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Medial Compartment Knee Contact Force During Gait Reflects Symptom Severity in Advanced Knee Osteoarthritis

Takaya Watabe[1,2*], Ryota Muramatsu[1], Yuta Taniguchi[3]

Affiliations:

[1]Section of Rehabilitation, Kanazawa University Hospital 13-1 Takaramachi, Kanazawa 920-8641, Ishikawa, Japan
[2]Institute of Science & Engineering, Kanazawa University, Kakuma-Machi, Kanazawa 920-1192, Ishikawa, Japan
[3]Department of Orthopedic Surgery, Graduate School of Medicine Sciences, Kanazawa University, 13-1 Takaramachi, Kanazawa 920-8641, Ishikawa, Japan
[*]Corresponding author: Takaya Watabe, Section of Rehabilitation, Kanazawa University Hospital 13-1 Takaramachi, Kanazawa 920-8641, Ishikawa, Japan, Institute of Science & Engineering, Kanazawa University, Kakuma-Machi, Kanazawa 920-1192, Ishikawa, Japan, e-mail address: takaya.watabe.pt@gmail.com

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Abstract

***Purpose*:** Patients with moderate-to-severe knee osteoarthritis commonly adopt altered gait patterns. A better understanding of how the medial compartment knee contact force during specific phases of gait reflects symptom burden and functional limitations may clarify the biomechanical mechanisms underlying disease progression. This study aimed to investigate the correlation between medial compartment knee contact force during gait and physical function, patient-reported outcome measures, and imaging findings in patients with knee osteoarthritis.

Methods: Thirteen patients with advanced knee osteoarthritis (Kellgren–Lawrence grade ≥ 3) walked a 5-m path at a self-selected speed. Physical function was assessed using passive knee range of motion, muscle strength, pain scores, and walking speed. Self-reported outcomes and imaging data, including medial meniscal extrusion and quadriceps measurements were obtained. Gait kinematic data were collected using markerless motion capture, and the knee contact forces were estimated using a musculoskeletal modeling system.

Results: The medial compartment knee contact forces during early and late stance were 1340.45 N and 984.54 N, respectively. Late stance force showed significant negative correlations with knee flexion range of motion and symptom scores ($r < -0.737$ and $r < -0.604$, respectively; $P < 0.05$). No correlations were observed in the early stance force.

Conclusions: Greater medial knee contact force during the late stance phase was correlated with reduced mobility and greater symptom severity. Late-stance mechanics may be a valuable target for knee osteoarthritis management.

Keywords: Knee osteoarthritis, Gait, Knee contact force, Musculoskeletal model

Introduction

Osteoarthritis (OA) of the knee is a prevalent, age-related condition characterized by pain, stiffness, and reduced knee function [26]. Given the increasing prevalence of KOA in aging populations and its substantial socioeconomic burden, identifying the biomechanical and clinical factors associated with disease progression is of great clinical relevance. Research indicates that physical function in patients with symptomatic knee OA (KOA) is more strongly predicted by the severity of self-reported symptoms than by the structural changes observed on radiography [19], [22], [23]. An association between gait biomechanics and knee-related symptoms in patients with KOA has been established. Therefore, gait biomechanics and self-reported knee-related symptoms offer valuable insights into strategies aimed at slowing disease progression and preserving physical function in KOA.

Aberrant knee joint loading has been identified as a contributor to KOA progression in advanced stages [13], [15]. Increased medial compartment loading is associated with more severe clinical symptoms and radiographic evidence of disease [8], [35]. Most studies have employed the knee adduction moment (KAM), the external frontal plane moment at the knee joint, as an indirect measure of the knee contact force (KCF), which represents the total compressive load across the joints. Specifically, the medial compartment KCF (KCF_{med}) refers to the portion of this load transmitted through the medial compartment during functional activities [3], [5], [10], [24]. However, data from instrumented knee implants show substantial variation in the correlation between KAM and KCF_{med} due to high inter-individual variability [11]. Thus, relying solely on KAM may not adequately capture the true magnitude of medial joint loading or its relationship with clinical outcome.

