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Potential Strategies to Reduce Medial Compartment Loading in Patients With Knee Osteoarthritis of Varying Severity

Reduced Walking Speed

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Objective. **To determine whether reducing walking speed is a strategy used by patients with knee osteoarthritis (OA) of varying disease severity to reduce the maximum knee adduction moment.**

Methods. **Self-selected walking speeds and maximum knee adduction moments of 44 patients with medial tibiofemoral OA of varying disease severity, as assessed by using the Kellgren/Lawrence grade, were compared with those of 44 asymptomatic control subjects matched for sex, age, height, and weight.**

Results. **Differences in self-selected normal walking speed explained only 8.9% of the variation in maximum knee adduction moment for the group of patients with knee OA. The severity of the disease influenced the adduction moment–walking speed relationship; the individual slopes of this relationship were significantly greater in patients with less severe OA than in asymptomatic matched control subjects. Self-selected walking speed did not differ between patients with knee OA, regardless of the severity, and asymptomatic control subjects. However, knees with more-severe OA had significantly greater adduction moments (mean ± SD 3.80 ± 0.89% body weight × height) and were in more varus alignment (6.0 ± 4.5°) than knees with less-severe OA (2.94 ± 0.70% body weight × height; and 0.0 ± 2.9°, respectively).**

Conclusion. **Patients with less-severe OA adapt a walking style that differs from that of patients with more-severe OA and controls. This walking style is associated with the potential to reduce the adduction moment when walking at slower speeds and could be linked to decreased disease severity.**

Mechanical loads placed upon the joint during walking have been related to the progression of knee osteoarthritis (OA) (1,2). Theoretical estimations show that loads transferred through the medial compartment of the knee are ~2.5 times greater than loads transferred through the lateral compartment of the knee (3), and the majority of symptomatic OA knees are radiographically diagnosed with degenerative changes in the medial compartment of the joint (4). Moreover, increased mechanical load on the medial compartment of the knee has been associated with knee varus alignment, typically measured statically as mechanical axis alignment (5) or dynamically as external knee adduction moment (3), and a positive correlation between mechanical axis alignment and maximum external knee adduction moment has been reported (6,7).

The relevance of the maximum knee adduction moment for the course of the disease has been emphasized by results of recent studies (1,2) that showed that high maximum adduction moments at the knee at a controlled walking speed are related to OA disease severity and to a higher rate of progression of knee OA. Nevertheless, it is still unclear whether the maximum knee adduction moment in patients with OA is higher than that of healthy control subjects when walking at

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self-selected normal speed and whether a high maximum knee adduction moment, and the related high mechanical load placed on the medial compartment of the knee, is a risk factor for the development of knee OA.

Patients with knee pathologies walk at slower speeds than do healthy control subjects, and it has been shown that the clinical state of a patient is reflected in his or her walking speed (8–10). However, it is not clear whether walking speed in groups of OA patients decreases primarily with increasing age or with disease severity. It is believed that pain will cause the patients with knee OA to reduce their walking speed, and it has been speculated that they walk at slower speeds to reduce loading in the medial compartment of the knee (11). Results of an earlier study (12) indicated that the external knee adduction moment might be correlated with walking speed in healthy adults. Yet, it is not known whether slower walking speed is associated with reduced knee adduction moments in patients with knee OA and whether reducing the loading on the medial compartment of the knee by reducing walking speed is a protective strategy that is unconsciously utilized by patients.

The purpose of this study was to determine whether walking speed is related to the maximum knee adduction moment in patients with knee OA and in healthy controls and whether reducing walking speed is a strategy used by patients with knee OA of varying disease severity to reduce the maximum knee adduction moment. We hypothesized that 1) for a group of patients with knee OA of varying disease severity and for an asymptomatic control group, the maximum knee adduction moment is correlated with walking speed, 2) for individual patients with knee OA of varying disease severity and for individual asymptomatic control subjects, the maximum knee adduction moment is correlated with walking speed, and 3) when walking at a self-selected speed, the maximum knee adduction moments are the same in OA patients with varying disease severity and in asymptomatic controls.

