Two other randomized clinical trials of home-based hip abductor strengthening also reported no effects on KAM despite significant gains in strength and improvements in pain and function.[16,181]

A potential explanation for the inconsistent findings regarding the influence of hip abductor muscle strengthening in reducing KAM is the lack of consideration for whether patients with knee OA actually presented with a contralateral pelvic drop. It could be argued that in the absence of a contralateral pelvic drop, hip abductor muscle weakness and, therefore, hip abductor strengthening may have no influence on KAM and medial compartment loading.[189] Alternatively, many patients with hip abductor muscle weakness will naturally adopt a compensatory ipsilateral trunk lean gait strategy. Given the effectiveness of ipsilateral trunk lean to substantially reduce KAM (**TABLE 5**),[137] it would be unlikely that strengthening of the hip abductor musculature in patients with ipsilateral trunk lean would lead to any further decreases in joint loading. Despite significant improvements in pain and function after hip abductor muscle strengthening, the biomechanical role of hip abductor musculature in terms of its ability to improve the loading environment of the knee joint in patients with knee OA remains inconclusive.

Neuromuscular Training

Recent findings from computational modeling efforts suggest that medial compartment loading represents the composite effect of contributions from both the knee-spanning and non–knee-spanning muscles.[121,175,185,203] Shelburne et al[175] and Winby et al[203] concluded that the cocontraction of the quadriceps, hamstrings, and gastrocnemius muscles significantly contributes to medial compartment compression during normal gait. Sritharan et al[185] also demonstrated that contraction of non–knee-spanning muscles, such as the gluteus medius and the soleus, can substantially influence the medial knee compartment compressive forces. Therefore, improvements in the loading environment of the knee joint may require targeting muscles beyond those that cross the knee joint. These findings also provide a potential explanation for why training strategies of single muscle groups (quadriceps or hip abductors) have been shown to be ineffective in reducing KAM in previous investigations.[16,60,118,181] To this end, the addition of a neuromuscular training program aimed at improving sensorimotor control and functional stability of the entire lower limb to traditional strengthening exercises may provide additional opportunities to capitalize on the beneficial effects of stronger muscles to achieve better knee joint biomechanics in patients with knee OA.[15,159] Evidence in support of this notion has been provided by recent pilot studies of combined neuromuscular training that includes balance, perturbation, agility, plyometrics, and endurance activities along with traditional lower-limb muscle strengthening exercises to lead to positive joint-protective reductions in loading across the knee joint.[143,193]

JOINT INSTABILITY AND KNEE OA

Episodic reports of knee joint instability (eg, giving way, buckling, or the shifting of arthritic knees) during activities of daily living are common and represent a significant cause of functional limitation in individuals with knee OA.[58,198] The sensation of joint instability is most likely associated with abnormal or excessive translations of the articular surfaces that subject the knee joint to harmful shear forces and accelerated rates of disease progression.[6] To this end, the presence of greater levels of muscle cocontraction in patients with knee OA, as a compensatory strategy for knee stabilization, has previously been reported.[116,117] However, greater muscle cocontraction can further increase the joint compressive forces and hasten the progression of OA.[85,203] In addition, recent evidence suggests that greater muscle cocontraction is an ineffective strategy for limiting knee joint instability.[166] As the combined effects of excessive shear forces and muscle cocontraction can adversely affect symptoms and the rate of disease progression, more appropriate interventions aimed at mitigating joint instability should be considered in the management of individuals with knee OA. Treatment of joint instability is especially important, as improvements in joint stability have been reported to increase the odds of a positive treatment response to therapeutic exercise in patients with knee OA.[59]

Physical impairments such as muscle weakness, impaired proprioception, and joint laxity have been hypothesized to be important causal factors in self-reported knee instability in patients with knee OA.[52,58,111,116,117,166,199] Therefore, exercise therapy and neuromuscular training have been suggested as potential treatment options in patients with reports of instability. In a case report of a single patient with knee OA and episodes of knee instability, 12 sessions of lower-limb stretching, strengthening, and endurance exercises, supplemented with agility and perturbation training techniques, resulted in significant improvements in pain and function and a reduction in occurrence of knee instability.[56] Agility and perturbation training has also been shown to be effective in the treatment of knee joint instability after anterior cruciate ligament injuries, by improving knee joint kinematics and reducing muscle cocontractions.[92] However, a recent randomized clinical trial involving individuals with knee OA reported only small improvements in the proportion of participants reporting knee instability after completing a 12-session agility and perturbation program.[57] The authors concluded that a more intense application of the agility and perturbation intervention might have yielded better results. Knee bracing has also been shown to be an effective option in providing pain relief and reducing harmful muscle cocontractions while diminishing self-reported instability in patients with knee OA.[156] The benefits of wearing a brace, in terms of reductions in pain and improved joint stability, may be the result of reduced muscle cocontractions, which are mediated by the brace as it mechanically stabilizes the knee joint.[156] Given that most episodes of knee instability occur during walking,[52,111] treatment strategies may need to specifically focus on knee-stabilization strategies during this functional task. As the optimal treatment option remains elusive, future randomized controlled trials and biomechanical studies are needed to demonstrate the effectiveness of various interventions in reducing knee joint instability in patients with knee OA.

PATELLOFEMORAL JOINT LOADING AND OA

Although the knee complex is a tricompartmental joint consisting of the lateral and medial tibiofemoral and the patellofemoral joints, OA of the knee has primarily been viewed as a disorder of the tibiofemoral joint alone. Therefore, the importance of patellofemoral joint disease has received less attention.[26,79] Pathology of the patellofemoral joint is of clinical relevance, as up to one third of individuals older than 60 years present with radiographic evidence of patellofemoral OA.[30] Presence of patellofemoral symptoms is also associated with high levels of disability, functional limitation, and a significant loss of independence in older adults.[36,130] Based on the current evidence, a multicompartmental approach to treatment of knee OA is warranted, as the combined radiographic disease pattern of tibiofemoral and patellofemoral OA is found in up to 40% of older adults with knee pain.[37] In addition, knees with structural damage in both the tibiofemoral and patellofemoral compartments are more likely to be painful and are associated with greater loss of function compared with isolated compartmental disease.[48,188]

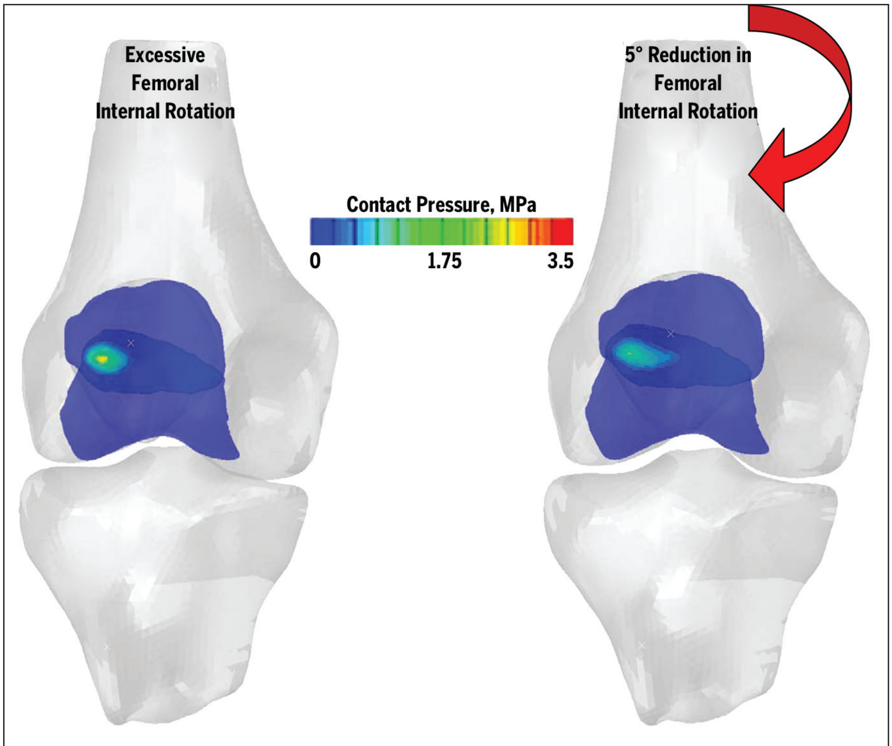

FIGURE 4. A 5° reduction in excessive femoral internal rotation can substantially reduce the stress environment of the patellofemoral joint through increasing the patellofemoral joint contact area and more efficiently distributing the contact forces.

Patella Malalignment and Tracking Issues

Although OA of the tibiofemoral joint is inherently associated with increases in frontal plane knee moments (ie, KAM), disorders of the patellofemoral joint have traditionally been linked to increased patellofemoral joint stress due to abnormal patella alignment and/or tracking.[68,74,96,136,148] The supposition that excessive patellofemoral joint stress plays a role in the genesis of patellofemoral joint disease is supported by animal studies that have provided histological evidence for surgically induced patella malalignment resulting in cartilage degeneration.[136,161] In addition, patella malalignment has been associated with manifestations of patellofemoral OA and higher rates of disease progression in large observational cohort studies.[91,105]

Taping and Bracing

Given the apparent relationship between patellofemoral malalignment, excessive joint loading, and OA, it stands to reason that interventions that aim to decrease loading through improving patella alignment (eg, taping or bracing) would be beneficial in the treatment of individuals with patellofemoral OA. Patellofemoral taping aimed to induce a medial glide of the patella has been suggested as an effective intervention option to realign the patella so as to reduce joint stress and to unload the painful soft tissues of the patellofemoral joint. Several randomized clinical trials in patients with knee OA, both with and without involvement of the patellofemoral joint, have shown reductions in pain with patella taping.[29,75,80] Although changes in patella alignment can occur immediately following taping,[28] whether the reported changes persist following prolonged use of the tape is unknown. Unlike taping, however, bracing may not be as effective for patients with patellofemoral OA, as a recent randomized clinical trial of a 6-week application of a specific realigning patellofemoral brace reported no clinical or statistical effects.[90] Lack of patient compliance combined with possible skin-related side effects associated with patella taping and bracing limits the long-term feasibility of such treatment options. Additionally, greater patellofemoral joint disease severity may limit the response to both taping and bracing. At best, taping and bracing appear to provide short-term symptomatic relief but show no evidence of a protective effect on disease progression.

