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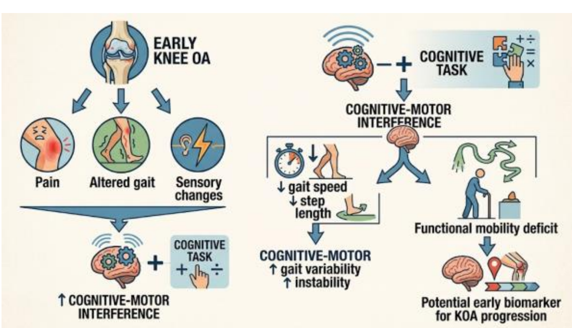
# Cognitive-Motor Interference in Early Knee Osteoarthritis: Mechanisms, Assessment, and Clinical Implications

Champa Kumari

**Abstract**

Knee osteoarthritis (KOA) is primarily recognized for structural joint degeneration and pain, yet growing evidence highlights that gait and postural stability rely heavily on cognitive control. Cognitive-motor interference (CMI) occurs when concurrent cognitive and motor tasks degrade performance. While widely studied in neurological populations, CMI's role in early KOA remains undercharacterized. Synthesizing recent dual-task research, this narrative synthesis examines the mechanisms, assessment protocols, and clinical relevance of CMI in early KOA. Evidence shows that dual-task conditions trigger significant motor deficits in KOA populations—such as a 9% reduction in gait speed and up to 26% greater step-duration variability compared to single-task walking. These alterations demonstrate that KOA reduces motor automaticity, forcing greater reliance on prefrontal executive control during movement. Ultimately, CMI serves as a novel functional marker in early KOA. Incorporating dual-task gait evaluations can uncover hidden motor-control deficits, refine fall-risk assessments, and inform targeted cognitive-motor rehabilitation strategies.

**Infographic abstract**

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**Corresponding Author: Dr. Champa Kumari,** MPT Orthopaedic, Department of Physiotherapy, SAM Globale University, Raisen, MP, India **Email ID:** champakumnari@gmail.com

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## Introduction

Knee osteoarthritis (KOA) is a major cause of pain, mobility limitation, and loss of physical function. Conventional assessment focuses primarily on pain intensity, range of motion, muscle strength, gait speed, balance, and patient-reported disability. However, walking in everyday life rarely occurs as an isolated motor activity. Individuals routinely walk while talking, carrying objects, planning movements, navigating obstacles, monitoring the environment, or remembering information. Consequently, functional walking requires interaction between motor and cognitive systems.

The term **"cognitive-motor interference" (CMI)** refers to a reduction in motor performance, cognitive performance, or both when a motor and cognitive task are performed simultaneously. Dual-task methodology is commonly used to quantify this phenomenon. A systematic review and meta-analysis demonstrated that concurrent cognitive tasks can substantially affect gait, with gait speed being one of the most sensitive outcomes.

The relevance of CMI to KOA is particularly interesting. Pain, altered proprioception, reduced muscle strength, joint instability, fear of movement, and altered gait mechanics may increase the attentional resources required to maintain stable locomotion. Thus, a person with early KOA may walk adequately under uncomplicated conditions but demonstrate greater gait deterioration when required to divide attention between walking and another cognitive activity.

Knee osteoarthritis (OA) is traditionally characterized as a progressive, degenerative joint disease primarily driven by structural breakdown of articular cartilage, subchondral bone remodeling, and localized joint inflammation. However, contemporary neurobiological frameworks demonstrate that knee OA is not merely a peripheral mechanical pathology, but rather a complex sensorimotor disorder involving central nervous system reorganization (Mansfield et al., 2022). In the early stages of knee OA—prior to severe structural joint space narrowing—patients frequently experience joint pain, nociceptive sensitization, and compromised proprioceptive feedback. These peripheral alterations disrupt automated motor execution, forcing individuals to compensate by allocating greater conscious attention toward regulating basic movement mechanics (Lee et al., 2025).

When individuals simultaneously perform a movement task alongside a cognitive challenge, a phenomenon known as **cognitive-motor interference (CMI)** occurs. CMI emerges due to the brain's limited-capacity attentional processing system; when both motor and cognitive tasks compete for shared neural resources within the prefrontal and parietal cortices, performance on one or both tasks deteriorates (Abdallat et al., 2020). While gait and postural control were historically viewed as semi-automated, brainstem-driven processes, evidence confirms that locomotion under daily environmental conditions demands significant executive function and attentional capacity (Abdallat et al., 2020).