Musculoskeletal modeling systems combined with dynamic motion data have been employed to calculate KCF_{med} [6], [15], [30]. In individuals with varus malalignment, the KCF_{med} during walking increases, whereas the lateral KCF (KCF_{lat}) decreases [33]. Musculoskeletal modeling has been increasingly applied to estimate KCF_{med}; however, few studies have investigated the correlation between internal joint forces and patient-reported knee symptoms and functional outcomes [30] [33]. This knowledge gap is particularly important in moderate-to-severe KOA, where patients typically adopt altered gait strategies. Understanding how KCFmed at specific phases of the gait cycle reflects symptom burden and functional impairment is crucial for advancing biomechanical insights and informing targeted rehabilitation strategies.

Consequently, in this study, we aimed to examine the correlation between KCF during gait and clinical characteristics in patients with medial compartment KOA. These characteristics include knee-related symptoms, joint range of motion (ROM), and muscle strength (MS). We hypothesized that KCF_{med} during the late stance phase would be negatively correlated with knee-related symptoms, indicating that greater symptom severity is correlated with increased medial joint loading.

Materials and Methods

Study participants

This prospective observational study was conducted in the Department of Orthopaedic Surgery at the Kanazawa University Hospital, Japan. All patients presented with radiographic evidence of medial compartment KOA and were diagnosed with Kellgren–Lawrence (K–L) grade ≥ 3 by an orthopaedic surgeon (Figure 1). The inclusion criteria were as follows: (1) no history of surgery on either limb; (2) no neurological or balance disorders requiring assistive devices; and (3) ability to walk independently, without an assistive device, in daily life. Predominant lateral or patellofemoral osteoarthritis, previous or planned hip replacement, hip or ankle arthritis, and rheumatoid arthritis were exclusion criteria. Thirteen patients with KOA who met the inclusion and exclusion criteria were consecutively recruited between February 2024 and November 2024 (Table 1). All data were collected on-site by experienced orthopedic surgeons and physical therapists trained in the study protocol. The study protocol and procedures were approved by the University Committee on Ethics in Research of Kanazawa University (approval number: 113786). This study was conducted in accordance with the principles of the Declaration of Helsinki and the reporting guidelines. Written informed consent was obtained from the patients for the publication of their deidentified data and images.

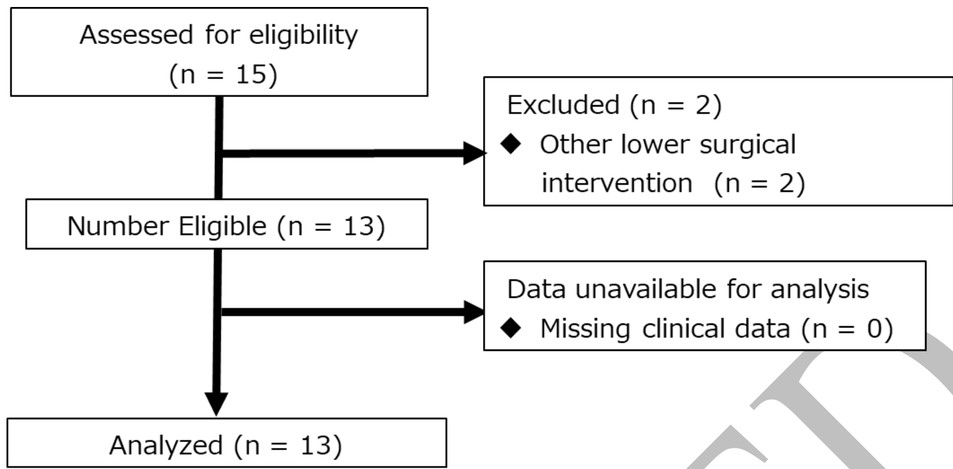

Figure 1 Flow diagram of patient selection for the study.

Table 1. Demographic and Clinical Characteristics of Patients with Knee Osteoarthritis

Characteristics	N or Mean (SD)
Sex, Male: Female	5: 8
Age (years)	70.5 (5.3)
Height (cm)	155.4 (10.3)
Weight (kg)	62.6 (8.7)
BMI (kg/m^2)	26.2 (4.5)
Kellgren–Lawrence Grade	III: 8; IV: 5

BMI= body mass index; SD= standard deviation.