Exercise Therapy

It has also been suggested that decreased quadriceps strength may play a role in pathogenesis of patellofemoral OA. In a rabbit model, a 4-week botulinum toxin type A–induced quadriceps weakness resulted in significant histologically verified cartilage degeneration, whereas the tibiofemoral joint remained unaffected.[157] A cross-sectional study of 2472 older adults over the age of 60 also demonstrated an association between decreased quadriceps strength and radiographic joint space narrowing of the lateral patellofemoral joint compartment.[8] Similarly, a prospective study of the natural history of knee OA concluded that greater quadriceps strength appears to have a protective effect against cartilage loss of the lateral compartment of the patellofemoral joint.[3] However, when these strong associations were tested in a prospective clinical trial, manipulating weakness of the quadriceps did not influence symptoms, suggesting that quadriceps weakness may be a consequence of patellofemoral OA rather than its cause. In a 10-week randomized clinical trial of supervised quadriceps exercises and functional training, along with patella taping, in 87 patients with patellofemoral OA, Quilty and colleagues[153] reported minimal long-term clinical benefits. Weakness of the vastus medialis portion of the quadriceps muscle has also been suggested as a potential mechanism for patellofemoral joint malalignment and excessive joint loading due to lateral tracking of the patella.[27,162,200] However, exercise programs designed to specifically address impairment of the vastus medialis have been shown to be comparable to generic exercise programs in improving joint biomechanics, pain, function, and quality of life.[13,187] Findings from these studies suggest that quadriceps strengthening with functional or vastus medialis training may not be sufficient for treatment of patellofemoral joint dysfunction and that additional exercises should be considered.

Improving Lower-Limb Dynamics

Evidence from studies of younger patients with patellofemoral pain also suggests that altered lower-limb dynamics, resulting from local factors as well as those both proximal and distal to the knee joint, may influence patellofemoral joint alignment and loading.[12,114,150,154] Proximal etiologic factors are related to hip, pelvis, and trunk mechanics, whereas distal factors are related to the mechanics of the foot and ankle.[31] To this end, magnetic resonance imaging studies of patellofemoral joint kinematics in patients with patellofemoral pain suggest that malalignment of the patellofemoral joint may be more related to excessive internal rotation of the femur underneath the patella than to the more commonly assumed excessive lateral displacement of the patella over the femur.[152,184] Using a previously published model of the patellofemoral joint[47] in a single case of an individual with patellofemoral symptoms (unpublished data), it was estimated that a 5° reduction in excessive internal rotation of the femur could decrease the peak patellofemoral joint articular cartilage compressive pressures and shear stresses by as much as 63% and 200%, respectively (**FIGURE 4**). Therefore, addressing factors that control excessive femoral internal rotation is recommended to improve the mechanical loading environment of the patellofemoral joint.[163] For instance, supplementation of hip abductor and lateral rotator muscle strengthening to quadriceps exercises resulted in additional pain reduction and improvement in function for patients with patellofemoral pain after 6 weeks of treatment.[144] Although strategies to address impairments of regions proximal and distal to the knee, such as hip muscle strengthening,[17,144] neuromuscular retraining,[38,128,146] and foot orthoses,[40,101,164] have been shown to result in significant reduction in symptoms in younger individuals with patellofemoral pain, further research is needed to substantiate the efficacy of such interventions in older adults with patellofemoral OA.

CLINICAL IMPLICATIONS

Though additional mechanistic studies and randomized controlled trials are needed before definitive treatment recommendations can be made, based on the current scientific evidence and clinical experience, it could be argued that the focus of physical therapy management of patients with knee OA should be individualized and based on both short- and long-term intervention plans. First, attention should be given to short-term intervention options to facilitate early management of symptoms and mitigation of barriers to performing everyday tasks and exercise. Short-term adaptive strategies may include providing equipment or modifying the demands of daily activities to limit excessive loading of the knee joint. However, caution must be exercised, as alleviation of knee pain alone without enhancing the biomechanical environment of the knee joint could result in additional increases in joint loading due to the loss of pain-induced adaptations.[72,95,167] Long-term treatment plans should then be implemented to restore or establish more permanent suitable joint biomechanics and improve functional capacity.

Short-Term Treatment Options

The overall goal of short-term interventions is an immediate reduction in the chronically high loads imparted to the injured knee joint, providing urgent symptomatic relief. As such, identifying easily measured clinical signs of high medial compartment loads may assist clinicians in deciding which load-modifying interventions would be most appropriate for their patients. Hunt and Bennell[86] recently reported that clinical measures of body mass, static tibial malalignment measured with calipers or an inclinometer,[82,86] and walking speed can explain up to 67% of variance in peak KAM in patients with medial compartment knee OA. Based on this finding, a combination of interventions aimed at reducing the effects of increased body mass and knee malalignment (if present) or reducing gait speed should be considered as viable short-term options for immediate lowering of the knee joint loads and symptoms in patients with knee OA. For example, instructions on proper use of a cane on the side contralateral to the arthritic knee joint can be used as an early offloading strategy, by shifting a portion of the body mass off the symptomatic knee tissues during weight-bearing activities such as walking.[107,125] Full-length laterally wedged insoles[45,76-78] or valgus knee bracing[46,120,170,197] may also be effective in modifying the tibiofemoral joint angle and the dynamic loading of the knee joint, thereby decreasing medial compartment compressive loads. Additionally, gait retraining strategies to reduce walking speed, especially in patients with less severe disease,[139] could be an effective offloading approach on a short-term basis. Similarly, an ipsilateral trunk lean gait strategy could provide significant offloading of the arthritic knee joint, given its reported potential as perhaps the most effective strategy to reduce KAM.[137] If present, an ipsilateral trunk lean during gait should be maintained; if absent, it should be encouraged through gait retraining as a short-term offloading strategy. However, the functional consequences of both a slower walking speed and an ipsilateral trunk lean make these strategies less appropriate as long-term options. Patella taping techniques are also recommended for patients with involvement of the patellofemoral joint, as they are relatively simple to apply and

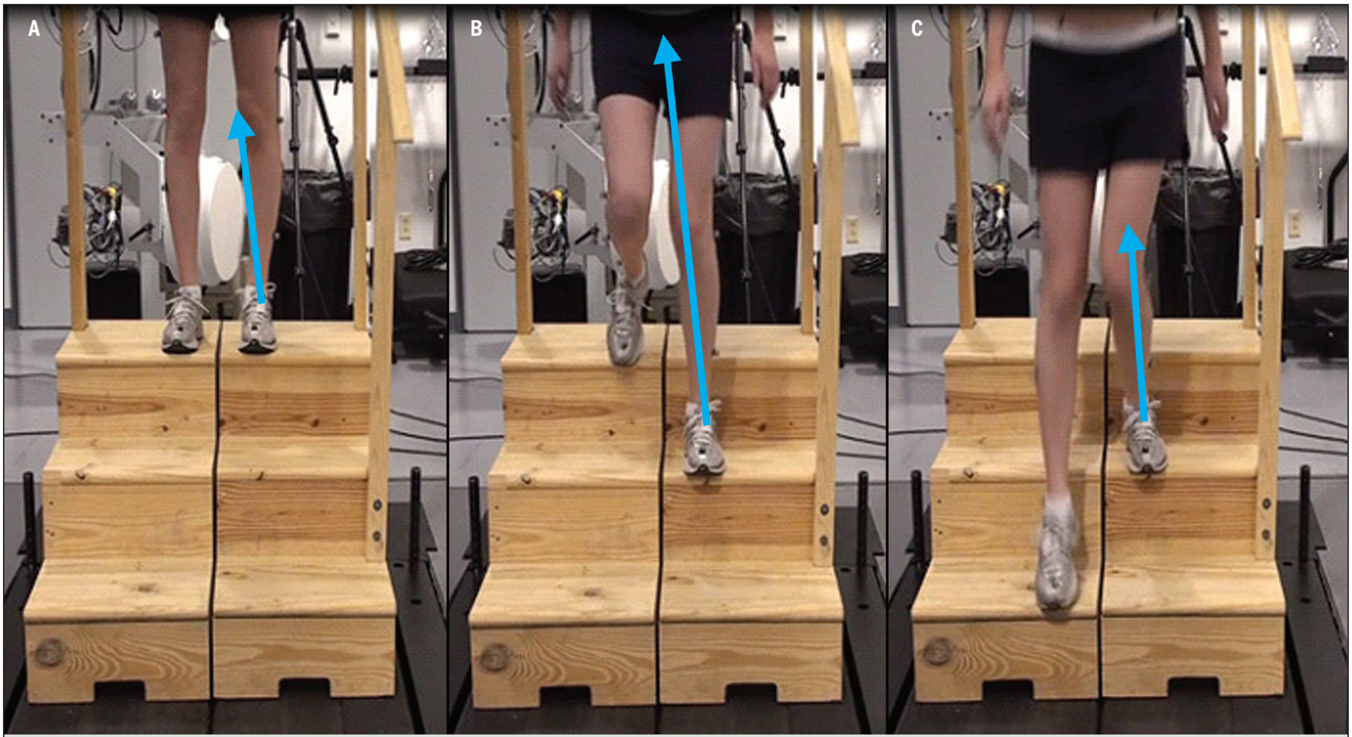

FIGURE 5. Example of an individual with left-sided, lower-limb varus malalignment demonstrating a medial knee thrust movement pattern while descending a set of stairs. During bilateral stance, the ground reaction force vector (blue line) passes medial to the left knee center of rotation (A), creating a knee adduction moment. During the loading phase of stair descent (B), medialization of the left knee moves the joint center of rotation closer to the ground reaction force vector and reduces the external lever arm, thus minimizing the knee adduction moment. The medialization of the left knee continues through the stance phase to the point where the ground reaction force passes lateral to the knee joint center (C), thus creating an abduction moment about the knee joint. An excessive knee abduction moment could potentially be undesirable, as it increases the loads imparted on the lateral tibiofemoral and patellofemoral compartments.

