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Knee Osteoarthritis Is Associated With Reduced Hip but Preserved Spinal Movement Quality: An Artificial Intelligence-Based Markerless Motion Capture Study

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ABSTRACT

Background and Aims: Knee osteoarthritis (KOA) is increasingly recognized as a disorder affecting the entire lower-extremity kinematic chain rather than as an isolated knee pathology. Biomechanical adaptations involving proximal segments may develop as the disease progresses. However, the relationship between radiographic KOA severity and movement quality within the proximal kinematic chain remains incompletely understood. Therefore, this study aimed to investigate the association between radiographic KOA severity and hip and spinal movement quality, assessed using an artificial intelligence (AI)-based markerless motion analysis system, in individuals without radiographic hip osteoarthritis (HOA).

Materials and Methods: A total of 177 participants were classified according to the Kellgren–Lawrence (KL) grading system as controls (n=21), Grade 1 (n=32), Grade 2 (n=63), Grade 3 (n=40), or Grade 4 (n=21). Hip and spinal movement quality were assessed using MAI Motion, an AI-based markerless motion analysis platform. Movement quality was quantified using the C.R.A.F.T. framework, which evaluates Control, Repetition, Asymmetry, Flow, and Twist. Group differences were analyzed using Kruskal–Wallis tests followed by Dunn–Bonferroni post hoc comparisons.

Results: No significant differences were observed in Hip-Repetition (p=0.182) or Hip-Asymmetry (p=0.615) scores. Significant overall group differences were found in Hip-Flow (p=0.011), Hip-Twist (p=0.032), and Hip-Overall (p=0.002) scores. Post hoc analyses showed significantly lower Hip-Twist scores in Grade 4 than in controls (p=0.012). Hip-Overall scores were significantly lower in Grades 2, 3, and 4 than in controls (p=0.002, p=0.040, and p=0.032, respectively). Among the spinal parameters, only Spine-Flow demonstrated a significant overall difference (p=0.024), with no significant pairwise differences.

Conclusion: Hip movement quality deteriorated with increasing KOA severity despite the absence of HOA, whereas spinal movement quality remained relatively preserved. AI-based markerless motion analysis may provide an objective tool for detecting proximal kinematic chain alterations associated with KOA progression.

Keywords: Artificial intelligence, biomechanics, hip joint, knee osteoarthritis, motion capture, spine.

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INTRODUCTION

Knee osteoarthritis (KOA) is one of the most prevalent musculoskeletal disorders worldwide.[1] It represents a leading cause of pain, disability, and reduced quality of life among older adults.[2] KOA has traditionally been viewed as a disease affecting the tibiofemoral joint.[3] However, growing evidence suggests that the biomechanical consequences of KOA extend beyond the knee and affect the entire lower-extremity kinematic chain.[4,5] Progressive joint degeneration alters movement strategies during functional activities, resulting in compensatory adaptations involving the hip, pelvis, trunk, and contralateral limb.[4,6]

Biomechanical investigations have demonstrated that individuals with KOA exhibit altered gait patterns, increased frontal-plane loading, reduced joint excursion, and impaired intersegmental coordination during activities of daily living.[4,6] These adaptations are believed to arise from pain-avoidance strategies, muscle weakness, proprioceptive deficits, and progressive changes in lower-limb alignment.[5,7] Recent studies have further shown that hip muscle dysfunction and impaired proximal control are associated with greater disease severity and functional limitations in individuals with KOA.[7,8] The hip joint plays a critical role in maintaining frontal-plane stability and controlling lower-extremity alignment during weight-bearing tasks.[9] Weakness of the hip abductors and altered hip mechanics may contribute to abnormal medial knee loading and disease progression.[5,8] Previous investigations have reported significant associations between hip strength deficits and higher Kellgren–Lawrence (KL) grades,[8] suggesting that proximal biomechanical alterations may accompany structural deterioration of the knee joint. In addition to hip dysfunction, trunk and spinal movement patterns may also be altered in response to KOA.[10] Increased trunk lean, altered center-of-mass control, and compensatory spinal strategies have been reported during gait and functional activities, potentially representing adaptive mechanisms aimed at reducing knee joint loading.[10,11] Nevertheless, the extent to which radiographic KOA severity influences spinal movement quality remains poorly understood.