PATIENTS AND METHODS

Patients. Patients were selected on the basis of 4 factors: definite osteophyte presence in the medial or lateral tibiofemoral compartment; a narrowest-point interbone distance of the medial compartment less than that of the lateral compartment; pain in and around at least 1 knee for most days in the past months; and at least some difficulty with 2 or more items in the Western Ontario and McMaster Universities Osteoarthritis Index (13). There were 22 exclusion criteria for patients with knee OA: rheumatoid or other systemic inflammatory arthritis; avascular necrosis; periarticular fracture; Paget's disease; villonodular synovitis; chronic knee joint infection; ochronosis; neuropathic arthropathy; acromegaly; hemochromatosis; Wilson's disease; osteochondromatosis; gout or recurrent pseudogout; osteopetrosis; total knee replacement in either knee; flexion contracture >15° in either knee; OA grade higher than moderate (scale of none, mild, moderate, severe) by examination in either ankle or either hip; morbid obesity (body mass index [BMI] >45 kg/m^2); intraarticular corticosteroid injection within last 2 months; knee surgery within last 6 months; plans for total knee replacement within the next year; and hip or spine disease as the major source of disability.

For the current analysis, patients were selected from a data pool of 73 patients from a larger study based on the availability of sex-, age-, height-, and weight-matched control subjects and successful gait tests. Forty-four patients (88 knees) with OA in the medial compartment of the knee were selected for this study (24 women, 20 men; mean ± SD age 65.4 ± 10.0 years; height 169.3 ± 9.8 cm; weight 78.4 ± 13.1 kg; BMI 27.39 ± 4.07 kg/m^2) after giving written consent in accordance with the Institutional Review Board.

Control subjects. For each patient, an asymptomatic control subject matched for sex, age, height, and weight was selected after giving written consent in accordance with the Institutional Review Board. All asymptomatic control subjects (24 women, 20 men; mean ± SD age 63.3 ± 10.7 years; height 169.2 ± 8.5 cm; weight 76.4 ± 12.7 kg; BMI 26.58 ± 3.35 kg/m^2) had no clinical diagnosis of OA or rheumatoid arthritis or history of knee trauma or pain. The patient and control groups did not differ in age, height, weight, or BMI ($P = 0.351$, $P = 0.981$, $P = 0.451$, and $P = 0.311$, respectively). None of the control subjects had previously been treated for any clinical lower back or lower extremity condition or had any activity-restricting medical or musculoskeletal condition.

Clinical assessment. Kellgren/Lawrence (K/L) grades for both knees for those in the patient group were determined based on clinical and radiographic data: 0 = no osteophytes; 1 = possible osteophyte lipping; 2 = definite osteophyte and possible joint space narrowing; 3 = moderate multiple osteophytes, definite joint space narrowing, some sclerosis, and possible bone contour deformity; and 4 = large osteophytes, marked joint space narrowing, severe sclerosis, and definite bone contour deformity (14). The mechanical axes of all knee joints were measured by the same investigator (LS) as the angle between a line from the center of the femoral head to the center of the femoral intercondylar notch, and as a line from the center of the tips of the tibial spines to the ankle talus, from a single radiograph that included the hip, knee, and ankle (5). To minimize measurement variation related to limb rotation, each patient was positioned with the tibial tubercle anterior. Neutral alignment was defined as 0, varus alignment as positive angles, and valgus alignment as negative angles.