can be taught to patients for self-management purposes to reduce pain during exercise and functional activities.[29,75,80]

Long-Term Restorative Treatment Plans

Unlike temporary intervention options that could be implemented immediately, the goal of long-term treatment solutions, which take longer to implement and yield results, is to permanently enhance the knee joint–loading environment. Individualization of long-term treatment programs is a key factor to consider, as the same treatment intervention may have a dissimilar effect on different knee subsets based on presence or absence of individual local risk factors, such as tibiofemoral malalignment or lower extremity muscle weakness. Thus, it stands to reason that treatment of symptomatic knee OA should always be tailored to the clinical presentation and individual needs of each patient.

Muscle-enhancing interventions of the entire lower limb and the trunk, encompassing both strengthening exercises and neuromuscular control components, should be considered for long-term treatment of individuals with knee OA to improve pain and function, while offering potentially joint-protective muscle activity.[172] Implementing a medial-thrust gait-training program could also be used as an offloading strategy to lessen KAM in patients with medial compartment knee OA.[11,201] Medial-thrust gait training, by verbally instructing patients to bring their thighs inward and to walk with their knees closer together, while providing them with feedback on their knee alignment, has previously been shown to result in a natural-feeling and less effortful execution of medial-thrust gait pattern, which was maintained at a 1-month follow-up visit.[11] As a medial-thrust gait has been associated with a tendency for an undesired increase in the peak knee flexion moment,[67,201] efforts to train patients with medial knee OA to perform a medial-thrust gait pattern (if indicated) should emphasize a minimal increase in knee flexion angle during gait.[201]

Further modification of daily activities or occupational factors by teaching new methods of performing daily tasks or by changing requirements of the desired activities should also be considered as a long-term treatment option. Task-specific exercises could be utilized to better provide the patient with the opportunity to practice and learn problem-solving skills for potentially problematic functional activities.[190] Additionally, a task-specific approach provides the opportunity to train the patient in joint-protective strategies by improving the biomechanical environment of the joint. For example, a patient with medial knee OA and a standing varus malalignment

(**FIGURE 5A**) who reports difficulty and increased pain with going up and down stairs could be trained to adopt a medial-thrust knee movement pattern intended to decrease medial compartment loads when negotiating a set of stairs. A positive response to this treatment strategy would be an immediate decrease in pain while going up and down stairs. As the knee joint shares its proximal and distal segments (ie, femur and tibia) with the hip and ankle joints, femoral internal rotation and adduction at the hip joint, and/or pronation of the midfoot along with abduction of the tibia at the ankle joint, can bring the knee joint center closer to the line of action of the GRF and thus decrease the loads imparted on the medial knee compartment (**FIGURE 5B**).[11] It is important to note, however, that excessive amounts of lower-limb valgus movement past a neutral alignment (**FIGURE 5C**) can lead to greater loading of the lateral tibiofemoral and patellofemoral compartments.[20,151] Therefore, whereas encouraging sufficient medial knee movement toward a more neutral alignment may be beneficial in patients with isolated medial knee OA, excessive amounts of lower-limb valgus should be avoided to protect the lateral compartment structures and the patellofemoral joint from degenerative changes.[39,174]

SUMMARY

When summarizing the overall data on physical therapy strategies for treatment of knee OA, considerations for maintaining a safe loading environment for the knee joint are recommended to aid physical therapists in developing more efficient and effective rehabilitation programs for patients with knee OA. Current evidence also suggests that management of joint instability and patellofemoral joint disease should be considered, along with tibiofemoral joint involvement, when tailoring an appropriate plan of care and to optimize outcomes. When patient-specific biomechanical factors are closely considered, interventions can have a more powerful impact, as the same intervention may have a different effect on different knee subsets, based on the presence or absence of individual biomechanical factors or physical impairments. Because of the observed positive associations between offloading interventions and symptoms and measures of disease progression, there is currently a great deal of interest to better elucidate the clinical effects of such strategies. However, the long-term clinical benefits of many of these interventions are not yet determined.

REFERENCES

1. Abdallah AA, Radwan AY. Biomechanical changes accompanying unilateral and bilateral use of laterally wedged insoles with medial arch supports in patients with medial knee osteoarthritis. *Clin Biomech (Bristol, Avon)*. 2011;26:783-789. http://dx.doi.org/10.1016/j.clinbiomech.2011.03.013
2. Alnahdi AH, Zeni JA, Snyder-Mackler L. Muscle impairments in patients with knee osteoarthritis. *Sports Health*. 2012;4:284-292. http://dx.doi.org/10.1177/1941738112445726
3. Amin S, Baker K, Niu J, et al. Quadriceps strength and the risk of cartilage loss and symptom progression in knee osteoarthritis. *Arthritis Rheum*. 2009;60:189-198. http://dx.doi.org/10.1002/art.24182
4. 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;51:371-376. http://dx.doi.org/10.1002/art.20396
5. Andriacchi TP. Dynamics of knee malalignment. *Orthop Clin North Am*. 1994;25:395-403.
6. Andriacchi TP, Mündermann A, Smith RL, Alexander EJ, Dyrby CO, Koo S. A framework for the in vivo pathomechanics of osteoarthritis at the knee. *Ann Biomed Eng*. 2004;32:447-457.
7. Baker K, Goggins J, Xie H, et al. A randomized crossover trial of a wedged insole for treatment of knee osteoarthritis. *Arthritis Rheum*. 2007;56:1198-1203. http://dx.doi.org/10.1002/art.22516
8. Baker KR, Xu L, Zhang Y, et al. Quadriceps weakness and its relationship to tibiofemoral and patellofemoral knee osteoarthritis in Chinese: the Beijing osteoarthritis study. *Arthritis Rheum*. 2004;50:1815-1821. http://dx.doi.org/10.1002/art.20261
9. Baliunas AJ, Hurwitz DE, Ryals AB, et al. Increased knee joint loads during walking are present in subjects with knee osteoarthritis. *Osteoarthritis Cartilage*. 2002;10:573-579.
10. Barrios JA, Crenshaw JR, Royer TD, Davis IS. Walking shoes and laterally wedged orthoses in the clinical management of medial tibiofemoral osteoarthritis: a one-year prospective controlled trial. *Knee*. 2009;16:136-142. http://dx.doi.org/10.1016/j.knee.2008.10.002
11. 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;43:2208-2213. http://dx.doi.org/10.1016/j.jbiomech.2010.03.040
12. Barton CJ, Bonanno D, Levinger P, Menz HB. Foot and ankle characteristics in patellofemoral pain syndrome: a case control and reliability study. *J Orthop Sports Phys Ther*. 2010;40:286-296. http://dx.doi.org/10.2519/jospt.2010.3227
13. Bennell K, Duncan M, Cowan S, McConnell J, Hodges P, Crossley K. Effects of vastus medialis oblique retraining versus general quadriceps strengthening on vasti onset. *Med Sci Sports Exerc*. 2010;42:856-864. http://dx.doi.org/10.1249/MSS.0b013e3181c12771
14. Bennell KL, Bowles KA, Payne C, et al. Lateral wedge insoles for medial knee osteoarthritis: 12 month randomised controlled trial. *BMJ*. 2011;342:d2912. http://dx.doi.org/10.1136/bmj.d2912
15. Bennell KL, Egerton T, Wrigley TV, et al. Comparison of neuromuscular and quadriceps strengthening exercise in the treatment of varus malaligned knees with medial knee osteoarthritis: a randomised controlled trial protocol. *BMC Musculoskelet Disord*. 2011;12:276. http://dx.doi.org/10.1186/1471-2474-12-276
16. Bennell KL, Hunt MA, Wrigley TV, et al. Hip strengthening reduces symptoms but not knee load in people with medial knee osteoarthritis and varus malalignment: a randomised controlled trial. *Osteoarthritis Cartilage*. 2010;18:621-628. http://dx.doi.org/10.1016/j.joca.2010.01.010
17. Boling MC, Bolgla LA, Mattacola CG, Uhl TL, Hosey RG. Outcomes of a weight-bearing rehabilitation program for patients diagnosed with patellofemoral pain syndrome. *Arch Phys Med Rehabil*. 2006;87:1428-1435. http://dx.doi.org/10.1016/j.apmr.2006.07.26
18. Brandt KD, Heilman DK, Slemenda C, et al. Quadriceps strength in women with radiographically progressive osteoarthritis of the knee and those with stable radiographic changes. *J Rheumatol*. 1999;26:2431-2437.
19. Brouwer RW, van Raaij TM, Verhaar JA, Coene LN, Bierma-Zeinstra SM. Brace treatment for osteoarthritis of the knee: a prospective randomized multi-centre trial. *Osteoarthritis Cartilage*. 2006;14:777-783. http://dx.doi.org/10.1016/j.joca.2006.02.004
20. Bruns J, Volkmer M, Luessenhop S. Pressure distribution at the knee joint. Influence of varus and valgus deviation without and with