Advances in computer vision and artificial intelligence (AI) have enabled the development of markerless motion capture systems capable of quantifying human movement without the need for laboratory-based equipment.[12] Compared with traditional marker-based motion analysis, these technologies offer greater accessibility, lower costs, and increased feasibility for routine clinical practice.[12,13] Recent validation studies have demonstrated acceptable reliability and validity of markerless systems for assessing lower-extremity kinematics during functional tasks such as gait, squatting, and sit-to-stand movements.[13–15] MAI Motion (https://maimotion.com/) is an AI-based markerless motion analysis platform that evaluates movement quality using the C.R.A.F.T. framework, which incorporates measures of Control, Repetition, Asymmetry, Flow, and Twist.[15] Although this technology has demonstrated promising utility in musculoskeletal assessment,[15] to the best of our knowledge, the application of this method in assessing changes in the proximal kinetic chain at different stages of KOA has not been extensively studied.

Therefore, the primary aim of this study was to investigate the association between radiographic KOA severity and hip movement quality in individuals without radiographic hip osteoarthritis (HOA). A secondary aim was to determine whether increasing KOA severity was associated with alterations in spinal movement quality. We hypothesized that greater radiographic KOA severity would be associated with progressively impaired hip movement quality and that similar, although less pronounced, alterations would be observed in spinal movement parameters. The research question was whether radiographic progression of KOA was associated with progressive deterioration in proximal kinematic chain movement quality, particularly at the hip and spine, in the absence of HOA.

MATERIALS AND METHODS

Study Design

This cross-sectional observational study investigated the association between radiographic knee osteoarthritis (KOA) severity and proximal kinematic chain movement quality using an artificial intelligence (AI)-based markerless motion analysis platform. The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki and complied with all relevant institutional and national regulations governing research involving human participants. Ethical approval was obtained from Hacettepe University Non-Interventional Clinical Research Ethics Committee (Approval Number: 2025/21-22, Date: 11.11.2025). All participants received detailed information regarding the study procedures and provided written informed consent before participation.

Participants

A total of 177 participants were included in the study and categorized according to the Kellgren–Lawrence (KL) grading system. The study cohort consisted of a control group (n=21), KL Grade 1 (n=32), KL Grade 2 (n=63), KL Grade 3 (n=40), and KL Grade 4 (n=21). Exclusion criteria included neurological disorders, hip osteoarthritis (HOA), inflammatory arthropathies, previous lower-extremity surgery, and any musculoskeletal condition that could substantially affect movement performance.

Radiographic Assessment

The radiographic severity of KOA was determined using the KL grading system based on standard weight-bearing anteroposterior knee radiographs. Participants were subsequently categorized into control, KL Grade 1, KL Grade 2, KL Grade 3, and KL Grade 4 groups according to established classification criteria.[16] The control group consisted of patients who presented at our outpatient clinic with upper limb problems, who had no knee or hip pain, and in whom no osteoarthritis was detected on the knee X-rays taken. To exclude the potential influence of concomitant HOA on movement quality outcomes, standard hip radiographs were also obtained from all participants. All knee and hip radiographs were independently evaluated by an orthopedic surgeon with more than 40 years of clinical experience in musculoskeletal disorders. Participants with radiographic evidence of HOA were excluded from the study. Radiographic KL grading was performed on the index knee, defined as the symptomatic knee or, when both knees were symptomatic, the more severely affected knee, because this joint drove the patient's clinical presentation and represented the principal target of any subsequent intervention. Because classification was based on the index knee rather than on both knees independently, a formal left-versus-right comparison of KL severity was not applicable to the present dataset; the index-knee approach was adopted deliberately because bilateral radiographic grading was not required to test the study's proximal compensation hypothesis. Specifically, all 177 participants were graded based on a single index knee, and none were graded independently on both knees; consequently, a paired left-versus-right statistical comparison of KL severity (e.g., a Wilcoxon signed-rank or Stuart–Maxwell test) was neither applicable nor performed. This uniform index-knee approach was adopted because the symptomatic or more severely affected knee determined the clinical presentation and guided management, and independent grading of both knees was not required to test the study's proximal compensation hypothesis.