Physical Function Assessment

Passive ROM was measured by licensed physical therapists using a goniometer (Toudaisiki Goniometer; OG Wellness Co., Ltd., Okayama, Japan). Quadriceps and hamstring strength were assessed using a handheld dynamometer (Tas F-1; ANIMA, Tokyo, Japan) employing a validated technique [29]. Knee pain at rest and during walking was recorded using the numerical rating scale (NRS), which ranges from 0 to 10, where 0 indicates no pain and 10 indicates the worst possible pain [17]. Walking speed over a 10-m distance was measured at a comfortable pace along a 14-m straight path that included a 2-m lead-in and an exit zone. The time to complete the 10-m walk was recorded using a stopwatch [32].

Japanese Knee Injury and Osteoarthritis Outcome Score (KOOS)

Patients completed the Japanese version of the KOOS while waiting for their initial consultation at our institution. Medical staff did not assist or influence the patients while completing their questionnaires, and only the patients' responses were recorded. The KOOS includes five subscales and serves as a patient-reported outcome measure (PROM) for patients with any knee disorder, allowing assessment of the effects of various conditions [20], [21]. Each question was scored on a five-point scale, with increments of 5, with 0 and 100 representing the worst and best conditions, respectively. The average score of all questions within each subscale was calculated to determine that subscale's score. Therefore, each subscale had a minimum and maximum score of 0 and 100, respectively.

Magnetic Resonance Imaging (MRI) and Radiological Evaluation

MRI was performed using a 1.5-T system (Singa HDxt; GE, Boston, MA, USA), with a 3-mm slice thickness and 1-mm interslice gap. Medial meniscal extrusion (MME) was defined as the displacement of the medial meniscus beyond the innermost border of the tibial plateau, assessed in the coronal plane of the knee joint [9]. Extrusion of the medial meniscal body was measured using validated methods, which implemented Synapse Vincent software (Fuji Films, Tokyo, Japan). The measurement procedure involved three steps: (1) placing a perpendicular line at the point where the medial tibial plateau transitions from horizontal to vertical; (2) placing a second perpendicular line intersecting the outermost edge of the medial meniscus; and (3) calculating the extrusion distance in millimeters between the two perpendicular lines (Figure 2A).

Muscle quantity was evaluated by measuring the cross-sectional area (CSA) on computed tomographic (CT) imaging. Scans were obtained at the mid-thigh level, defined as the midpoint between the superior pole of the patella and inguinal crease, using the following settings: 120 kV, 120 mA, 1-s rotation time, and a 233-mm field of view. Image analysis was performed using EV Insite software (PSP Corporation, Tokyo, Japan) [14], [28]. For each patient, manual segmentation of the vastus medialis, vastus lateralis, vastus intermedius, and rectus femoris was conducted to calculate the CSA of each muscle (Figure 2B).

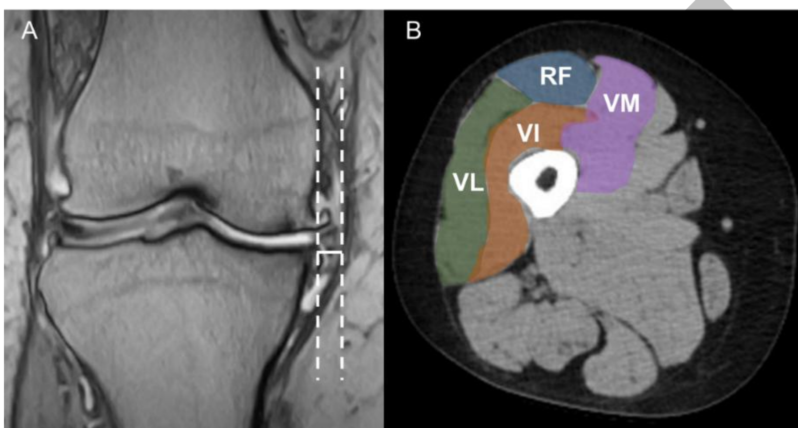

Figure 2 Measurement of medial meniscal extrusion and quadriceps femoris.
(A) Measure meniscal extrusion as the distance between the two perpendicular lines. (B) Measurement of quadriceps femoris using computed tomography. Abbreviations: RF = Rectus femoris; VM = Vastus medialis; VL = Vastus lateralis; VI = Vastus intermedius.