Gait analysis. All patients and control subjects performed walking trials in their own low-top, comfortable walking shoes. Each patient was instructed to walk at 3 speeds: slow, self-selected normal, and fast. Reflective markers were placed on the leg along the superior iliac spine, greater trochanter, lateral joint line of the knee, lateral malleolus, lateral aspect of the calcaneus, and head of the fifth metatarsal. Marker data were captured using 4 high-speed cameras (120 frames/second) (MCU240; Qualisys Medical, Gothenburg, Sweden). Ground reaction force data were collected using a force platform (sampling frequency 120 Hz; Bertec, Columbus, OH) that was placed in the center of the walkway, level with the ground. Walking speed for each trial was calculated as the average velocity of the superior iliac spine marker in the walking direction. Each limb segment (thigh, shank, and foot) was idealized as a rigid body with a local coordinate system defined to coincide with a set of anatomic axes. Intersegmental moments and forces were calculated from the position of the markers, ground reaction force measurements, and limb segment mass/inertia properties. The moment at the knee was resolved into a coordinate system fixed in a tibial reference system with axes defining flexion–extension, abduction–adduction, and internal–external rotation. The approach used is identical to that described in previous investigations (15,16). The maximum knee adduction moment was defined as the maximum external adduction moment about the abduction–adduction axis of the knee.

Statistical analysis. Linear regression analysis was used to relate the maximum knee adduction moment at self-selected normal walking speed to self-selected normal walking speed for all subjects of each group and to relate maximum knee adduction moment to walking speed over a range of walking speeds for each individual. For the overall regression analysis between self-selected normal walking speed and adduction moment, an average value of 3 trials per subject was used. All 9 trials (3 trials × 3 speeds) were entered for the individual regression lines for each subject. The slopes of individual regression lines between patients and control subjects and between patients with OA of varying severity were compared using Student's *t*-tests. Bonferroni correction for multiple comparisons was applied to the significance level. Repeated-measures Student's paired *t*-tests were used to detect significant differences in maximum knee adduction moment at self-selected normal walking speed and self-selected normal walking speed between the control and patient groups. The joint with more-severe OA may primarily determine walking speed, and thus, all analyses that included walking speed were performed on a patient basis. Differences in maximum knee adduction moment between the control, less-severe OA (K/L grade ≤ 2), and more-severe OA (K/L grade ≥ 3) were determined using repeated-measures analysis of variance (ANOVA). The adduction moment may be determined primarily by the severity of OA in an individual joint. In many cases, the severity is different between both joints and, thus, the adduction moment was presented on a knee basis. The 5% significance level was used.

RESULTS

The distribution of K/L grades for the knees of patients with OA is given in Table 1. Four patients were diagnosed with unilateral knee OA, and 40 were diagnosed with bilateral knee OA. Including the contralateral knee of these 4 patients in the analyses had no effect on any of the results.

Table 1. Distribution of Kellgren/Lawrence (K/L) grades for all patients with knee osteoarthritis

K/L grade	No. of knees
0	4
1	4
2	48
3	19
4	13

The maximum knee adduction moment at self-selected normal walking speed was linearly correlated with self-selected normal walking speed for patients with knee OA when data from patients with all disease severities were combined. However, differences in self-selected normal walking speed between patients explained only 8.9% of variance in the maximum knee adduction moment at this speed ($P = 0.005$) (Figure 1), and the self-selected normal walking speed–maximum knee adduction moment relationship was not significant for the control group ($P = 0.158$).

Slopes of regression lines for each individual showed a large range for all groups of subjects. Patients with less severe knee OA had significantly greater slopes of individual regression lines than did matched asymptomatic control subjects (mean ± SD 0.90 ± 0.59 in those with less-severe OA and 0.33 ± 0.73 in control subjects; $P = 0.015$) (Figure 2), while the slopes of the individual regression lines were similar for patients with more-severe knee OA and matched asymptomatic control subjects. The maximum knee adduction moment at