Motion Analysis

Movement quality was assessed using MAI Motion, an AI-based markerless motion capture platform that uses computer vision algorithms to quantify human movement from conventional red-green-blue (RGB) video recordings. Video recordings were obtained using a standard RGB camera positioned in the frontal plane and subsequently uploaded to the MAI Motion platform for automated analysis. The platform uses machine learning-based pose-estimation algorithms to identify anatomical landmarks and quantify movement quality characteristics.[15] Recordings were performed in a controlled indoor clinical environment with consistent lighting and a neutral background free of visual obstructions; the camera position was adjusted to ensure full-body (head-to-toe) visibility within the frame, which is required for accurate markerless motion analysis because incomplete visual capture prevents successful kinematic processing.

Participants performed a standardized three-repetition sit-to-stand (STS) task. Each participant began in a seated position on a chair with both feet flat on the floor, shoulder-width apart, and aligned in a neutral position. Participants were instructed to rise to a fully upright standing position and subsequently return to the seated position. This movement sequence was repeated continuously for three consecutive repetitions at a self-selected speed. The three-repetition protocol was selected based on previous validation research demonstrating biomechanical equivalence to traditional five-repetition STS protocols while reducing participant burden and fatigue.[15]

Outcome Measures

Movement quality was quantified using the C.R.A.F.T. framework implemented within the MAI Motion platform, which generates scores ranging from 0 to 10. This framework evaluates multiple dimensions of movement performance, including control, repetition, asymmetry, movement flow, and rotational dynamics (twist). Separate movement quality scores were generated for the hip and spinal regions. Composite overall scores were also calculated to provide a global representation of movement quality for each anatomical region. Higher scores reflected better movement quality and motor control performance. The C.R.A.F.T. scores are proprietary composite kinematic indices of movement quality derived from markerless video; they are not kinetic (joint-moment) or electromyographic measurements, and the individual dimensions represent correlated descriptors of the same movement rather than independently validated, torque-referenced constructs. For the STS task, the platform generated Repetition, Asymmetry, Flow, and Twist subscores together with a composite Overall score for each region; a discrete Control subscore was generated for the spine but not for the hip, and Hip-Control was therefore not reported. Although the platform additionally generates knee-region scores, the present analysis focused *a priori* on the proximal and adjacent segments (hip and spine) because movement quality scores at the knee itself are directly confounded by the primary pathology (pain-related guarding and restricted range of motion) and would not provide an independent test of the proximal compensation hypothesis.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 29.0 (IBM Corp., Armonk, NY, USA). Data distributions were evaluated using the Shapiro–Wilk test.

Table 1. Demographic characteristics of participants according to Kellgren–Lawrence grade

Variable	Control (n=21)	KL Grade 1 (n=32)	KL Grade 2 (n=63)	KL Grade 3 (n=40)	KL Grade 4 (n=21)	Total (n=177)	p
Age (years)	69.1±3.1	66.8±1.2	67.0±1.2	69.6±1.6	72.0±2.0	68.4±0.7	0.185
Female (%)	28.6	65.6	73.0	67.5	90.5	67.2	<0.001
Male (%)	71.4	34.4	27.0	32.5	9.5	32.8	<0.001

Values are presented as mean±standard deviation for continuous variables and percentages for categorical variables. Group differences in age were assessed using the Kruskal–Wallis test. Sex distribution across Kellgren–Lawrence grades was evaluated using the chi-square test. Statistical significance was set at p<0.05. KL: Kellgren–Lawrence.