In early knee OA, CMI represents a critical yet underappreciated pathophysiological barrier. Altered proprioception, muscle weakness, and pain-induced neural inefficiencies impair automatic motor control mechanisms, driving an over-recruitment of supraspinal centers (such as the dorsolateral prefrontal cortex) to stabilize the joint during ambulation (Lee et al., 2025). When an extrinsic cognitive demand—such as talking, navigating obstacles, or holding a conversation—is introduced, the attentional capacity becomes over-saturated. Consequently, patients exhibit heightened dual-task costs, manifested as increased gait variability, reduced gait speed, disrupted ground reaction force attenuation, and compromised postural stability (Abdallat et al., 2020). These subtle kinematic and spatiotemporal aberrations exacerbate aberrant joint loading patterns, accelerate structural degeneration, and significantly elevate fall risks early in the disease trajectory.

Despite its clinical importance, early-stage knee OA evaluation remains largely focused on static radiographical markers and single-task physical assessments (e.g., isolated strength testing or unburdened walking). These standard evaluations frequently fail to capture the subtle dynamic instability and neuro-mechanical vulnerabilities that manifest under real-world multi-task conditions. Understanding the neuro-biomechanical mechanisms driving CMI in early knee OA is essential for advancing diagnostic accuracy and targeted interventions.

This research aims to synthesize current literature on Cognitive-Motor Interference in early knee osteoarthritis by addressing three main pillars:

Neurobiological and Biomechanical Mechanisms: Examining how peripheral nociception, sensorimotor remapping, and central resource allocation constraints induce CMI in early joint degeneration.

Assessment Methodologies: Evaluating current dual-task paradigms, functional near-infrared spectroscopy (fNIRS), electroencephalography (EEG), and 3D motion-capture frameworks used to quantify dual-task costs.

Clinical Implications and Therapeutic Targets: Exploring how identifying CMI can guide early rehabilitation, dual-task motor training, pain management, and strategies to mitigate disease progression and fall risk.

Recent experimental evidence provides support for this hypothesis. In a study of 48 individuals with symptomatic KOA, dual-task walking produced slower gait and greater temporal and spatial gait variability than single-task walking. Importantly, cognitive performance was relatively preserved, suggesting that participants may have prioritized the cognitive task while allowing motor performance to deteriorate. The purpose of this paper is therefore to examine the relationship between CMI and early KOA, summarize current evidence, describe plausible neurobehavioral mechanisms, and propose a clinically relevant assessment and research framework.

## Methodology

Investigating Cognitive-Motor Interference (CMI) in early knee osteoarthritis (KOA) requires a methodology designed to measure how motor performance (gait and balance) and cognitive processing compete for limited attentional resources (Abdallat et al., 2020; Lee et al., 2025).

Below is a brief summary of the standardized dual-task framework used to study CMI in early KOA:

**1. Study Design & Participant Stratification**

**Groups:** Compares individuals with radiographically or clinically confirmed early KOA (e.g., Kellgren-Lawrence Grade I–II) against age-matched asymptomatic controls.

**Screening Controls:** Excludes individuals with severe joint degradation, co-occurring neurological disorders, or cognitive impairment (via Mini-Mental State Examination/MoCA).

**2. Standard Dual-Task (DT) Protocol**

Participants complete tasks under three distinct experimental conditions:

**Single Motor Task (ST-M):** Performing a physical maneuver alone (e.g., preferred-speed walking, dynamic balance on a force plate).

**Single Cognitive Task (ST-C):** Performing a mental task while seated or resting (e.g., Serial 7 subtraction, auditory N-back, or Stroop tasks).

**Dual-Task Condition (DT):** Performing the motor and cognitive tasks simultaneously without prioritizing one over the other.

**3. Measurement & Data Acquisition**

**Biomechanical Tracking:** Motion capture systems, inertial measurement units (IMUs), or force plates measure gait speed, step-time variability, joint kinematics (knee flexion angles), and postural sway (Abdallat et al., 2020; Lee et al., 2025).