ligament dissection. *Arch Orthop Trauma Surg*. 1993;113:12-19.
21. Butler RJ, Marchesi S, Royer T, Davis IS. The effect of a subject-specific amount of lateral wedge on knee mechanics in patients with medial knee osteoarthritis. *J Orthop Res*. 2007;25:1121-1127. http://dx.doi.org/10.1002/jor.20423
22. Chan GN, Smith AW, Kirtley C, Tsang WW. Changes in knee moments with contralateral versus ipsilateral cane usage in females with knee osteoarthritis. *Clin Biomech (Bristol, Avon)*. 2005;20:396-404. http://dx.doi.org/10.1016/j.clinbiomech.2004.12.005
23. Chang A, Hayes K, Dunlop D, et al. Hip abduction moment and protection against medial tibiofemoral osteoarthritis progression. *Arthritis Rheum*. 2005;52:3515-3519. http://dx.doi.org/10.1002/art.21406
24. Chang A, Hurwitz D, Dunlop D, et al. The relationship between toe-out angle during gait and progression of medial tibiofemoral osteoarthritis. *Ann Rheum Dis*. 2007;66:1271-1275. http://dx.doi.org/10.1136/ard.2006.062927
25. Cheng YJ, Hootman JM, Murphy LB, Langmaid GA, Helmick CG. Prevalence of doctor-diagnosed arthritis and arthritis-attributable activity limitation—United States, 2007-2009. *MMWR Morb Mortal Wkly Rep*. 2010;59:1261-1265.
26. Clark AL. Osteoarthritis: what we have been missing in the patellofemoral joint. *Exerc Sport Sci Rev*. 2008;36:30-37. http://dx.doi.org/10.1097/jes.0b013e31815e4217
27. Cowan SM, Bennell KL, Hodges PW, Crossley KM, McConnell J. Delayed onset of electromyographic activity of vastus medialis obliquus relative to vastus lateralis in subjects with patellofemoral pain syndrome. *Arch Phys Med Rehabil*. 2001;82:183-189. http://dx.doi.org/10.1053/apmr.2001.19022
28. Crossley KM, Marino GP, Macilquham MD, Schache AG, Hinman RS. Can patellar tape reduce the patellar malalignment and pain associated with patellofemoral osteoarthritis? *Arthritis Rheum*. 2009;61:1719-1725. http://dx.doi.org/10.1002/art.24872
29. Cushnaghan J, McCarthy C, Dieppe P. Taping the patella medially: a new treatment for osteoarthritis of the knee joint? *BMJ*. 1994;308:753-755.
30. Davies AP, Vince AS, Shepstone L, Donell ST, Glasgow MM. The radiologic prevalence of patellofemoral osteoarthritis. *Clin Orthop Relat Res*. 2002:206-212.
31. Davis IS, Powers CM. Patellofemoral pain syndrome: proximal, distal, and local factors, an international retreat, April 30-May 2, 2009, Fells Point, Baltimore, MD. *J Orthop Sports Phys Ther*. 2010;40:A1-A16. http://dx.doi.org/10.2519/jospt.2010.0302
32. Deyle GD, Allison SC, Matekel RL, et al. Physical therapy treatment effectiveness for osteoarthritis of the knee: a randomized comparison of supervised clinical exercise and manual therapy procedures versus a home exercise program. *Phys Ther*. 2005;85:1301-1317.
33. Deyle GD, Henderson NE, Garber MB, Matekel RL, Ryder MG, Allison SC. Is manual physical therapy distinct from physical therapy clinical practice? *Phys Ther*. 2002;82:287-288; author reply 288-292.
34. Dillon CF, Rasch EK, Gu Q, Hirsch R. Prevalence of knee osteoarthritis in the United States: arthritis data from the Third National Health and Nutrition Examination Survey 1991-94. *J Rheumatol*. 2006;33:2271-2279.
35. Draganich L, Reider B, Rimington T, Piotrowski G, Mallik K, Nasson S. The effectiveness of self-adjustable custom and off-the-shelf bracing in the treatment of varus gonarthrosis. *J Bone Joint Surg Am*. 2006;88:2645-2652. http://dx.doi.org/10.2106/JBJS.D.02787
36. Duncan R, Peat G, Thomas E, Wood L, Hay E, Croft P. Does isolated patellofemoral osteoarthritis matter? *Osteoarthritis Cartilage*. 2009;17:1151-1155. http://dx.doi.org/10.1016/j.joca.2009.03.016
37. Duncan RC, Hay EM, Saklatvala J, Croft PR. Prevalence of radiographic osteoarthritis—it all depends on your point of view. *Rheumatology (Oxford)*. 2006;45:757-760. http://dx.doi.org/10.1093/rheumatology/kei270
38. Earl JE, Hoch AZ. A proximal strengthening program improves pain, function, and biomechanics in women with patellofemoral pain syndrome. *Am J Sports Med*. 2011;39:154-163. http://dx.doi.org/10.1177/0363546510379967
39. Elahi S, Cahue S, Felson DT, Engelman L, Sharma L. The association between varus-valgus alignment and patellofemoral osteoarthritis. *Arthritis Rheum*. 2000;43:1874-1880. http://dx.doi.org/10.1002/1529-0131(200008)43:8<1874::AID-ANR25>3.0.CO;2-2
40. Eng JJ, Pierrynowski MR. Evaluation of soft foot orthotics in the treatment of patellofemoral pain syndrome. *Phys Ther*. 1993;73:62-68; discussion 68-70.
41. Erhart JC, Dyrby CO, D'Lima DD, Colwell CW, Andriacchi TP. Changes in in vivo knee loading with a variable-stiffness intervention shoe correlate with changes in the knee adduction moment. *J Orthop Res*. 2010;28:1548-1553. http://dx.doi.org/10.1002/jor.21183
42. Erhart JC, Mündermann A, Elspas B, Giori NJ, Andriacchi TP. Changes in knee adduction moment, pain, and functionality with a variable-stiffness walking shoe after 6 months. *J Orthop Res*. 2010;28:873-879. http://dx.doi.org/10.1002/jor.21077
43. Erhart JC, Mündermann A, Elspas B, Giori NJ, Andriacchi TP. A variable-stiffness shoe lowers the knee adduction moment in subjects with symptoms of medial compartment knee osteoarthritis. *J Biomech*. 2008;41:2720-2725. http://dx.doi.org/10.1016/j.jbiomech.2008.06.016
44. Erhart-Hledik JC, Elspas B, Giori NJ, Andriacchi TP. Effect of variable-stiffness walking shoes on knee adduction moment, pain, and function in subjects with medial compartment knee osteoarthritis after 1 year. *J Orthop Res*. 2012;30:514-521. http://dx.doi.org/10.1002/jor.21563
45. Fantini Pagani CH, Hinrichs M, Brüggemann GP. Kinetic and kinematic changes with the use of valgus knee brace and lateral wedge insoles in patients with medial knee osteoarthritis. *J Orthop Res*. 2012;30:1125-1132. http://dx.doi.org/10.1002/jor.22032
46. Fantini Pagani CH, Potthast W, Brüggemann GP. The effect of valgus bracing on the knee adduction moment during gait and running in male subjects with varus alignment. *Clin Biomech (Bristol, Avon)*. 2010;25:70-76. http://dx.doi.org/10.1016/j.clinbiomech.2009.08.010
47. Farrokhi S, Keyak JH, Powers CM. Individuals with patellofemoral pain exhibit greater patellofemoral joint stress: a finite element analysis study. *Osteoarthritis Cartilage*. 2011;19:287-294. http://dx.doi.org/10.1016/j.joca.2010.12.001
48. Farrokhi S, Piva SR, Gil AB, Oddis CV, Brooks MM, Fitzgerald GK. Association of severity of coexisting patellofemoral disease with increased impairments and functional limitations in patients with knee osteoarthritis. *Arthritis Care Res (Hoboken)*. 2013;65:544-551. http://dx.doi.org/10.1002/acr.21866
49. Felson DT. Osteoarthritis as a disease of mechanics. *Osteoarthritis Cartilage*. 2013;21:10-15. http://dx.doi.org/10.1016/j.joca.2012.09.012
50. Felson DT, Lawrence RC, Dieppe PA, et al. Osteoarthritis: new insights. Part 1: the disease and its risk factors. *Ann Intern Med*. 2000;133:635-646.
51. Felson DT, Naimark A, Anderson J, Kazis L, Castelli W, Meenan RF. The prevalence of knee osteoarthritis in the elderly. The Framingham Osteoarthritis Study. *Arthritis Rheum*. 1987;30:914-918.
52. Felson DT, Niu J, McClennan C, et al. Knee buckling: prevalence, risk factors, and associated limitations in function. *Ann Intern Med*. 2007;147:534-540.
53. Felson DT, Zhang Y, Hannan MT, et al. The incidence and natural history of knee osteoarthritis in the elderly. The Framingham Osteoarthritis Study. *Arthritis Rheum*. 1995;38:1500-1505.
54. Fisher NM, Gresham GE, Abrams M, Hicks J, Horrigan D, Pendergast DR. Quantitative effects of physical therapy on muscular and functional performance in subjects with osteoarthritis of the knees. *Arch Phys Med Rehabil*. 1993;74:840-847.
55. Fisher NM, Pendergast DR. Reduced muscle function in patients with osteoarthritis. *Scand J Rehabil Med*. 1997;29:213-221.
56. Fitzgerald GK, Childs JD, Ridge TM, Irrgang JJ.