Because the movement quality variables did not satisfy the assumptions of normality, nonparametric statistical methods were employed. Differences among KL groups were examined using Kruskal–Wallis tests. When significant overall group effects were identified, Dunn–Bonferroni post hoc analyses were conducted to determine pairwise differences between groups. Statistical significance was established at p<0.05.

RESULTS

Participant Characteristics

A total of 177 participants were included in the final analysis and categorized according to radiographic knee osteoarthritis (KOA) severity as controls (n=21), Kellgren–Lawrence (KL) Grade 1 (n=32), KL Grade 2 (n=63), KL Grade 3 (n=40), and KL Grade 4 (n=21). The mean age of the study population was 68.4±0.7 years. The study cohort consisted of 119 females and 58 males. Participant demographic characteristics are presented in Table 1.

Hip Movement Quality

Analysis of hip movement quality revealed significant differences across KOA severity groups in Hip-Flow, Hip-Twist, and Hip-Overall scores. In contrast, no significant differences were observed in Hip-Repetition or Hip-Asymmetry scores.

The Kruskal–Wallis test demonstrated significant overall group effects for Hip-Flow (p=0.011), Hip-Twist (p=0.032), and Hip-Overall (p=0.002) scores. However, Hip-Repetition (p=0.182) and Hip-Asymmetry (p=0.615) scores did not differ significantly among KL grades.

Subsequent Dunn–Bonferroni post hoc analyses identified significantly lower Hip-Twist scores in participants with KL Grade 4 KOA than in the control group (p=0.012). Furthermore, Hip-Overall scores were significantly lower in participants with KL Grade 2, KL Grade 3, and KL Grade 4 KOA than in controls (p=0.002, p=0.040, and p=0.032, respectively). No significant pairwise differences were identified for Hip-Flow despite the significant overall group effect.

The distribution of hip movement quality outcomes across KOA severity groups is presented in Table 2.

Spinal Movement Quality

Analysis of spinal movement quality demonstrated relatively limited alterations across KOA severity groups. Among the evaluated spinal parameters, only Spine-Flow exhibited a significant overall group difference (p=0.024). Despite this overall effect, Dunn–Bonferroni post hoc analyses did not identify statistically significant pairwise differences between specific KL grades. No significant differences were observed in the remaining spinal movement quality parameters, including Spine-Control, Spine-Repetition, Spine-Asymmetry, Spine-Twist, and Spine-Overall scores (all p>0.05).

The distribution of spinal movement quality outcomes across KOA severity groups is presented in Table 2.

DISCUSSION

The present study investigated the association between radiographic knee osteoarthritis (KOA) severity and proximal kinematic chain movement quality using an artificial intelligence (AI)-based markerless motion analysis platform. The principal finding of this study was that hip movement quality progressively deteriorated with increasing radiographic KOA severity despite the absence of radiographic hip osteoarthritis (HOA). Specifically, significant impairments were observed in Hip-Twist and Hip-Overall scores, whereas spinal movement quality remained largely preserved. These findings suggest that proximal biomechanical adaptations occur during KOA progression and may be detectable before structural degeneration develops in adjacent joints.[17]

Traditionally, KOA has been considered a localized degenerative disorder primarily affecting the tibiofemoral joint.[18,19] However, contemporary biomechanical research increasingly supports the concept that KOA influences the entire lower-extremity kinematic chain.[4,5] Alterations in lower-limb alignment, joint loading, neuromuscular control, and intersegmental coordination have all been reported in

Table 2. Comparison of hip and spinal C.R.A.F.T. scores according to Kellgren–Lawrence grade