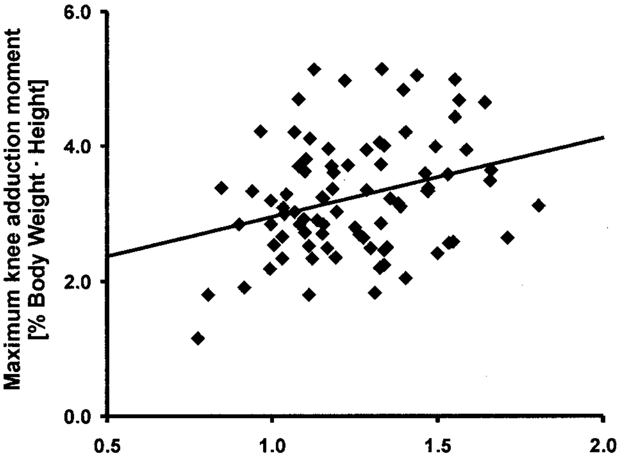

Figure 1. Relationship of maximum knee adduction moment ($M_{adduction}$) at self-selected normal walking speed to self-selected normal walking speed ($v_{walking}$) for patients with knee osteoarthritis (n = 88 knees). $M_{adduction} = 1.784 + 1.172 \times v_{walking}$. $R^2 = 0.089$, $P = 0.005$.

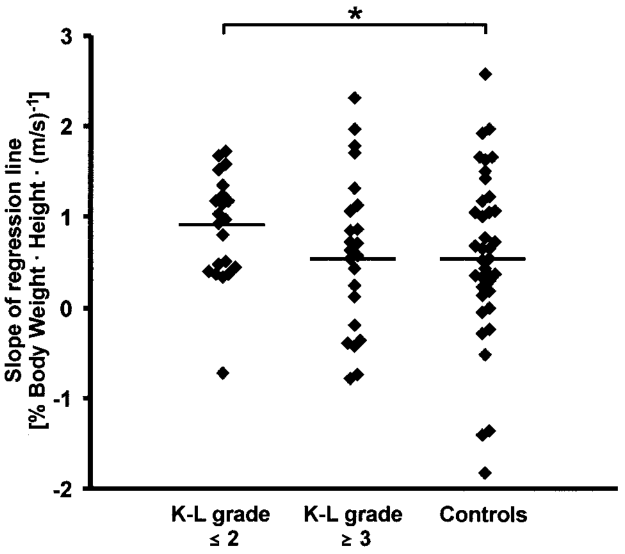

Figure 2. Individual slopes of regression lines showing the relationship between maximum knee adduction moment and walking speed for the more severely affected knee of all patients with osteoarthritis and the knee of a control subject matched for side, sex, age, height, and weight. Horizontal lines show the means. $* = P = 0.015$ by paired *t*-test. K/L = Kellgren/Lawrence.

self-selected normal walking speed was not significantly different between all OA knees and asymptomatic control knees (mean ± SD in OA knees 3.27 ± 0.88% body weight × height versus control knees 3.16 ± 0.92% body weight × height; $P = 0.421$). However, when the data were stratified on the basis of disease severity, the maximum knee adduction moment was significantly higher in knees with more-severe OA (3.80 ± 0.89% body weight × height) than in asymptomatic matched control knees ($P = 0.039$) and in knees with less-severe OA (2.94 ± 0.70% body weight × height; $P < 0.001$) (Figure 3) based on the ANOVA testing for interaction between groups (patient–control) and K/L grade ($P = 0.009$). Knees with more-severe OA also had greater varus alignment than did knees with less-severe OA (6.0 ± 4.5° and 0.0 ± 2.9°, respectively; $P < 0.001$) (Figure 4). The average self-selected normal walking speed did not differ between patients with less-severe or more-severe knee OA and asymptomatic control subjects (Table 2). Post hoc power calculations of all significant test results showed a power >75%.