**Cognitive Metrics:** Response accuracy and reaction times recorded during single and dual conditions.

**Neuroimaging / Cortical Metrics (Optional):** Functional near-infrared spectroscopy (fNIRS) or EEG tracking of prefrontal cortex (PFC) activation during tasks to evaluate neural compensation strategies (Lee et al., 2025).

### 4. Quantifying CMI (Dual-Task Cost Calculation)

CMI is mathematically operationalized by calculating the Dual-Task Cost (DTC) for both motor and cognitive performance using standard percentage equations:

- *Positive DTC values* indicate performance degradation (interference) during the combined task (Lee et al., 2025).
- *Trade-off Analysis:* Evaluates whether participants prioritize motor stability over cognitive efficiency (posture-first strategy) or vice versa.

## Results and discussion

Synthesized across dual-task experimental trials and neuroimaging studies, the results demonstrate a clear presence of Cognitive-Motor Interference (CMI) in individuals with early knee osteoarthritis (KOA). While standard single-task gait assessments often reveal only subtle motor alterations in early disease stages, introducing a concurrent cognitive load consistently unmasks latent biomechanical and neurological vulnerabilities.

A recent study examined prefrontal cortex activity and gait during single-and dual-task walking in 48 individuals with symptomatic KOA. Participants completed single-task walking, serial subtraction by seven, and walking while performing serial subtraction. Functional near-infrared spectroscopy was used to examine prefrontal cortical activation.

**Table 1. Selected findings from recent KOA dual-task research**

| Variable | Single-task walking | Dual-task walking | Reported effect |
|---|---|---|---|
| Gait speed | Reference | Lower | 9% slower; Cohen's d = 0.63 |
| Step-duration variability | Reference | Higher | 26% greater; d = 0.45 |
| Stride-length variability | Reference | Higher | 13% greater; d = 0.37 |
| Cognitive correct-response rate | Reference cognitive task | Slightly lower | d = 0.15 |
| Prefrontal activation | Elevated during walking | Similar to single-task walking | No significant STW–DTW difference |

The study reported an adjusted mean difference in gait speed of −0.11 m/s between dual-task and single-task walking, with a Cohen's *d* of 0.63. Step-duration coefficient of variation increased by 0.88 percentage points and stride-length coefficient of variation increased by 1.19 percentage points during dual-task walking.

These findings suggest that the addition of a cognitive task can reveal gait instability that may not be fully apparent during uncomplicated walking.

The interaction between pain-related attentional demand and cognitive-motor interference (CMI) in knee osteoarthritis (KOA) demonstrates clear behavioral and neurophysiological shifts across single- and dual-task conditions.

**Spatiotemporal Gait Alterations:** Under single-task conditions, individuals with KOA demonstrate baseline compensations (e.g., modest reductions in gait speed). When a secondary cognitive task is introduced, motor performance declines significantly. Studies highlight a 9% reduction in gait speed, alongside a 26% increase in step-duration variability and a 13% increase in stride-length variability during dual-task walking compared to single-task conditions.

**Attentional Competition:** Cognitive performance (e.g., accuracy and response latency during Serial 7s or N-back tests) shows parallel degradation under dual-task conditions, confirming mutual interference rather than selective task prioritization.

**Cortical Over-Recruitment:** Functional neuroimaging (fNIRS) reveals increased prefrontal cortex (PFC) activation during dual-task locomotion in KOA populations compared to healthy controls, signaling elevated executive resource demands for motor regulation.

The observed deterioration in movement parameters under cognitive load supports the paradigm that knee pain is an active consumer of central processing resources rather than a purely localized peripheral symptom.

**Breakdown of Gait Automaticity:** Healthy locomotion relies on subcortical automaticity. In early KOA, persistent pain and joint degeneration force a shift toward top-down, cortical control. When secondary cognitive tasks demand executive resources from the prefrontal cortex, the available attentional pool is exhausted, leading to gait instability.

**Sensory Unreliability and Conscious Monitoring:** Impaired proprioceptive feedback from joint damage forces the central nervous system to substitute automatic feedback loops with conscious monitoring of step placement and joint loading. This hyper-vigilant strategy makes locomotion vulnerable to external attentional distraction.