Variable	Control (n=21)	KL Grade 1 (n=32)	KL Grade 2 (n=63)	KL Grade 3 (n=40)	KL Grade 4 (n=21)	Total (n=177)	p
Hip-Repetition	7.6±1.7	6.4±2.9	6.6±2.6	5.7±2.9	5.8±3.3	6.4±2.7	0.182
Hip-Asymmetry	7.5±1.9	8.4±1.4	7.5±2.5	7.7±2.5	7.8±2.2	7.8±2.2	0.615
Hip-Flow	8.5±2.0	8.8±1.3	8.1±1.6	8.2±2.3	8.4±1.2	8.3±1.8	0.011
Hip-Twist	7.7±1.6	6.2±2.8	6.2±2.8	6.0±3.1	4.6±3.3	6.1±2.9	0.032
Hip-Overall	8.1±1.0	7.5±1.4	7.2±1.4	7.0±1.7	6.6±1.3	7.2±1.5	0.002
Spine-Control	4.5±3.3	4.0±3.3	4.9±3.4	3.9±3.9	3.5±3.1	4.2±3.3	0.412
Spine-Repetition	7.7±1.7	6.8±2.5	7.0±2.5	6.4±2.6	5.4±3.1	6.7±2.6	0.179
Spine-Asymmetry	5.9±2.1	6.4±2.3	6.6±2.6	8.5±1.3	5.7±2.7	6.8±2.7	0.189
Spine-Flow	8.0±2.2	9.0±0.6	8.5±1.2	8.4±1.9	8.5±1.1	8.5±1.5	0.024
Spine-Twist	4.5±2.9	4.0±3.2	4.8±3.4	4.2±3.5	3.7±3.3	4.3±3.3	0.324
Spine-Overall	5.7±1.6	5.7±1.7	6.1±1.9	5.8±2.2	5.1±2.0	5.8±1.9	0.205

Values are presented as mean±standard deviation for descriptive purposes. Because the data were not normally distributed, group comparisons were performed using nonparametric statistical methods. Group differences were analyzed using the Kruskal–Wallis test, followed by Dunn–Bonferroni post hoc comparisons where appropriate. Higher scores indicate better movement quality and motor control performance. Statistical significance was defined as $p<0.05$. C.R.A.F.T.: Control, Repetition, Asymmetry, Flow, and Twist; KL: Kellgren–Lawrence. Hip-Control is not reported because the MAI Motion platform did not generate a Control subscore for the hip region during the sit-to-stand task.

individuals with progressive disease severity.[5,20,21] Recent evidence indicates that dynamic biomechanical variables provide more clinically meaningful information than static radiographic parameters alone because they capture functional adaptations occurring during daily activities.[17] The findings of the present study support this perspective by demonstrating measurable deficits in hip movement quality despite the absence of radiographic hip pathology.

One of the most notable findings was the progressive decline in Hip-Overall movement quality beginning at moderate stages of radiographic disease. Significant differences were observed between controls and the KL Grade 2, 3, and 4 groups, suggesting that functional deterioration of proximal segments emerges relatively early during disease progression. This observation aligns with previous investigations demonstrating altered lower-extremity coordination and compensatory movement strategies among individuals with KOA.[4] Chai et al.[4] reported impaired interjoint coordination among the hip, knee, and ankle during stair ascent in individuals with KOA, indicating that disease-related biomechanical adaptations extend beyond the affected joint itself. Similarly, Bytyqi et al.[6] demonstrated altered three-dimensional gait kinematics characterized by abnormal frontal-plane alignment and rotational mechanics in patients with medial KOA. Together, these studies support the concept that KOA should be viewed as a disorder of integrated movement rather than as an isolated articular pathology.[4,6]

The deterioration observed in Hip-Twist scores may be particularly important from a biomechanical perspective. Rotational control plays a critical role in maintaining lower-extremity alignment and efficiently distributing loads across the kinetic chain.[5,9] Reduced rotational quality may reflect impaired neuromuscular control, altered motor strategies, or compensatory adaptations developed to minimize painful knee loading.[22] Previous biomechanical studies have shown that medial KOA is frequently associated with abnormal frontal- and transverse-plane mechanics,[5] including increased knee adduction moments, dynamic varus thrust, altered tibial rotation, and modified foot progression angles.[5] The significant reduction in Hip-Twist scores observed in advanced KOA may therefore represent an objective marker of progressive kinetic-chain dysfunction.