Gait Assessment by Motion Capture

After a static trial to calibrate the gait model, the patients walked along a 5-m path at a comfortable speed. Kinematic data during walking were collected using a markerless motion capture system (OpenCap, Oxford, UK) operated using two mobile devices (iPhone XS and iPhone 13; Apple, USA) [25]. Each mobile device was positioned approximately 4 m in front of the patient and spaced 3 m apart at a 45° angle. OpenCap system calibration (OpenCap, Oxford, UK) was performed by placing a 720 × 540 mm checkerboard, obtained directly from the OpenCap website, perpendicular to the floor on a 90 cm chair at the center. This setup established a global coordinate system. The OpenCap system captured motion data at 60 Hz and uploaded them to a laptop for cloud-based joint kinematic analysis [12]. The patients performed five practice trials, and the variables were averaged from the three successful trials used in the analysis.

Musculoskeletal Model

We used the AnyBody Modeling System version 7.4 (AnyBody, Aalborg, Denmark) to estimate KCF_{med} and KCF_{lat}. The model included 11 segments: pelvis, bilateral femurs, patellae, shanks, talus, and feet. Each lower limb model contained 55 muscles represented by 169 muscle elements based on the Hill model. To divide the total internal knee joint contact force into medial and lateral compartments, the model incorporated 12 nodes distributed evenly across the scaled medial and lateral tibial condyles to calculate the joint reaction forces, in addition to the knee center [15], [33]. We defined the medial and lateral internal contact forces as the sum of the reaction forces measured at the 12 nodes and reported them as KCF_{med} and KCF_{lat}, respectively. For further analysis, we extracted the peak values of KCF_{med} and KCF_{lat} during the first (KCF_{med_p1} and KCF_{lat_p1}) and second (KCFmed_p2 and KCFlat_p2) halves of the stance phase (Figure 3).

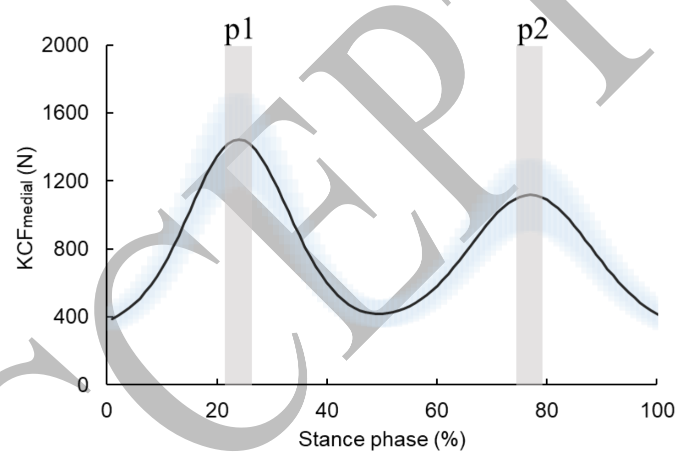

Figure 3 Time profiles of Knee contact force on the medial compartment.
Averaged across subject data are shown with standard deviation shades from initial contact (0%) to toe off (100%) of the more affected side. We extracted the peak values of KCFmed and KCFlat during the first (p1) and second halves of the stance phase (p2).
Abbreviations: KCFmed = medial compartment knee contact force; KCFlat = lateral compartment knee contact force.

Data Analysis

As a preliminary step to examine the correlation between physical function variables and KCF during gait, the normality of the continuous variables was confirmed using the Shapiro–Wilk test. Pearson's correlation analyses were performed to test the correlation between KCF and Clinical, Functional, and Imaging Variables. IBM SPSS Statistics for Windows, version 29.0.1.0 (IBM Corp., Armonk, NY, USA) was used for all statistical analysis. Statistical significance was set at $P < 0.05$.

Results

Tables 1 and 2 present the demographic and physical characteristics of the 13 patients included in this study. The mean femorotibial angle (FTA) was 188.96°, and the mean MME was 3.94 mm (Table 3). The mean KCFs during the first and second halves of the stance phase were as follows: KCF_{med_p1} = 1340.45 N; KCF_{med_p2} = 984.54 N; KCF_{lat_p1} = 474.18 N; and KCF_{lat_p2} = 255.71 N (Table 4).