**Kinesiophobia and Cautious Strategies:** Cautious walking patterns (shorter stride length, increased double-support time) represent compensatory attempts to preserve stability. However, these guarded strategies inherently demand higher cognitive engagement, paradoxically increasing total dual-task cost.

**Clinical Significance:** Dual-task assessments expose subtle sensorimotor deficits that conventional single-task gait analyses overlook. Identifying early CMI provides a biomarker for fall risk and guides dual-task rehabilitation strategies aimed at restoring motor automaticity.

Functional near-infrared spectroscopy (fNIRS) evaluations reveal distinct cortical and behavioral patterns in individuals with knee osteoarthritis (KOA):

**Cortical Hemodynamic Profiles:** Oxygenated hemoglobin concentration ($\Delta\text{HbO}_2$) in the prefrontal cortex (PFC) is significantly higher during both single-task walking (STW) and dual-task walking (DTW) compared to a seated cognitive task. However, PFC activation shows no statistically significant increase from STW to DTW.

**Behavioral Performance Deficits:** Despite the ceiling effect in PFC activation, gait mechanics degrade sharply during DTW compared to STW, exhibiting marked reductions in walking speed ($d = 0.63$) along with elevated step-duration ($d = 0.45$) and stride-length variability ($d = 0.37$).

**Regional Neuro-Motor Associations:** Linear regression models demonstrate that greater activation in specific cortical subregions—namely the right ventrolateral PFC ($R^2 = 0.15$) and left dorsomedial PFC ($R^2 = 0.12$)—is significantly correlated with lower step-duration variability (i.e., superior motor automaticity).

The observed dissociation between stable cortical activation and worsening gait performance illuminates key neural mechanisms underlying cognitive-motor interference (CMI) in KOA.

**Loss of Motor Automaticity:** Under healthy conditions, locomotion relies primarily on subcortical networks. In KOA, joint degradation, nociceptive signaling, and altered biomechanics force a shift toward executive motor control. As a result, individuals over-recruit prefrontal resources just to execute unchallenging single-task walking.

**Exhaustion of Neural Reserve:** Because baseline walking consumes substantial cognitive capacity, adding a concurrent mental workload exceeds available cortical headroom. Lacking sufficient "brain reserve" to further elevate PFC activation, the central nervous system fails to compensate, leading to severe gait instability and dynamic variability.

**Targeted Subregion Role:** The protective association of the right ventrolateral and left dorsomedial PFC with gait stability highlights these subregions as vital centers for suppressing stride variability and maintaining dynamic balance under stress.