Another possible explanation for declining hip movement quality involves hip abductor dysfunction.[8] Hip abductors contribute substantially to pelvic stability, frontal-plane control, and force transmission during weight-bearing activities.[8] Weakness of these muscles has been associated with altered lower-extremity alignment and increased medial compartment loading.[5,8] Kini et al.[8] demonstrated a significant relationship between reduced hip abductor strength and higher KL grades in individuals with bilateral KOA. Likewise, recent rehabilitation studies have shown that interventions targeting the hip abductors improve postural stability, dynamic balance, and functional performance in

patients with KOA.[7] Although muscle strength was not directly measured in the present investigation, deterioration in Hip-Overall and Hip-Twist scores may partially reflect declining neuromuscular function of the hip musculature as disease severity increases. This interpretation is consistent with evidence that mediolateral (frontal-plane) balance is governed primarily by the hip abductor–adductor load/unload mechanism,[23] underscoring the role of the hip as the principal frontal-plane controller, whose dysfunction would be expected to manifest as reduced rotational movement quality.

A further question concerns why, among the hip C.R.A.F.T. dimensions, significant differences emerged for Flow and Twist but not for Repetition or Asymmetry. It should first be noted that the MAI Motion platform did not generate a discrete Hip-Control subscore for the sit-to-stand (STS) task, so Control could not be evaluated at the hip. Of the remaining dimensions, those that discriminated among KL grades were precisely those capturing dynamic, whole-movement rotational behavior, whereas the nonsignificant dimensions reflected within-trial consistency or between-side balance, which this task tends to preserve. Hip-Twist, which quantifies transverse- and frontal-plane rotational dynamics, showed the steepest gradient of any hip metric, declining from 7.7 in controls to 4.6 in KL Grade 4, an approximately 40% reduction; frontal- and transverse-plane hip control is the domain most directly implicated in medial KOA through mechanisms such as increased knee adduction moment, dynamic varus thrust, and altered tibial rotation, making it the mechanistically expected locus of the earliest measurable deficit. Hip-Flow, which integrates temporal smoothness across the entire movement, is sensitive to the slowed, segmented pacing adopted to offload the painful knee, yielding a significant overall effect; the absence of significant pairwise differences after correction most likely reflects the conservative Dunn–Bonferroni adjustment rather than a true absence of a trend. By contrast, Asymmetry and Repetition were relatively preserved: the STS task performed with the feet positioned shoulder-width apart is quasi-symmetric, so between-side asymmetry indices are attenuated when compensation is shared across both limbs; Repetition reflects intratrial reproducibility across the three cycles rather than the magnitude of any single deviation and can remain stable even as overall quality declines; and both dimensions had high baseline values, leaving limited dynamic range and suggesting a possible ceiling effect. This pattern is also consistent with motor-control accounts of the STS transition: uncontrolled-manifold analysis indicates that the nervous system preferentially stabilizes the sagittal-plane center of mass while leaving other degrees of freedom less tightly regulated,[24] which may explain why deficits emerge selectively in specific movement-quality dimensions. These interpretations remain hypothesis-generating in the absence of kinetic and electromyographic confirmation.