Regarding the primary outcome of this study, KCF_{med_p2} was negatively correlated with knee flexion ROM ($r < -0.737$, $P = 0.004$) and KOOS scores ($r < -0.604$, $P = 0.029$) (Table 5). In contrast, KCF_{med_p1} showed no significant correlations with physical characteristics, PROMs assessed using the KOOS, or MRI and CT findings ($P > 0.050$).

Table 2. Physical Characteristics and Patient-Reported Outcome Measures in Patients with Knee Osteoarthritis

Variable	Mean (SD)	95% Confidence Interval	
		Lower	Upper
Knee Flexion Range of Motion, °	109.23 (15.79)	100.65	117.81
Knee Extension Range of Motion, °	-7.69 (4.65)	-5.17	-10.21
Quadriceps Strength, N/kg	3.32 (1.50)	2.50	4.41
Hamstrings Strength, N/kg	1.68 (0.51)	1.41	1.96
Resting Numerical Rating Scale	2.23 (1.67)	1.32	3.14
Walking Numerical Rating Scale	3.77 (1.18)	3.12	4.41
Self-Selected Walking Speed, m/s	0.96 (0.19)	0.86	1.06
PROMs			
KOOS Symptoms	59.06 (13.98)	51.46	66.64
KOOS Pain	55.34 (16.61)	46.31	64.37
KOOS ADL	57.24 (13.27)	50.02	64.45
KOOS Sport/Rec	23.62 (14.44)	15.77	31.47
KOOS QOL	26.63 (14.36)	18.82	34.44

KOOS= Knee Injury and Osteoarthritis Outcome Score; PROMs= patient-reported outcome measures; ADL= activities of daily living; QOL= quality of life; Sport/Rec= function in sport and recreation; SD= Standard deviation.

Table 3. Magnetic Resonance Imaging and Radiographic Assessment Data

Variable	Mean (SD)	95% Confidence Interval	
		Lower	Upper
Femorotibial Angle, °	188.96 (4.88)	186.30	191.61
Medial Meniscus Extrusion, cm	3.94 (0.89)	3.45	4.43
Vastus Medialis, cm^2	43.21 (2.82)	41.68	44.75
Vastus Lateralis, cm^2	18.96 (1.16)	18.33	19.59
Vastus Intermedius, cm^2	17.11 (1.09)	16.52	17.71
Rectus Femoris, cm^2	6.38 (0.45)	6.14	6.63

SD= standard deviation.

Table 4. Medial and Lateral Knee Contact Forces (KCF) During the Gait Task

Variable	Mean (SD)	95% Confidence Interval	
		Lower	Upper
KCF_{med_p1} (N)	1340.45 (343.44)	1153.75	1527.15
KCF_{med_p2} (N)	984.54 (195.42)	878.30	1090.77
KCF_{lat_p1} (N)	474.18 (222.89)	353.01	595.35
KCF_{lat_p2} (N)	255.71 (72.69)	216.19	295.23

KCF_{med}= medial knee contact force; KCF_{lat}, lateral knee contact force; SD= standard deviation.

Table 5. Correlation Coefficients Between Medial Knee Contact Force and Clinical, Functional, and Imaging Variables

Variable	KCF_{med_p1}	KCF_{med_p2}
Knee Flexion Range of Motion, °	-0.425	**-0.737***
Knee Extension Range of Motion, °		-0.228
Quadriceps Strength, N/kg	-0.064	-0.079
Hamstrings Strength, N/kg	-0.289	-0.236
Resting Numerical Rating Scale	-0.545	-0.171
Walking Numerical Rating Scale	-0.355	0.007
PROMs		
KOOS Symptoms	-0.128	**-0.604***
KOOS Pain	0.198	-0.164
KOOS ADL	-0.072	-0.450
KOOS Sport/Rec	0.033	-0.077
KOOS QOL	0.274	0.098
MRI and radiological evaluation		
Femorotibial Angle	0.458	0.192
Medial Meniscus Extrusion	0.304	0.309
Vastus Medialis, cm^2	-0.186	-0.133
Vastus Lateralis, cm^2	-0.271	-0.040
Vastus Intermedius, cm^2	0.080	0.305
Rectus Femoris, cm^2	0.189	0.256

KCF_{med}= medial knee contact force; PROMs= patient-reported outcome measures; KOOS= Knee Injury and Osteoarthritis Outcome Score; ADL= activities of daily living; QOL= quality of life; Sport/Rec= function in sports and recreation; MRI= Magnetic resonance imaging. *$p < 0.050$

Discussion

In this study, the peak KCF_{med_p2} demonstrated notable correlations with both passive knee flexion ROM and the KOOS. However, no meaningful correlations were observed between KCF_{med_p1} and any physical assessment or PROM. Our findings partially support the hypothesis that more severe self-reported knee symptoms are correlated with increased medial knee joint loading during the late stance phase of gait. This is the first study to demonstrate that self-reported knee symptoms are specifically associated with increased medial knee joint loading during the late stance phase of gait.