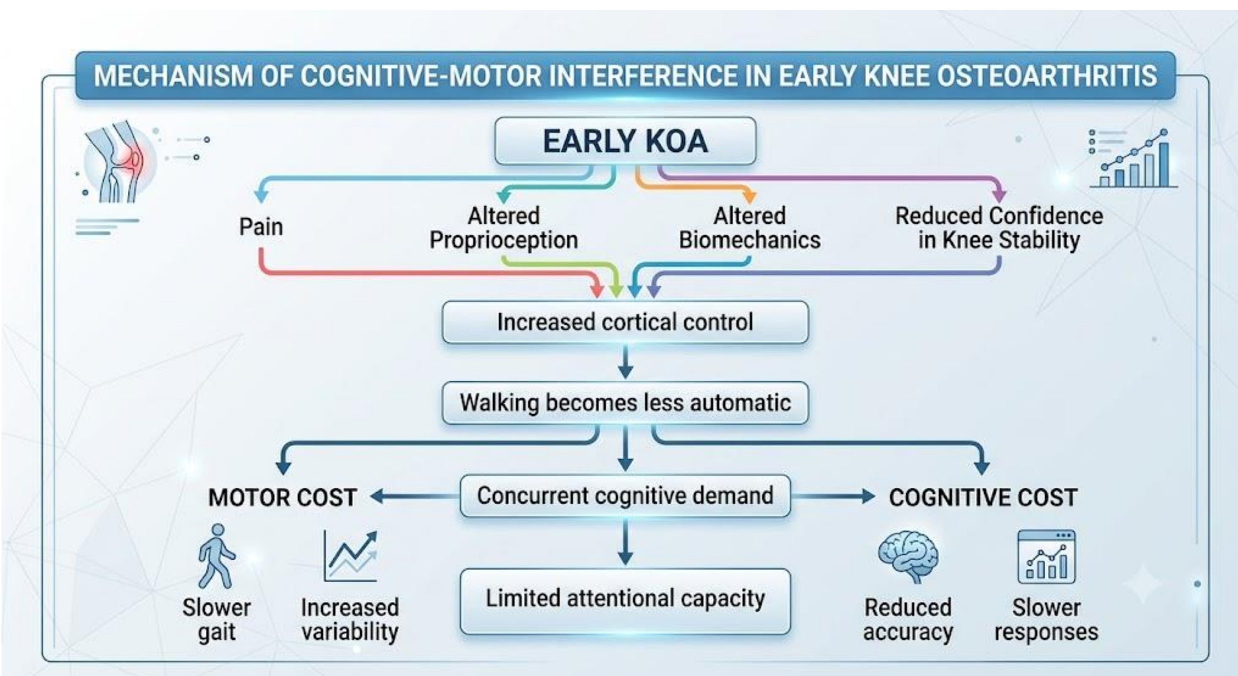


*Figure 1. Proposed relationship among knee pathology, cortical control, and dual-task performance.*

**Table 2. Suggested assessment framework for early KOA**

| Domain | Single-task condition | Cognitive task | Dual-task condition | Potential outcome |
|---|---|---|---|---|
| Walking | Comfortable-speed gait | Serial subtraction | Walk + subtraction | Gait speed, variability |
| Walking | Comfortable-speed gait | Verbal fluency | Walk + category naming | Step length, cadence |
| Walking | Comfortable-speed gait | Working memory | Walk + digit recall | Dual-task cost |
| Balance | Quiet standing | Counting | Stand + counting | Sway area |
| Mobility | Timed walking | Simple attention task | Timed walking + attention | Completion time |
| Functional gait | Obstacle walking | Cognitive task | Obstacle + cognitive task | Errors, hesitation |
| Turning | Walk and turn | Mental arithmetic | Walk/turn + arithmetic | Turning time, instability |

The choice of cognitive task should be standardized because different tasks place different demands on working memory, attention, executive function, and response selection. The broader CMI literature emphasizes that methodological variation can influence observed dual-task effects.

## Quantifying Dual-Task Cost

A major advantage of dual-task testing is that performance can be expressed quantitatively.

For a motor outcome:

$$DTC_{motor}(\%) =\frac{Single\ Task-Dual\ Task}{Single\ Task}\times100$$

For variables in which a larger value indicates worse performance, the direction should be interpreted appropriately.

For example, if gait speed decreases from 1.00 m/s during single-task walking to 0.90 m/s during dual-task walking:

$$DTC = \frac{1.00-0.90}{1.00}\times 100 = 10\%$$

Thus, the participant has a **10% dual-task cost in gait speed**.