Agility and perturbation training for a physically active individual with knee osteoarthritis. *Phys Ther*. 2002;82:372-382.
57. Fitzgerald GK, Piva SR, Gil AB, Wisniewski SR, Oddis CV, Irrgang JJ. Agility and perturbation training techniques in exercise therapy for reducing pain and improving function in people with knee osteoarthritis: a randomized clinical trial. *Phys Ther*. 2011;91:452-469. http://dx.doi.org/10.2522/ptj.20100188
58. Fitzgerald GK, Piva SR, Irrgang JJ. Reports of joint instability in knee osteoarthritis: its prevalence and relationship to physical function. *Arthritis Rheum*. 2004;51:941-946. http://dx.doi.org/10.1002/art.20825
59. Fitzgerald GK, White DK, Piva SR. Associations for change in physical and psychological factors and treatment response following exercise in knee osteoarthritis: an exploratory study. *Arthritis Care Res (Hoboken)*. 2012;64:1673-1680. http://dx.doi.org/10.1002/acr.21751
60. Foroughi N, Smith RM, Lange AK, Baker MK, Fiatarone Singh MA, Vanwanseele B. Dynamic alignment and its association with knee adduction moment in medial knee osteoarthritis. *Knee*. 2010;17:210-216. http://dx.doi.org/10.1016/j.knee.2009.09.006
61. Foroughi N, Smith RM, Lange AK, Baker MK, Fiatarone Singh MA, Vanwanseele B. Lower limb muscle strengthening does not change frontal plane moments in women with knee osteoarthritis: a randomized controlled trial. *Clin Biomech (Bristol, Avon)*. 2011;26:167-174. http://dx.doi.org/10.1016/j.clinbiomech.2010.08.011
62. Foroughi N, Smith RM, Lange AK, Singh MA, Vanwanseele B. Progressive resistance training and dynamic alignment in osteoarthritis: a single-blind randomised controlled trial. *Clin Biomech (Bristol, Avon)*. 2011;26:71-77. http://dx.doi.org/10.1016/j.clinbiomech.2010.08.013
63. Fransen M, Crosbie J, Edmonds J. Physical therapy is effective for patients with osteoarthritis of the knee: a randomized controlled clinical trial. *J Rheumatol*. 2001;28:156-164.
64. Fransen M, McConnell S. Land-based exercise for osteoarthritis of the knee: a metaanalysis of randomized controlled trials. *J Rheumatol*. 2009;36:1109-1117. http://dx.doi.org/10.3899/jrheum.090058
65. Franz JR, Dicharry J, Riley PO, Jackson K, Wilder RP, Kerrigan DC. The influence of arch supports on knee torques relevant to knee osteoarthritis. *Med Sci Sports Exerc*. 2008;40:913-917. http://dx.doi.org/10.1249/MSS.0b013e3181659c81
66. Fregly BJ, Reinbolt JA, Chmielewski TL. Evaluation of a patient-specific cost function to predict the influence of foot path on the knee adduction torque during gait. *Comput Methods Biomech Biomed Engin*. 2008;11:63-71. http://dx.doi.org/10.1080/10255840701552036
67. Fregly BJ, Reinbolt JA, Rooney KL, Mitchell KH, Chmielewski TL. Design of patient-specific gait modifications for knee osteoarthritis rehabilitation. *IEEE Trans Biomed Eng*. 2007;54:1687-1695. http://dx.doi.org/10.1109/TBME.2007.907637
68. Fulkerson JP. *Disorders of the Patellofemoral Joint*. 4th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2004.
69. Gaasbeek RD, Groen BE, Hampsink B, van Heerwaarden RJ, Duysens J. Valgus bracing in patients with medial compartment osteoarthritis of the knee. A gait analysis study of a new brace. *Gait Posture*. 2007;26:3-10. http://dx.doi.org/10.1016/j.gaitpost.2006.07.007
70. Guo M, Axe MJ, Manal K. The influence of foot progression angle on the knee adduction moment during walking and stair climbing in pain free individuals with knee osteoarthritis. *Gait Posture*. 2007;26:436-441. http://dx.doi.org/10.1016/j.gaitpost.2006.10.008
71. Heiden TL, Lloyd DG, Ackland TR. Knee joint kinematics, kinetics and muscle co-contraction in knee osteoarthritis patient gait. *Clin Biomech (Bristol, Avon)*. 2009;24:833-841. http://dx.doi.org/10.1016/j.clinbiomech.2009.08.005
72. Henriksen M, Graven-Nielsen T, Aaboe J, Andriacchi TP, Bliddal H. Gait changes in patients with knee osteoarthritis are replicated by experimental knee pain. *Arthritis Care Res (Hoboken)*. 2010;62:501-509. http://dx.doi.org/10.1002/acr.20033
73. Hewett TE, Noyes FR, Barber-Westin SD, Heckmann TP. Decrease in knee joint pain and increase in function in patients with medial compartment arthrosis: a prospective analysis of valgus bracing. *Orthopedics*. 1998;21:131-138.
74. Heywood AWB. Recurrent dislocation of the patella: a study of its pathology and treatment in 106 knees. *J Bone Joint Surg Br*. 1961;43-B:508-517.
75. Hinman RS, Bennell KL, Crossley KM, McConnell J. Immediate effects of adhesive tape on pain and disability in individuals with knee osteoarthritis. *Rheumatology (Oxford)*. 2003;42:865-869. http://dx.doi.org/10.1093/rheumatology/keg233
76. Hinman RS, Bowles KA, Bennell KL. Laterally wedged insoles in knee osteoarthritis: do biomechanical effects decline after one month of wear? *BMC Musculoskelet Disord*. 2009;10:146. http://dx.doi.org/10.1186/1471-2474-10-146
77. Hinman RS, Bowles KA, Metcalf BB, Wrigley TV, Bennell KL. Lateral wedge insoles for medial knee osteoarthritis: effects on lower limb frontal plane biomechanics. *Clin Biomech (Bristol, Avon)*. 2012;27:27-33. http://dx.doi.org/10.1016/j.clinbiomech.2011.07.010
78. Hinman RS, Bowles KA, Payne C, Bennell KL. Effect of length on laterally-wedged insoles in knee osteoarthritis. *Arthritis Rheum*. 2008;59:144-147. http://dx.doi.org/10.1002/art.23249
79. Hinman RS, Crossley KM. Patellofemoral joint osteoarthritis: an important subgroup of knee osteoarthritis. *Rheumatology (Oxford)*. 2007;46:1057-1062. http://dx.doi.org/10.1093/rheumatology/kem114
80. Hinman RS, Crossley KM, McConnell J, Bennell KL. Efficacy of knee tape in the management of osteoarthritis of the knee: blinded randomised controlled trial. *BMJ*. 2003;327:135. http://dx.doi.org/10.1136/bmj.327.7407.135
81. Hinman RS, Hunt MA, Creaby MW, Wrigley TV, McManus FJ, Bennell KL. Hip muscle weakness in individuals with medial knee osteoarthritis. *Arthritis Care Res (Hoboken)*. 2010;62:1190-1193. http://dx.doi.org/10.1002/acr.20199
82. Hinman RS, May RL, Crossley KM. Is there an alternative to the full-leg radiograph for determining knee joint alignment in osteoarthritis? *Arthritis Rheum*. 2006;55:306-313. http://dx.doi.org/10.1002/art.21836
83. Hinman RS, Payne C, Metcalf BR, Wrigley TV, Bennell KL. Lateral wedges in knee osteoarthritis: what are their immediate clinical and biomechanical effects and can these predict a three-month clinical outcome? *Arthritis Rheum*. 2008;59:408-415. http://dx.doi.org/10.1002/art.23326
84. Hochberg MC, Altman RD, April KT, et al. American College of Rheumatology 2012 recommendations for the use of nonpharmacologic and pharmacologic therapies in osteoarthritis of the hand, hip, and knee. *Arthritis Care Res (Hoboken)*. 2012;64:465-474. http://dx.doi.org/10.1002/acr.21596
85. Hodge WA, Fijan RS, Carlson KL, Burgess RG, Harris WH, Mann RW. Contact pressures in the human hip joint measured in vivo. *Proc Natl Acad Sci U S A*. 1986;83:2879-2883.
86. Hunt MA, Bennell KL. Predicting dynamic knee joint load with clinical measures in people with medial knee osteoarthritis. *Knee*. 2011;18:231-234. http://dx.doi.org/10.1016/j.knee.2010.05.014
87. Hunt MA, Birmingham TB, Giffin JR, Jenkyn TR. Associations among knee adduction moment, frontal plane ground reaction force, and lever arm during walking in patients with knee osteoarthritis. *J Biomech*. 2006;39:2213-2220. http://dx.doi.org/10.1016/j.jbiomech.2005.07.002
88. Hunt MA, Simic M, Hinman RS, Bennell KL, Wrigley TV. Feasibility of a gait retraining strategy for reducing knee joint loading: increased trunk lean guided by real-time biofeedback. *J Biomech*. 2011;44:943-947. http://dx.doi.org/10.1016/j.jbiomech.2010.11.027
89. Hunt MA, Wrigley TV, Hinman RS, Bennell KL. Individuals with severe knee osteoarthritis (OA) exhibit altered proximal walking mechanics compared with individuals with less severe OA and those without knee pain. *Arthritis Care Res (Hoboken)*. 2010;62:1426-1432. http://dx.doi.org/10.1002/acr.20248
90. Hunter DJ, Harvey W, Gross KD, et al. A randomized trial of patellofemoral bracing for