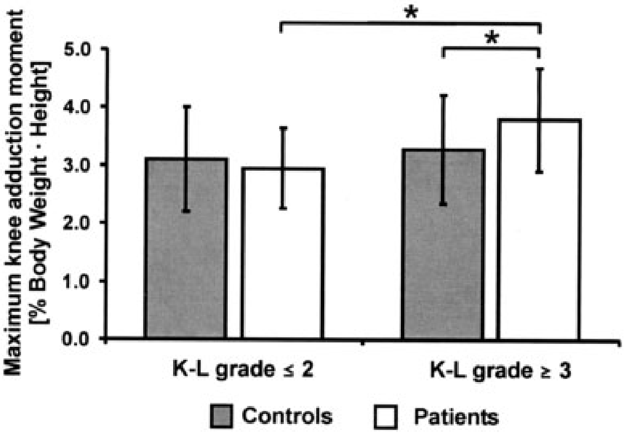

Figure 3. Comparison of maximum knee adduction moment in patients with less-severe knee osteoarthritis (OA) (Kellgren/Lawrence [K/L] grade ≤ 2) and asymptomatic control subjects, and of patients with more-severe knee OA (K/L grade ≥ 3) and matched asymptomatic control subjects, walking at self-selected normal walking speed. Values are the mean ± SD. Analysis of variance revealed a significant interaction between group (patient–control) and K/L grade ($P = 0.009$). $* = P = 0.05$.

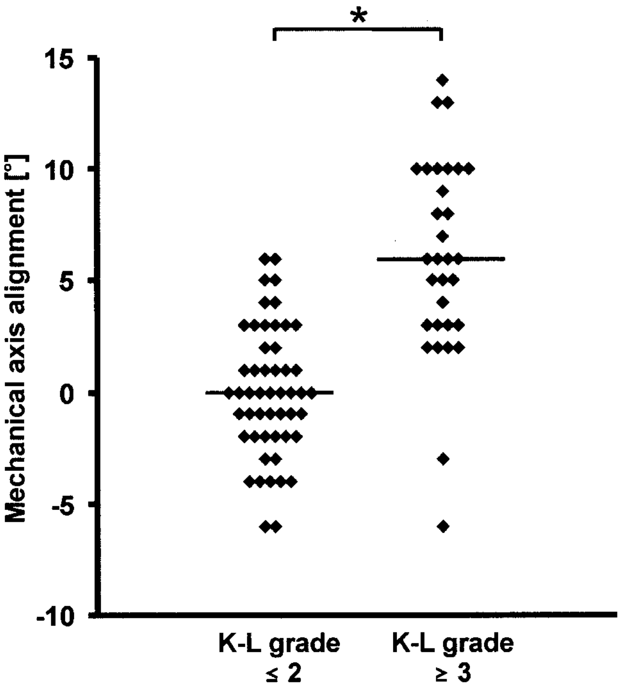

Figure 4. Lower extremity alignment measured as mechanical axis alignment in knees with less-severe osteoarthritis (OA) (Kellgren/Lawrence [K/L] grade ≤ 2; n = 56) and more-severe OA (K/L grade ≥ 3; n = 32). Mechanical axis alignment was defined as the angle between a line from the center of the femoral head to the center of the femoral intercondylar notch, and a line from the center of the tips of the tibial spines to the ankle talus, from a single radiograph that included the hip, knee, and ankle. Positive values correspond to varus alignment, and negative values correspond to valgus alignment. Horizontal lines show the means. $* = P < 0.001$.

DISCUSSION

When patients of all disease severities were considered, walking speed explained only 8.9% of the variation in maximum knee adduction moment at the self-selected normal walking speed. The relationship was weak because the self-selected walking speed was similar for patients of all disease severities, while patients with more-severe knee OA had greater maximum knee adduction moments than patients with less-severe knee OA. In fact, patients with knee OA and asymptomatic subjects who walk at similar self-selected normal speeds experience a wide range of maximum knee adduction moment during each step. These intersubject differences in maximum knee adduction moment may be due to individual differences in lower extremity alignment, joint geometry, and/or muscle strength. The results of this study suggest that patients with knee OA and asymptomatic control subjects who walk at slower speeds compared with other individuals do not necessarily experience smaller loads on the medial compartment of the knee.

For individual patients with knee OA of varying disease severity and for individual asymptomatic control subjects, the relationship between maximum knee adduction moment and walking speed ranged from negative associations to positive associations (Figure 2). Thus, changes in the maximum knee adduction moment may not be readily predicted from walking speed for all patient and control groups because they are subject to large individual variability. In general, subjects with a large positive slope have the potential to reduce the adduction moment by reducing walking speed, whereas subjects with a lower or negative slope gain no advantage by reducing walking speed. The individual slopes of the walking speed–maximum adduction knee moment relationship were significantly greater in patients with less-severe knee OA than in asymptomatic control subjects. Thus, reducing walking speed will most likely benefit those patients with less-severe knee OA.