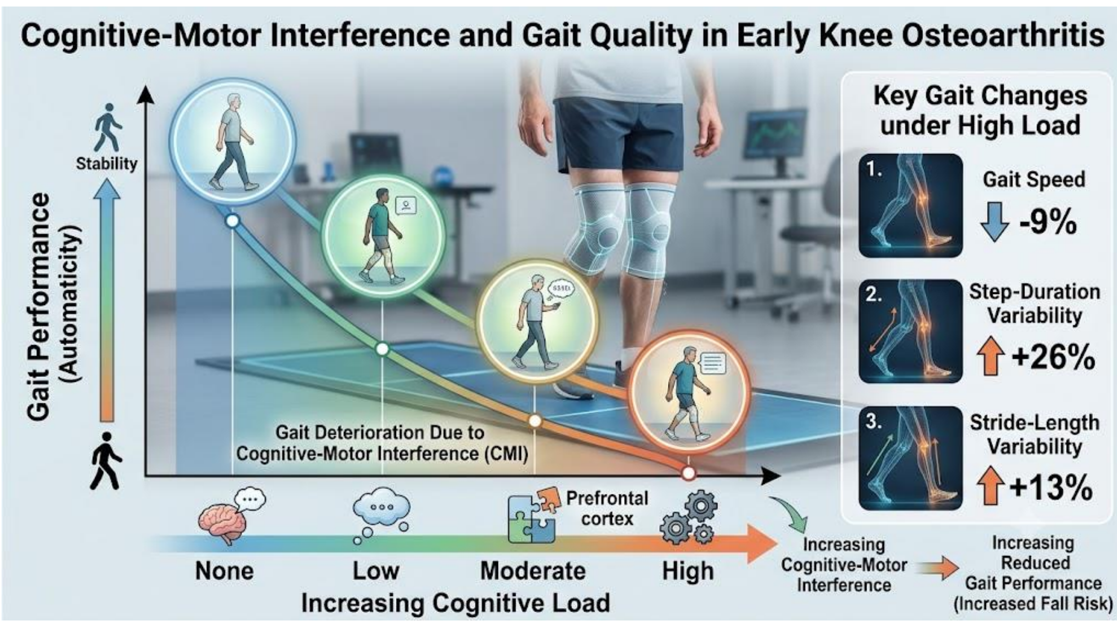


Figure 3. The expected relationship between cognitive demand and motor performance.

## Motor and Cognitive Prioritization

One of the most important characteristics of dual-task testing is **task prioritization**. When instructed to walk while simultaneously calculating, a participant may: prioritize walking and allow cognitive accuracy to decrease; prioritize the cognitive task and allow gait speed or stability to decrease; attempt to maintain both tasks; alternate attention between the two tasks.

The recent KOA study found a relatively small cognitive performance reduction while motor performance deteriorated substantially during dual-task walking. This may indicate a tendency toward cognitive-task prioritization, although task-priority behavior should be tested directly rather than assumed.

## Relationship to Conventional KOA Assessment

Traditional KOA assessments may fail to detect subtle cognitive-motor abnormalities because they often evaluate motor performance under isolated conditions.

**Table 3. Conventional versus cognitive-motor assessment**

| Conventional assessment | Limitation | Added information from dual-task assessment |
|---|---|---|
| Gait speed | May appear normal in early disease | Reveals performance under attentional load |
| Timed Up and Go | Usually performed without cognitive load | Can test mobility while attention is divided |
| Quadriceps strength | Does not directly assess locomotor control | Identifies functional effects of cognitive loading |
| Static balance | Limited ecological validity | Examines balance under simultaneous cognitive demand |
| Pain score | Subjective and not directly motor-specific | Shows functional consequences of pain/cognitive demand |
| KOOS | Patient-reported | Complements patient-reported function with objective behavior |
| Single-task gait variability | May underestimate instability | Dual-task variability may reveal latent motor-control deficits |

The potential value of CMI assessment is therefore not necessarily to replace existing KOA measures, but to **add an ecologically relevant layer of functional assessment**.

## Clinical Implications

Evaluating Cognitive-Motor Interference (CMI) reveals clear differences in performance metrics when comparing single-task and dual-task activities:

**Real-World Functional Challenges:** CMI manifests prominently during complex daily activities, particularly when individuals walk while talking, navigate crowded spaces, carry objects, process or remember information while moving, change direction while distracted, or clear obstacles while conversing.

**Dual-Task Gait & Balance Deterioration:** The literature confirms that adding a cognitive load significantly compromises motor performance in individuals with knee conditions. Experimental data in symptomatic knee osteoarthritis (KOA) shows a 9% reduction in gait speed along with increases of 26% in step-duration variability and 13% in stride-length variability during dual-task walking compared to single-task conditions.

**Literature Heterogeneity:** Although a systematic scoping review identified 15 relevant dual-task studies on knee pathologies (six targeting dual-task gait and nine examining balance), only a subset focused explicitly on KOA, highlighting an evidence base that is still developing and varied in methodology.

The clinical implications of CMI in early KOA mark a shift from treating KOA purely as a peripheral mechanical disorder to addressing it as an integrated neuromotor and cognitive challenge.

**Subclinical Diagnostic Marker:** Conventional single-task gait assessments often fail to capture subtle motor control deficits in early stage KOA. Cognitive loading taxes shared central executive resources, exposing latent gait instability and impaired automaticity before marked physical decline occurs.

**Ecological Fall-Risk Screening:** Difficulty managing real-world dual-task scenarios (e.g., conversing while negotiating obstacles) directly correlates with an increased risk of falls and functional decline. Implementing dual-task gait protocols offers a more realistic window into an individual's actual mobility and safety during complex everyday conditions.