treatment of patellofemoral osteoarthritis. *Osteoarthritis Cartilage*. 2011;19:792-800. http://dx.doi.org/10.1016/j.joca.2010.12.010
91. Hunter DJ, Zhang YQ, Niu JB, et al. Patella malalignment, pain and patellofemoral progression: the Health ABC Study. *Osteoarthritis Cartilage*. 2007;15:1120-1127. http://dx.doi.org/10.1016/j.joca.2007.03.020
92. Hurd WJ, Chmielewski TL, Snyder-Mackler L. Perturbation-enhanced neuromuscular training alters muscle activity in female athletes. *Knee Surg Sports Traumatol Arthrosc*. 2006;14:60-69. http://dx.doi.org/10.1007/s00167-005-0624-y
93. Hurley MV. The role of muscle weakness in the pathogenesis of osteoarthritis. *Rheum Dis Clin North Am*. 1999;25:283-298.
94. Hurwitz DE, Ryals AB, Case JP, Block JA, Andriacchi TP. The knee adduction moment during gait in subjects with knee osteoarthritis is more closely correlated with static alignment than radiographic disease severity, toe out angle and pain. *J Orthop Res*. 2002;20:101-107. http://dx.doi.org/10.1016/S0736-0266(01)00081-X
95. Hurwitz DE, Ryals AR, Block JA, Sharma L, Schnitzer TJ, Andriacchi TP. Knee pain and joint loading in subjects with osteoarthritis of the knee. *J Orthop Res*. 2000;18:572-579. http://dx.doi.org/10.1002/jor.1100180409
96. Insall J, Falvo KA, Wise DW. Chondromalacia patellae. A prospective study. *J Bone Joint Surg Am*. 1976;58:1-8.
97. Jefferson RJ, Collins JJ, Whittle MW, Radin EL, O'Connor JJ. The role of the quadriceps in controlling impulsive forces around heel strike. *Proc Inst Mech Eng H*. 1990;204:21-28.
98. Jenkinson CM, Doherty M, Avery AJ, et al. Effects of dietary intervention and quadriceps strengthening exercises on pain and function in overweight people with knee pain: randomised controlled trial. *BMJ*. 2009;339:b3170.
99. Jenkyn TR, Erhart JC, Andriacchi TP. An analysis of the mechanisms for reducing the knee adduction moment during walking using a variable stiffness shoe in subjects with knee osteoarthritis. *J Biomech*. 2011;44:1271-1276. http://dx.doi.org/10.1016/j.jbiomech.2011.02.013
100. Jenkyn TR, Hunt MA, Jones IC, Giffin JR, Birmingham TB. Toe-out gait in patients with knee osteoarthritis partially transforms external knee adduction moment into flexion moment during early stance phase of gait: a tri-planar kinetic mechanism. *J Biomech*. 2008;41:276-283. http://dx.doi.org/10.1016/j.jbiomech.2007.09.015
101. Johnston LB, Gross MT. Effects of foot orthoses on quality of life for individuals with patellofemoral pain syndrome. *J Orthop Sports Phys Ther*. 2004;34:440-448. http://dx.doi.org/10.2519/jospt.2004.1384
102. Jones A, Silva PG, Silva AC, et al. Evaluation of immediate impact of cane use on energy expenditure during gait in patients with knee osteoarthritis. *Gait Posture*. 2012;35:435-439. http://dx.doi.org/10.1016/j.gaitpost.2011.11.003
103. Jones A, Silva PG, Silva AC, et al. Impact of cane use on pain, function, general health and energy expenditure during gait in patients with knee osteoarthritis: a randomised controlled trial. *Ann Rheum Dis*. 2012;71:172-179. http://dx.doi.org/10.1136/ard.2010.140178
104. Jones RK, Nester CJ, Richards JD, et al. A comparison of the biomechanical effects of valgus knee braces and lateral wedged insoles in patients with knee osteoarthritis. *Gait Posture*. 2013;37:368-372. http://dx.doi.org/10.1016/j.gaitpost.2012.08.002
105. Kalichman L, Zhang Y, Niu J, et al. The association between patellar alignment and patellofemoral joint osteoarthritis features—an MRI study. *Rheumatology (Oxford)*. 2007;46:1303-1308. http://dx.doi.org/10.1093/rheumatology/kem095
106. Keating EM, Faris PM, Ritter MA, Kane J. Use of lateral heel and sole wedges in the treatment of medial osteoarthritis of the knee. *Orthop Rev*. 1993;22:921-924.
107. Kemp G, Crossley KM, Wrigley TV, Metcalf BR, Hinman RS. Reducing joint loading in medial knee osteoarthritis: shoes and canes. *Arthritis Rheum*. 2008;59:609-614. http://dx.doi.org/10.1002/art.23578
108. Kerrigan DC, Lelas JL, Goggins J, Merriman GJ, Kaplan RJ, Felson DT. Effectiveness of a lateral-wedge insole on knee varus torque in patients with knee osteoarthritis. *Arch Phys Med Rehabil*. 2002;83:889-893.
109. Kirkley A, Webster-Bogaert S, Litchfield R, et al. The effect of bracing on varus gonarthrosis. *J Bone Joint Surg Am*. 1999;81:539-548.
110. Kito N, Shinkoda K, Yamasaki T, et al. Contribution of knee adduction moment impulse to pain and disability in Japanese women with medial knee osteoarthritis. *Clin Biomech (Bristol, Avon)*. 2010;25:914-919. http://dx.doi.org/10.1016/j.clinbiomech.2010.06.008
111. Knoop J, van der Leeden M, van der Esch M, et al. Association of lower muscle strength with self-reported knee instability in osteoarthritis of the knee: results from the Amsterdam Osteoarthritis cohort. *Arthritis Care Res (Hoboken)*. 2012;64:38-45. http://dx.doi.org/10.1002/acr.20597
112. Komistek RD, Dennis DA, Northcut EJ, Wood A, Parker AW, Traina SM. An in vivo analysis of the effectiveness of the osteoarthritic knee brace during heel-strike of gait. *J Arthroplasty*. 1999;14:738-742.
113. Ledingham J, Regan M, Jones A, Doherty M. Radiographic patterns and associations of osteoarthritis of the knee in patients referred to hospital. *Ann Rheum Dis*. 1993;52:520-526.
114. Lee TQ, Morris G, Csintalan RP. The influence of tibial and femoral rotation on patellofemoral contact area and pressure. *J Orthop Sports Phys Ther*. 2003;33:686-693.
115. Leitch KM, Birmingham TB, Jones IC, Giffin JR, Jenkyn TR. In-shoe plantar pressure measurements for patients with knee osteoarthritis: reliability and effects of lateral heel wedges. *Gait Posture*. 2011;34:391-396. http://dx.doi.org/10.1016/j.gaitpost.2011.06.008
116. Lewek MD, Ramsey DK, Snyder-Mackler L, Rudolph KS. Knee stabilization in patients with medial compartment knee osteoarthritis. *Arthritis Rheum*. 2005;52:2845-2853. http://dx.doi.org/10.1002/art.21237
117. Lewek MD, Rudolph KS, Snyder-Mackler L. Control of frontal plane knee laxity during gait in patients with medial compartment knee osteoarthritis. *Osteoarthritis Cartilage*. 2004;12:745-751. http://dx.doi.org/10.1016/j.joca.2004.05.005
118. Lim BW, Hinman RS, Wrigley TV, Sharma L, Bennell KL. Does knee malalignment mediate the effects of quadriceps strengthening on knee adduction moment, pain, and function in medial knee osteoarthritis? A randomized controlled trial. *Arthritis Rheum*. 2008;59:943-951. http://dx.doi.org/10.1002/art.23823
119. Lim BW, Kemp G, Metcalf B, et al. The association of quadriceps strength with the knee adduction moment in medial knee osteoarthritis. *Arthritis Rheum*. 2009;61:451-458. http://dx.doi.org/10.1002/art.24278
120. Lindenfeld TN, Hewett TE, Andriacchi TP. Joint loading with valgus bracing in patients with varus gonarthrosis. *Clin Orthop Relat Res*. 1997:290-297.
121. Lloyd DG, Buchanan TS. Strategies of muscular support of varus and valgus isometric loads at the human knee. *J Biomech*. 2001;34:1257-1267.
122. Loeser RF. Molecular mechanisms of cartilage destruction: mechanics, inflammatory mediators, and aging collide. *Arthritis Rheum*. 2006;54:1357-1360. http://dx.doi.org/10.1002/art.21813
123. Lynn SK, Costigan PA. Effect of foot rotation on knee kinetics and hamstring activation in older adults with and without signs of knee osteoarthritis. *Clin Biomech (Bristol, Avon)*. 2008;23:779-786. http://dx.doi.org/10.1016/j.clinbiomech.2008.01.012
124. Lynn SK, Kajaks T, Costigan PA. The effect of internal and external foot rotation on the adduction moment and lateral-medial shear force at the knee during gait. *J Sci Med Sport*. 2008;11:444-451. http://dx.doi.org/10.1016/j.jsams.2007.03.004
125. Lyu SR, Ogata K, Hoshiko I. Effects of a cane on floor reaction force and center of force during gait. *Clin Orthop Relat Res*. 2000:313-319.
126. Maly MR, Culham EG, Costigan PA. Static and dynamic biomechanics of foot orthoses in people with medial compartment knee osteoarthritis. *Clin Biomech (Bristol, Avon)*. 2002;17:603-610.

127. Mancuso CA, Ranawat CS, Esdaile JM, Johanson NA, Charlson ME. Indications for total hip and total knee arthroplasties. Results of orthopaedic surveys. *J Arthroplasty*. 1996;11:34-46.