Interestingly, spinal movement quality remained relatively stable across disease stages, with only Spine-Flow demonstrating a significant overall difference. However, no significant pairwise differences were identified in the post hoc analysis. These findings suggest that compensatory adaptations associated with knee osteoarthritis (KOA) may initially occur primarily at the hip rather than at the trunk or spine.[10] From a biomechanical standpoint, this observation is reasonable because the hip represents the first major proximal joint capable of modifying lower-extremity loading strategies.[10] The trunk may become substantially involved only when compensatory mechanisms at more distal segments become insufficient.[25] Previous studies have reported increased trunk lean and altered center-of-mass control in individuals with severe KOA; however, such changes may be task-specific and less consistently detectable than hip-related alterations.[10,11,26]

The current findings also highlight the potential value of markerless motion capture technologies in musculoskeletal assessment.[12,13] Traditional biomechanical evaluation typically requires laboratory-based systems that use multiple cameras, reflective markers, force platforms, and specialized personnel.[27] Although these systems remain the gold standard, their cost and complexity limit widespread clinical adoption.[28] Advances in computer vision and artificial intelligence (AI) have enabled the development of markerless systems capable of quantifying movement quality in routine clinical environments.[13] Recent validation studies have demonstrated acceptable reliability and validity of markerless motion capture for assessing lower-extremity kinematics during functional tasks.[13–15,29] Systematic reviews have further concluded that markerless systems provide reliable measurements for many clinically relevant kinematic variables and may facilitate large-scale functional screening outside specialized laboratories.[13,30]

MAI Motion represents one such technological advancement.[15] Unlike conventional biomechanical systems that focus primarily on joint angles, MAI Motion evaluates broader aspects of movement quality through the C.R.A.F.T. framework, incorporating control, repetition, asymmetry, flow, and rotational dynamics.[15] The ability of this framework to identify significant differences across KOA severity groups suggests that movement-quality metrics may capture functional deterioration that is not readily apparent on radiographic imaging.[17] This finding is consistent with growing evidence indicating that functional impairment and biomechanical adaptation may precede observable structural changes.[8,17]

The discrepancy between radiographic findings and movement

quality observed in this study deserves particular attention. All participants were free of radiographic hip osteoarthritis (HOA), yet significant reductions in hip movement quality were detected with increasing KOA grades. This observation supports the notion that biomechanical dysfunction may emerge before structural degeneration becomes radiographically visible.[17] Consequently, markerless motion analysis may offer opportunities for earlier identification of individuals at risk of developing secondary biomechanical impairments or adjacent-joint degeneration.[27,30]

From a clinical perspective, these findings have important implications. Early identification of proximal kinematic chain dysfunction may allow clinicians to implement targeted interventions before severe biomechanical deterioration occurs.[31] Rehabilitation strategies focusing on hip strength, neuromuscular control, movement coordination, and rotational stability may potentially reduce compensatory movement patterns and improve functional outcomes.[7] Furthermore, objective monitoring of movement quality may provide a useful adjunct to conventional radiographic assessment when evaluating disease progression or treatment response.[17] Because the present kinematic data cannot establish which specific impairments should be targeted, such strategies should be regarded as hypotheses requiring validation through kinetic and electromyographic assessment.