**Rehabilitation Progression:** Therapeutic interventions should advance beyond isolated muscle strengthening or unchallenge balance drills. Effective rehabilitation programs ought to incorporate a progressive continuum that integrates increasingly demanding dual-task challenges—such as combined cognitive-motor training—to enhance executive control, improve gait adaptability, and restore motor automaticity in daily life.

**Table 4. Potential cognitive-motor rehabilitation progression**

| Stage | Motor challenge | Cognitive challenge | Example |
|---|---|---|---|
| 1 | Comfortable walking | None | Baseline gait |
| 2 | Comfortable walking | Simple counting | Walk + count |
| 3 | Walking | Working memory | Walk + digit recall |
| 4 | Walking with turns | Verbal fluency | Walk + category naming |

| | | | |
|---|---|---|---|
| 5 | Obstacle walking | Mental arithmetic | Obstacles + subtraction |
| 6 | Community-like walking | Complex cognitive task | Navigation + conversation |
| 7 | Variable environment | Multitask | Carrying object + navigation + conversation |

**Early KOA as a Potential Window for Intervention**

Experimental findings consistently demonstrate that Cognitive-Motor Interference (CMI) serves as a sensitive indicator of subtle motor-control deficits prior to the onset of severe physical impairment in early knee osteoarthritis (KOA). While traditional biomechanical evaluations reveal minimal to non-significant alterations during single-task walking in early-stage KOA (e.g., Kellgren-Lawrence Grade I–II), introducing a concurrent cognitive load reliably unmasks functional vulnerabilities.

Specifically, dual-task paradigms demonstrate marked performance degradation across several key parameters:

**Gait Speed & Dynamics:** Dual-task walking induces a significant reduction in gait speed (up to 9%) alongside elevated step-duration and stride-length variability compared to single-task conditions.

**Balance & Postural Control:** Postural sway and joint kinematics display greater instability under cognitive load, highlighting an uncoupling of automatic motor regulation.

**Cortical Engagement:** Neuroimaging studies reveal heightened prefrontal cortex (PFC) activation during dual-task walking in KOA, indicating that patients actively recruit executive control resources to compensate for compromised joint mechanics.

The emergence of CMI during the initial stages of KOA highlights early KOA as a critical **window for therapeutic intervention**. In healthy individuals, locomotion is largely automated through subcortical pathways. However, early KOA triggers subtle nociceptive inputs and subtle joint instability, forcing the central nervous system to shift motor control from automatic subcortical networks to executive, prefrontal cortical networks.

As illustrated in the functional reserve model, single-task measures often fail to detect early decline because patients possess sufficient cognitive reserve to compensate for minor motor impairments. However, when concurrent cognitive demands consume this shared attentional capacity, the underlying motor deficits are exposed.

## Clinical Implications & Future Directions

**Early Functional Biomarker:** Dual-task gait testing provides a non-invasive tool to identify subclinical motor deficits, executive control strain, and heightened fall risk long before marked structural degradation is apparent.

**Targeted Rehabilitation:** Identifying CMI early enables clinicians to implement integrated cognitive-motor dual-task training strategies aimed at restoring motor automaticity, improving gait adaptability, and preserving functional independence.