128. Mascal CL, Landel R, Powers C. Management of patellofemoral pain targeting hip, pelvis, and trunk muscle function: 2 case reports. *J Orthop Sports Phys Ther*. 2003;33:647-660.

129. Matsuno H, Kadowaki KM, Tsuji H. Generation II knee bracing for severe medial compartment osteoarthritis of the knee. *Arch Phys Med Rehabil*. 1997;78:745-749.

130. McAlindon TE, Snow S, Cooper C, Dieppe PA. Radiographic patterns of osteoarthritis of the knee joint in the community: the importance of the patellofemoral joint. *Ann Rheum Dis*. 1992;51:844-849.

131. McQuade KJ, de Oliveira AS. Effects of progressive resistance strength training on knee biomechanics during single leg step-up in persons with mild knee osteoarthritis. *Clin Biomech (Bristol, Avon)*. 2011;26:741-748. http://dx.doi.org/10.1016/j.clinbiomech.2011.03.006

132. Mikesky AE, Mazzuca SA, Brandt KD, Perkins SM, Damush T, Lane KA. Effects of strength training on the incidence and progression of knee osteoarthritis. *Arthritis Rheum*. 2006;55:690-699. http://dx.doi.org/10.1002/art.22245

133. Mikesky AE, Meyer A, Thompson KL. Relationship between quadriceps strength and rate of loading during gait in women. *J Orthop Res*. 2000;18:171-175. http://dx.doi.org/10.1002/jor.1100180202

134. Miyazaki T, Wada M, Kawahara H, Sato M, Baba H, Shimada S. Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. *Ann Rheum Dis*. 2002;61:617-622.

135. Moe RH, Fernandes L, Østerås N. Daily use of a cane for two months reduced pain and improved function in patients with knee osteoarthritis. *J Physiother*. 2012;58:128. http://dx.doi.org/10.1016/S1836-9553(12)70094-2

136. Møller BN, Møller-Larsen F, Frich LH. Chondromalacia induced by patellar subluxation in the rabbit. *Acta Orthop Scand*. 1989;60:188-191.

137. Mündermann A, Asay JL, Mündermann L, Andriacchi TP. Implications of increased mediolateral trunk sway for ambulatory mechanics. *J Biomech*. 2008;41:165-170. http://dx.doi.org/10.1016/j.jbiomech.2007.07.001

138. Mündermann A, Dyrby CO, Andriacchi TP. Secondary gait changes in patients with medial compartment knee osteoarthritis: increased load at the ankle, knee, and hip during walking. *Arthritis Rheum*. 2005;52:2835-2844. http://dx.doi.org/10.1002/art.21262

139. Mündermann 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;50:1172-1178. http://dx.doi.org/10.1002/art.20132

140. Mündermann A, Mündermann L, Andriacchi TP. Amplitude and phasing of trunk motion is critical for the efficacy of gait training aimed at reducing ambulatory loads at the knee. *J Biomech Eng*. 2012;134:011010. http://dx.doi.org/10.1115/1.4005540

141. Muraki S, Oka H, Akune T, et al. Prevalence of radiographic knee osteoarthritis and its association with knee pain in the elderly of Japanese population-based cohorts: the ROAD study. *Osteoarthritis Cartilage*. 2009;17:1137-1143. http://dx.doi.org/10.1016/j.joca.2009.04.005

142. Murphy L, Schwartz TA, Helmick CG, et al. Lifetime risk of symptomatic knee osteoarthritis. *Arthritis Rheum*. 2008;59:1207-1213. http://dx.doi.org/10.1002/art.24021

143. Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res*. 2005;19:51-60. http://dx.doi.org/10.1519/13643.1

144. Nakagawa TH, Muniz TB, de Marche Baldon R, Maciel CD, de Menezes Reiff RB, Serrão FV. The effect of additional strengthening of hip abductor and lateral rotator muscles in patellofemoral pain syndrome: a randomized controlled pilot study. *Clin Rehabil*. 2008;22:1051-1060. http://dx.doi.org/10.1177/0269215508095357

145. National Collaborating Centre for Chronic Conditions. *Osteoarthritis: National Clinical Guideline for Care and Management in Adults*. London, UK: National Institute for Health and Care Excellence; 2008.

146. 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;45:691-696. http://dx.doi.org/10.1136/bjsm.2009.069112

147. O'Reilly SC, Muir KR, Doherty M. Effectiveness of home exercise on pain and disability from osteoarthritis of the knee: a randomised controlled trial. *Ann Rheum Dis*. 1999;58:15-19.

148. Outerbridge RE. The etiology of chondromalacia patellae. *J Bone Joint Surg Br*. 1961;43-B:752-757.

149. Pollo FE, Otis JC, Backus SI, Warren RF, Wickiewicz TL. Reduction of medial compartment loads with valgus bracing of the osteoarthritic knee. *Am J Sports Med*. 2002;30:414-421.

150. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther*. 2010;40:42-51. http://dx.doi.org/10.2519/jospt.2010.3337

151. Powers CM. The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *J Orthop Sports Phys Ther*. 2003;33:639-646.

152. Powers CM, Ward SR, Fredericson M, Guillet M, Shellock FG. Patellofemoral kinematics during weight-bearing and non-weight-bearing knee extension in persons with lateral subluxation of the patella: a preliminary study. *J Orthop Sports Phys Ther*. 2003;33:677-685.

153. Quilty B, Tucker M, Campbell R, Dieppe P. Physiotherapy, including quadriceps exercises and patellar taping, for knee osteoarthritis with predominant patello-femoral joint involvement: randomized controlled trial. *J Rheumatol*. 2003;30:1311-1317.

154. Rabin A, Kozol Z. Measures of range of motion and strength among healthy women with differing quality of lower extremity movement during the lateral step-down test. *J Orthop Sports Phys Ther*. 2010;40:792-800. http://dx.doi.org/10.2519/jospt.2010.3424

155. Radin EL, Yang KH, Riegger C, Kish VL, O'Connor JJ. Relationship between lower limb dynamics and knee joint pain. *J Orthop Res*. 1991;9:398-405. http://dx.doi.org/10.1002/jor.1100090312

156. Ramsey DK, Briem K, Axe MJ, Snyder-Mackler L. A mechanical theory for the effectiveness of bracing for medial compartment osteoarthritis of the knee. *J Bone Joint Surg Am*. 2007;89:2398-2407. http://dx.doi.org/10.2106/JBJS.F.01136

157. Rehan Youssef A, Longino D, Seerattan R, Leonard T, Herzog W. Muscle weakness causes joint degeneration in rabbits. *Osteoarthritis Cartilage*. 2009;17:1228-1235. http://dx.doi.org/10.1016/j.joca.2009.03.017

158. Reilly KA, Barker KL, Shamley D. A systematic review of lateral wedge orthotics—how useful are they in the management of medial compartment osteoarthritis? *Knee*. 2006;13:177-183. http://dx.doi.org/10.1016/j.knee.2006.02.003

159. Roos EM, Herzog W, Block JA, Bennell KL. Muscle weakness, afferent sensory dysfunction and exercise in knee osteoarthritis. *Nat Rev Rheumatol*. 2011;7:57-63. http://dx.doi.org/10.1038/nrrheum.2010.195

160. Rubin R, Menz HB. Use of laterally wedged custom foot orthoses to reduce pain associated with medial knee osteoarthritis: a preliminary investigation. *J Am Podiatr Med Assoc*. 2005;95:347-352.

161. Ryu J, Saito S, Yamamoto K. Changes in articular cartilage in experimentally induced patellar subluxation. *Ann Rheum Dis*. 1997;56:677-681.

162. Sakai N, Luo ZP, Rand JA, An KN. The influence of weakness in the vastus medialis oblique muscle on the patellofemoral joint: an in vitro biomechanical study. *Clin Biomech (Bristol, Avon)*. 2000;15:335-339.

163. Salsich GB, Perman WH. Patellofemoral joint contact area is influenced by tibiofemoral rotation alignment in individuals who have patellofemoral pain. *J Orthop Sports Phys Ther*. 2007;37:521-528. http://dx.doi.org/10.2519/jospt.2007.2589

164. Saxena A, Haddad J. The effect of foot orthoses on patellofemoral pain syndrome. *J Am Podiatr Med Assoc*. 2003;93:264-271.

165. Schache AG, Fregly BJ, Crossley KM, Hinman RS, Pandy MG. The effect of gait modification on the external knee adduction moment is reference frame dependent. *Clin Biomech (Bristol, Avon)*. 2008;23:601-608. http://dx.doi.org/10.1016/j.clinbiomech.2007.12.008

166. Schmitt LC, Rudolph KS. Muscle stabilization strategies in people with medial knee osteoarthritis: the effect of instability. *J Orthop Res*. 2008;26:1180-1185. http://dx.doi.org/10.1002/jor.20619

167. Schnitzer TJ, Popovich JM, Andersson GB, Andriacchi TP. Effect of piroxicam on gait in patients with osteoarthritis of the knee. *Arthritis Rheum*. 1993;36:1207-1213.

168. Segal NA, Foster NA, Dhamani S, Ohashi K, Yack HJ. Effects of concurrent use of an ankle support with a laterally wedged insole for medial knee osteoarthritis. *PM R*. 2009;1:214-222. http://dx.doi.org/10.1016/j.pmrj.2008.09.005

169. Segal NA, Torner JC, Felson D, et al. Effect of thigh strength on incident radiographic and symptomatic knee osteoarthritis in a longitudinal cohort. *Arthritis Rheum*. 2009;61:1210-1217. http://dx.doi.org/10.1002/art.24541

170. Self BP, Greenwald RM, Pflaster DS. A biomechanical analysis of a medial unloading brace for osteoarthritis in the knee. *Arthritis Care Res*. 2000;13:191-197.