All but 1 patient with less-severe knee OA showed a positive correlation between walking speed and maximum knee adduction moment (Figure 2). Although their self-selected normal walking speed in the laboratory setting was similar to that of control subjects, it is very likely that these patients reduce their maximum knee adduction moment when walking at slower speeds during everyday activities. The difference in magnitude and slope of the theoretical relationship between maximum knee adduction moment and walking speed for the 3 groups of subjects (Figure 5) suggests that patients with less-severe knee OA walk with unique gait mechanics that are different from the gait mechanics of asymptomatic control subjects and patients with more-severe knee OA despite similar age and sex distributions in all 3 subject groups. This unique walking pattern may lead to reduced loading of the medial compartment of the knee when walking at slower speeds. In comparison, similar to asymptomatic control subjects, walking slower during everyday activities will affect the maximum knee adduction moment in only some patients with more-severe knee OA (Figure 5).

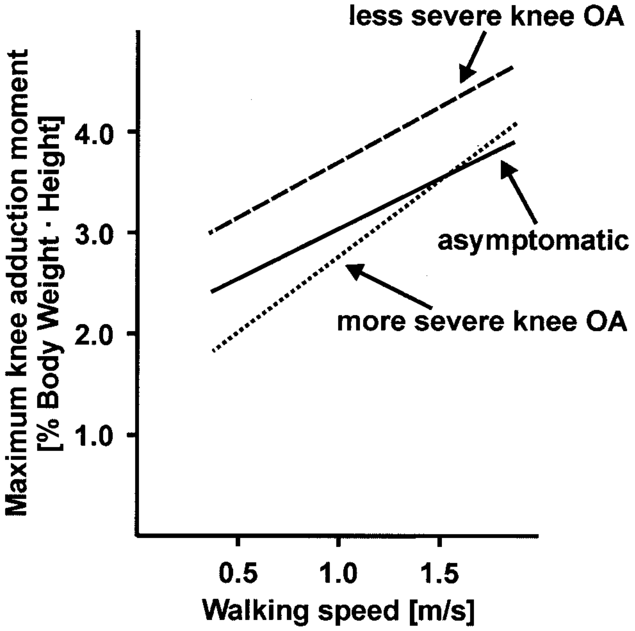

Figure 5. Relationship between maximum knee adduction moment in patients with less-severe knee osteoarthritis (OA), patients with more-severe OA, and matched control subjects.

The regression equation obtained in this study predicts a reduction of the maximum knee adduction moment of ~10.2% when walking at 0.8 meters/second compared with 1.2 meters/second. In comparison, other noninvasive treatments for patients with knee OA reduce the maximum knee adduction moment by 13.0% using bracing (17) or by 6.0% or 8.2% using 5° or 10° valgus insoles (18), respectively. Based on the results of a previous investigation (19) involving healthy subjects, a reduction in maximum knee adduction moment by ~10.0% with a 10° greater foot progression angle (more toe-out foot placement) can be expected. Thus, the theoretically estimated reduction based on the current data set is within the range of potential reductions in maximum knee adduction moment due to other nonin-

Table 2. Self-selected normal walking speed for all patients with osteoarthritis (OA), patients with less-severe (Kellgren/Lawrence [K/L] grade ≤2) and more-severe (K/L grade ≥3) OA, and matched asymptomatic controls*

Subjects (no. of pairs)†	OA patients	Controls	*P*
All (44)	1.243 ± 0.206	1.240 ± 0.185	0.946
K/L grade ≤2 (22)	1.255 ± 0.219	1.190 ± 0.136	0.351
K/L grade ≥3 (22)	1.231 ± 0.297	1.289 ± 0.217	0.485

* Values are the mean ± SD meters/second.