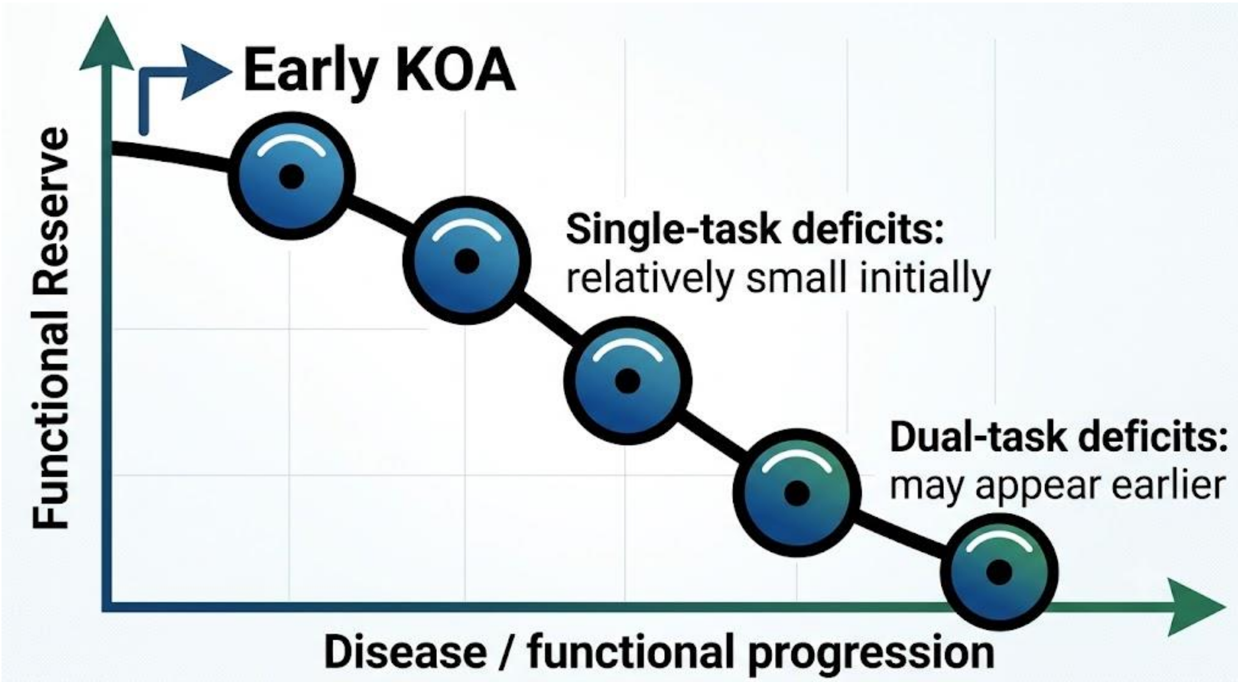


Figure 4. Proposed trajectory of CMI across KOA progression

**Proposed Research Design for Early KOA**

A future prospective study could compare three groups:

adults with early KOA;adults with established KOA;age- and sex-matched healthy controls.

Participants could perform:single-task walking;walking + serial subtraction;walking + verbal fluency;walking + working-memory task;obstacle negotiation;dual-task turning;

static and dynamic balance.

Motor outcomes should include gait speed, cadence, step length, stride length, stance time, step-time variability, stride-length variability, and turning performance.

Cognitive outcomes should include accuracy, reaction time, omissions, and response consistency.

**Table 5. Proposed variables for a longitudinal CMI study**

| Category | Variable | Hypothesized early-KOA change |
| --- | --- | --- |
| Motor | Gait speed | ↓ |
| Motor | Step-length variability | ↑ |
| Motor | Step-time variability | ↑ |
| Motor | Turning time | ↑ |
| Motor | Obstacle errors | ↑ |
| Cognitive | Accuracy | ↔ or slight ↓ |
| Cognitive | Reaction time | ↑ |
| Dual-task | Motor DTC | ↑ |
| Dual-task | Cognitive DTC | ↑/↔ |
| Clinical | Pain | ↑ |
| Clinical | KOOS function | ↓ |
| Psychological | Fear of movement | ↑ |
| Neural | PFC recruitment | Potential ↑/altered |

## Conclusion

Cognitive-motor interference provides a useful framework for understanding functional mobility in knee osteoarthritis. Walking in KOA is not simply a mechanical consequence of joint pathology; it is also a cognitively regulated behavior. Pain, altered biomechanics, proprioceptive changes, and reduced gait automaticity may increase the attentional resources required for locomotion. When a cognitive task is added, these limited resources may be insufficient to maintain optimal motor performance. Current evidence demonstrates that individuals with symptomatic KOA can exhibit meaningful reductions in gait speed and increases in gait variability during dual-task walking. Recent neurophysiological evidence additionally suggests that prefrontal cortical resources are involved in walking in KOA. Although evidence specifically addressing **early KOA** remains limited, CMI represents a promising area for research because it may reveal subtle functional abnormalities that conventional single-task assessments overlook. Standardized dual-task gait testing, combined with cognitive assessment and, where feasible, neural measurements, could improve understanding of the interaction between pain, cognition, and locomotor control. The most important next step is to establish whether CMI is merely a consequence of symptomatic KOA or whether it can serve as an early, clinically meaningful marker of impaired mobility and future functional decline.

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