171. Shakoor N, Block JA. Walking barefoot decreases loading on the lower extremity joints in knee osteoarthritis. *Arthritis Rheum*. 2006;54:2923-2927. http://dx.doi.org/10.1002/art.22123

172. Sharma L, Dunlop DD, Cahue S, Song J, Hayes KW. Quadriceps strength and osteoarthritis progression in malaligned and lax knees. *Ann Intern Med*. 2003;138:613-619.

173. Sharma L, Hurwitz DE, Thonar EJ, et al. Knee adduction moment, serum hyaluronan level, and disease severity in medial tibiofemoral osteoarthritis. *Arthritis Rheum*. 1998;41:1233-1240. http://dx.doi.org/10.1002/1529-0131(199807)41:7<1233::AID-ART14>3.0.CO;2-L

174. Sharma L, Song J, Felson DT, Cahue S, Shamiyeh E, Dunlop DD. The role of knee alignment in disease progression and functional decline in knee osteoarthritis. *JAMA*. 2001;286:188-195.

175. Shelburne KB, Torry MR, Pandy MG. Contributions of muscles, ligaments, and the ground-reaction force to tibiofemoral joint loading during normal gait. *J Orthop Res*. 2006;24:1983-1990. http://dx.doi.org/10.1002/jor.20255

176. Shimada S, Kobayashi S, Wada M, et al. Effects of disease severity on response to lateral wedged shoe insole for medial compartment knee osteoarthritis. *Arch Phys Med Rehabil*. 2006;87:1436-1441. http://dx.doi.org/10.1016/j.apmr.2006.08.018

177. Simic M, Bennell KL, Hunt MA, Wrigley TV, Hinman RS. Contralateral cane use and knee joint load in people with medial knee osteoarthritis: the effect of varying body weight support. *Osteoarthritis Cartilage*. 2011;19:1330-1337. http://dx.doi.org/10.1016/j.joca.2011.08.008

178. Simic M, Hinman RS, Wrigley TV, Bennell KL, Hunt MA. Gait modification strategies for altering medial knee joint load: a systematic review. *Arthritis Care Res (Hoboken)*. 2011;63:405-426. http://dx.doi.org/10.1002/acr.20380

179. 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;64:1545-1553. http://dx.doi.org/10.1002/acr.21724

180. Singer JC, Lamontagne M. The effect of functional knee brace design and hinge misalignment on lower limb joint mechanics. *Clin Biomech (Bristol, Avon)*. 2008;23:52-59. http://dx.doi.org/10.1016/j.clinbiomech.2007.08.013

181. Sled EA, Khoja L, Deluzio KJ, Olney SJ, Culham EG. Effect of a home program of hip abductor exercises on knee joint loading, strength, function, and pain in people with knee osteoarthritis: a clinical trial. *Phys Ther*. 2010;90:895-904. http://dx.doi.org/10.2522/ptj.20090294

182. Slemenda C, Brandt KD, Heilman DK, et al. Quadriceps weakness and osteoarthritis of the knee. *Ann Intern Med*. 1997;127:97-104.

183. Slemenda C, Heilman DK, Brandt KD, et al. Reduced quadriceps strength relative to body weight: a risk factor for knee osteoarthritis in women? *Arthritis Rheum*. 1998;41:1951-1959. http://dx.doi.org/10.1002/1529-0131(199811)41:11<1951::AID-ART9>3.0.CO;2-9

184. 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;40:277-285. http://dx.doi.org/10.2519/jospt.2010.3215

185. Sritharan P, Lin YC, Pandy MG. Muscles that do not cross the knee contribute to the knee adduction moment and tibiofemoral compartment loading during gait. *J Orthop Res*. 2012;30:1586-1595. http://dx.doi.org/10.1002/jor.22082

186. Sturnieks DL, Besier TF, Hamer PW, et al. Knee strength and knee adduction moments following arthroscopic partial meniscectomy. *Med Sci Sports Exerc*. 2008;40:991-997. http://dx.doi.org/10.1249/MSS.0b013e318167812a

187. Syme G, Rowe P, Martin D, Daly G. Disability in patients with chronic patellofemoral pain syndrome: a randomised controlled trial of VMO selective training versus general quadriceps strengthening. *Man Ther*. 2009;14:252-263. http://dx.doi.org/10.1016/j.math.2008.02.007

188. Szebenyi B, Hollander AP, Dieppe P, et al. Associations between pain, function, and radiographic features in osteoarthritis of the knee. *Arthritis Rheum*. 2006;54:230-235. http://dx.doi.org/10.1002/art.21534

189. Takacs J, Hunt MA. The effect of contralateral pelvic drop and trunk lean on frontal plane knee biomechanics during single limb standing. *J Biomech*. 2012;45:2791-2796. http://dx.doi.org/10.1016/j.jbiomech.2012.08.041

190. Teixeira PE, Piva SR, Fitzgerald GK. Effects of impairment-based exercise on performance of specific self-reported functional tasks in individuals with knee osteoarthritis. *Phys Ther*. 2011;91:1752-1765. http://dx.doi.org/10.2522/ptj.20100269

191. Thorp LE, Sumner DR, Wimmer MA, Block JA. Relationship between pain and medial knee joint loading in mild radiographic knee osteoarthritis. *Arthritis Rheum*. 2007;57:1254-1260. http://dx.doi.org/10.1002/art.22991

192. Thorp LE, Wimmer MA, Foucher KC, Sumner DR, Shakoor N, Block JA. The biomechanical effects of focused muscle training on medial knee loads in OA of the knee: a pilot, proof of concept study. *J Musculoskelet Neuronal Interact*. 2010;10:166-173.

193. Thorstensson CA, Henriksson M, von Porat A, Sjödahl C, Roos EM. The effect of eight weeks of exercise on knee adduction moment in early knee osteoarthritis – a pilot study. *Osteoarthritis Cartilage*. 2007;15:1163-1170. http://dx.doi.org/10.1016/j.joca.2007.03.012

194. Toda Y, Segal N, Kato A, Yamamoto S, Irie M. Correlation between body composition and efficacy of lateral wedged insoles for medial compartment osteoarthritis of the knee. *J Rheumatol*. 2002;29:541-545.

195. Toda Y, Segal N, Kato A, Yamamoto S, Irie M. Effect of a novel insole on the subtalar joint of patients with medial compartment osteoarthritis of the knee. *J Rheumatol*. 2001;28:2705-2710.

196. Toda Y, Tsukimura N. A six-month followup of a randomized trial comparing the efficacy of a lateral-wedge insole with subtalar strapping and an in-shoe lateral-wedge insole in patients with varus deformity osteoarthritis of the knee. *Arthritis Rheum*. 2004;50:3129-3136. http://dx.doi.org/10.1002/art.20569

197. Toriyama M, Deie M, Shimada N, et al. Effects of unloading bracing on knee and hip joints for patients with medial compartment knee osteoarthritis. *Clin Biomech (Bristol, Avon)*. 2011;26:497-503. http://dx.doi.org/10.1016/j.clinbiomech.2011.01.003

198. van der Esch M, Knoop J, van der Leeden M, et al. Self-reported knee instability and activity limitations in patients with knee osteoarthritis: results of the Amsterdam osteoarthritis cohort. *Clin Rheumatol*. 2012;31:1505-1510. http://dx.doi.org/10.1007/s10067-012-2025-1

199. van der Esch M, Steultjens M, Harlaar J, Knol D, Lems W, Dekker J. Joint proprioception, muscle strength, and functional ability in patients with osteoarthritis of the knee. *Arthritis Rheum*. 2007;57:787-793. http://dx.doi.org/10.1002/art.22779
200. Van Tiggelen D, Cowan S, Coorevits P, Duvigneaud N, Witvrouw E. Delayed vastus medialis obliquus to vastus lateralis onset timing contributes to the development of patellofemoral pain in previously healthy men: a prospective study. *Am J Sports Med*. 2009;37:1099-1105. http://dx.doi.org/10.1177/0363546508331135
201. Walter JP, D'Lima DD, Colwell CW, Jr., Fregly BJ. Decreased knee adduction moment does not guarantee decreased medial contact force during gait. *J Orthop Res*. 2010;28:1348-1354. http://dx.doi.org/10.1002/jor.21142
202. Weidenhielm L, Svensson OK, Broström LA, Mattsson E. Adduction moment of the knee compared to radiological and clinical parameters in moderate medical osteoarthrosis of the knee. *Ann Chir Gynaecol*. 1994;83:236-242.
203. Winby CR, Lloyd DG, Besier TF, Kirk TB. Muscle and external load contribution to knee joint contact loads during normal gait. *J Biomech*. 2009;42:2294-2300. http://dx.doi.org/10.1016/j.jbiomech.2009.06.019
204. Zeni JA, Rudolph K, Higginson JS. Alterations in quadriceps and hamstrings coordination in persons with medial compartment knee osteoarthritis. *J Electromyogr Kinesiol*. 2010;20:148-154. http://dx.doi.org/10.1016/j.jelekin.2008.12.003
205. Zhang W, Moskowitz RW, Nuki G, et al. OARSI recommendations for the management of hip and knee osteoarthritis, part I: critical appraisal of existing treatment guidelines and systematic review of current research evidence. *Osteoarthritis Cartilage*. 2007;15:981-1000. http://dx.doi.org/10.1016/j.joca.2007.06.014
206. Zhang W, Moskowitz RW, Nuki G, et al. OARSI recommendations for the management of hip and knee osteoarthritis, part II: OARSI evidence-based, expert consensus guidelines. *Osteoarthritis Cartilage*. 2008;16:137-162. http://dx.doi.org/10.1016/j.joca.2007.12.013