Patients with KOA demonstrated a peak KCF_{med_p2} that was considerably correlated with passive knee flexion ROM. A previous study found that patients with KOA who present with more severe symptoms exhibit higher KCF_{med_p2} levels than those with mild symptoms [2, 33], which is consistent with our findings. However, unlike earlier studies that primarily linked joint loading with radiographic severity, our results extend this evidence by demonstrating a direct association with passive joint mobility, suggesting that reduced knee flexion ROM may serve as a functional marker for elevated medial loading. From a biomechanical perspective, walking with a straighter knee reduces the ability of the quadriceps to eccentrically absorb impact forces, which increases vertical ground reaction forces and contributes to greater compressive loading at the knee joint [18]. These biomechanical adaptations may contribute to the progression of joint degeneration in patients with medial compartment KOA.

The observed negative correlation between KCFmed_p2 and KOOS also supports prior reports that greater knee joint loading is associated with worse self-reported symptoms [4, 27]. Importantly, to our knowledge, our study is the first to show that patient-reported outcomes correlate with objective loading measures during the late stance phase, emphasizing the clinical relevance of gait mechanics in understanding symptom severity. This extends earlier biomechanical studies by integrating PROMs into the analysis, thereby bridging subjective symptoms and objective joint loading data. A possible biomechanical explanation for the absence of a correlation between KCF_{med_p1} and clinical or structural measures relates to the early stance phase, which is primarily governed by passive dynamics rather than by active neuromuscular control. During the initial loading response, which occurs within the first 0%–15% of the gait cycle, the body weight is rapidly transferred to the stance limb [34]. At this stage, knee flexion is limited, and the ground reaction force vector is largely determined by the initial contact angle and the overall limb alignment. Because muscle activity, particularly that of the quadriceps and hamstrings, contributes minimally to joint loading during this brief phase of gait [16], variations in strength, joint ROM, or pain-related adaptations may have a limited influence on KCF_{med_p1}. Moreover, individual differences in heel-strike mechanics may contribute to variability in loading patterns [26], [31], further reducing associations with patient-specific anatomical or symptomatic factors. Therefore, KCF_{med_p1} may reflect a general mechanical response to impact loading, rather than a joint-specific or symptom-driven adaptation.

This is the first study to demonstrate a direct association between patient-reported knee symptoms and medial knee joint loading during the late stance phase of gait in patients with KOA. By integrating biomechanical analysis with patient-reported outcomes, our findings provide novel evidence linking subjective symptom severity with objective gait mechanics. This study advances the current understanding of KOA pathomechanics and highlights the importance of considering both mechanical loading and patient-reported measures in the development of targeted rehabilitation and management strategies.

Study Limitations

This study had some limitations. First, its cross-sectional design limited the ability to infer causal relationships between KCF_{med} and clinical or functional measures. To address this limitation, future research should consider longitudinal designs to monitor changes in KCF_{med} and clinical outcomes over time. Second, the relatively small sample size, which was due to the use of MRI and CT imaging. These techniques are time-consuming and costly, limiting the number of participants that could be included. Future studies with larger cohorts are warranted to confirm these findings. Finally, the estimation of KCFs was based on a musculoskeletal model that assumes constant muscle–tendon properties and simplified joint mechanics. These assumptions may not fully reflect individual variability in joint loading.

Conclusions

This study found that a greater KCF_{med_p2} was correlated with reduced knee flexion ROM and more severe knee symptoms in patients with KOA. These findings suggest that impaired joint mobility and symptom-related gait adaptations may increase medial knee joint loading. Addressing gait mechanics during the late stance phase may be important for managing joint loads in patients with KOA.

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