Limitations

Several limitations should be acknowledged. First, the cross-sectional design precludes determination of causal relationships between knee osteoarthritis (KOA) progression and deterioration in movement quality. Longitudinal investigations are necessary to establish whether declining hip movement quality precedes or follows structural disease progression. Second, the absence of direct measurements of muscle strength, pain severity, and functional performance limits interpretation of the mechanisms underlying the observed findings. Third, movement quality metrics were obtained using a single assessment platform, and comparisons with laboratory-based motion capture systems were not performed. Finally, demographic variables and potential confounding factors, such as physical activity level and symptom duration, should be explored in future research. In addition, several constraints arise from the measurement platform and study scope. The analysis was based solely on kinematically derived movement-quality indices; joint kinetics (net moments and torques), external force-plate data, and electromyography were not acquired, precluding inference regarding the neuromuscular mechanisms underlying the observed deficits and any prescriptive rehabilitation recommendations based on these data alone. The C.R.A.F.T. scores are composite indices that are not referenced to estimated joint torques, so their individual dimensions cannot be interpreted as mechanically independent constructs. Side-resolved (left/right) decomposition of the hip and knee scores and the associated knee–hip correlational analyses could not be extracted within the current workflow, limiting inferences regarding laterality and intersegmental coupling; these represent important directions for future research. Similarly, per-frame joint-angle time series could not be exported from the platform, precluding presentation of representative frontal-plane (abduction–adduction) angle trajectories across severity grades. Finally, radiographic severity was classified based on the index knee only. Furthermore, the proportion of female participants increased markedly with radiographic severity (from 28.6% in controls to 90.5% in Kellgren–Lawrence [KL] Grade 4; $p<0.001$), and this uneven sex distribution may itself influence movement-quality metrics; future analyses should therefore adjust for or stratify by sex and ideally incorporate pain, muscle strength, and physical activity covariates alongside kinetic and electromyographic measurements within a longitudinal design. Several of these constraints reflect specific limitations of the markerless motion analysis platform used and directly constrained the additional analyses requested during peer review. Because the system did not permit export of side-resolved (left/right) hip or knee scores, a laterality table, a KL-grade-by-side analysis (e.g., an aligned-rank-transform analysis of variance [ANOVA] or a rank-based mixed model), and left/right knee–hip Spearman correlations could not be performed. Because the platform does not compute a Control subscore for the hip, Hip-Control could not be reported. Because per-frame joint-angle time series are not exportable, representative frontal-plane (abduction–adduction) angle trajectories across severity grades could not be presented. Finally, although the platform generates a knee-region composite score, knee scores were not incorporated into the present analysis; this decision and the inability to resolve scores by side are acknowledged as limitations of the motion analysis system and as priorities for future research using platforms or laboratory systems that provide side-resolved and angle-level data.

Despite these limitations, the present study provides novel evidence that increasing radiographic severity of KOA is associated with progressive deterioration in hip movement quality, even in the absence of hip osteoarthritis (HOA). The findings further demonstrate the utility of artificial intelligence (AI)-based markerless motion analysis for quantifying clinically relevant biomechanical alterations in routine practice.

CONCLUSION

Radiographic severity of KOA was associated with deterioration in hip movement quality, particularly in rotational dynamics and overall movement performance, despite the absence

of radiographic HOA. In contrast, spinal movement quality remained largely preserved across disease stages. These findings support the concept that KOA affects the broader proximal kinetic chain and that functional biomechanical adaptations extend beyond the affected joint itself. Because the approach requires only a single conventional red-green-blue (RGB) camera and no markers or laboratory infrastructure, it is well suited for large-scale, low-cost screening in community and outpatient settings, where earlier detection of proximal compensation could help prioritize patients for closer biomechanical evaluation. Given the cross-sectional and kinematic nature of the present data, however, these inferences remain associative and require confirmation through longitudinal studies incorporating kinetic and electromyographic measurements.

AI-based markerless motion analysis detected these alterations and may represent a practical and objective tool for assessing movement quality in clinical settings. Early identification of proximal biomechanical dysfunction may facilitate targeted rehabilitation strategies aimed at preserving movement quality and slowing functional decline throughout the progression of KOA. Hip osteoarthritis can be a comorbidity of KOA. Movement may deteriorate before clinical and radiologic symptoms appear. Early intervention for the treatment of KOA should therefore be considered whenever available.

Ethics Committee Approval: Ethics committee approval was obtained from Hacettepe University Non-Interventional Clinical Research Ethics Committee (Approval Number: 2025/21-22, Date: 11.11.2025).

Informed Consent: Written informed consent was obtained from all participants prior to enrollment in the study. All participants were informed about the study procedures, potential risks, and benefits, and voluntarily agreed to participate.

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