† Each pair consisted of 1 knee (the more severely affected) from a patient and 1 knee from a control who was matched to the patient for side, sex, age, height, and weight.

vasive interventions. Because the relationship between maximum knee adduction moment and walking speed is stronger in patients with less-severe knee OA, an even greater reduction in maximum knee adduction moment could be achieved with a reduction in speed for this patient group. Conversely, walking fast may be even more detrimental for patients with less-severe knee OA.

Hypothesis 3 was motivated by earlier reports of slower walking speeds in patients with knee OA compared with healthy subjects (8–10). However, those studies did not control for sex, age, height, or weight between patients and healthy subjects. In an attempt to control for walking speed, previous studies quantifying the maximum knee adduction moment in patients with knee OA analyzed walking trials at a speed closest to 1 meters/second (1,7,20,21), 0.7 meters/second (2), or 0.6 meters/second (6), respectively. The percentage of patients with a K/L grade ≥3 in these studies ranged from 36% to 67%. In contrast, patients in our study (50% had a K/L grade ≥3) walked at the same self-selected normal walking speeds (~1.2 meters/second) as the asymptomatic control subjects (Table 2). Thus, values for knee adduction moments reported in earlier studies (1,2,6,7,20,21) correspond to a walking speed that is >20% slower than the walking speed in our study, although the distribution of K/L grades in our study was not different from the distributions in those studies. As a result, adduction moments at such slow walking speeds may not truly represent the mechanical loads most frequently placed upon the knee.

It should be noted that, as disease severity increases, it is likely that walking speed will be reduced during everyday activities. Studies of patients with severe tibiofemoral joint degeneration who were tested prior to reconstructive surgery found values of self-selected normal walking speed for patients with knee OA between 0.6 and 0.9 meters/second (8–10,22). In comparison, patients in our study were diagnosed with a range of clinical symptoms, as indicated by the distribution of K/L grades, but none was severe enough to be considered for surgery.

The results of this study suggest that increased maximum knee adduction moment may not be the initial cause of OA, but rather, the effect of morphologic changes in the pathologic joint. Medial compartment joint space narrowing secondary to the progression of OA would cause increased knee varus alignment. Indeed, knees with more-severe OA were in more varus alignment than knees with less-severe OA (Figure 4), and it has previously been shown (7) that static alignment, as assessed by the mechanical axis alignment, is the best single predictor of the dynamic load on the medial compartment of the knee, as assessed by the maximum knee adduction moment in patients with knee OA. This increase in adduction moment at later stages of OA may then lead to an accelerated rate of disease progression (2). Some patients may be able to alter their walking mechanics and to reduce their maximum knee adduction moment at very early stages of the disease and reduce the rate of progression. This explanation is supported by the fact that patients with less-severe knee OA appear to have different gait mechanics than asymptomatic control subjects (Figure 5) and are able to reduce the adduction moment by walking slower during everyday activities. Lower adduction moments during everyday activities may result in a slower rate of progression in these patients, which is reflected in lower K/L grades. However, to date, it is not known whether patients with less-severe knee OA in fact walk slower during everyday activities than in a laboratory setting.

In conclusion, when patients of all disease severities were considered, the relationship between maximum knee adduction moment at self-selected normal walking speed and self-selected normal walking speed was weak. This association was highly patient-specific and depended on disease severity, indicating that only some patients may reduce the mechanical loading of the knee by reducing walking speed. Patients with less-severe knee OA can reduce the maximum knee adduction moment by reducing walking speed. Knees with more-severe OA had significantly greater maximum knee adduction moments than did knees with less-severe OA and asymptomatic control knees, and were in more varus alignment than were knees with less-severe OA. These results suggest that increased maximum knee adduction moment may not be the initial cause of OA, but rather, the effect of morphologic changes in the pathologic joint. However, prospective studies are needed to identify the specific role of the knee adduction moment during walking in the development of knee OA. Future research should also determine whether reduced walking speed might be used as a primary intervention or whether available noninvasive interventions may cause a reduction in walking speed.

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