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Cognitive Dual-Task Interference Alters Dynamic Balance and Kinetics in Early Knee Osteoarthritis

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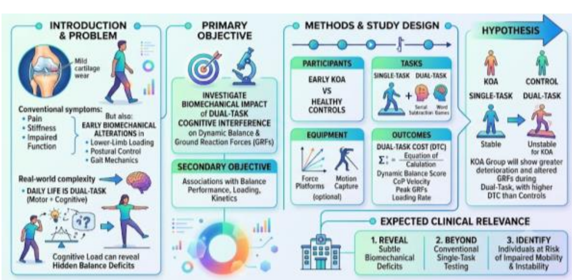
Abstract

Knee osteoarthritis (KOA) involves early biomechanical alterations in lower-limb loading, gait, and dynamic balance. Adding cognitive tasks during movement may reveal balance control deficits undetected in single-task assessments. This study aims to investigate the impact of dual-task cognitive interference on dynamic balance and ground reaction forces (GRFs) in individuals with early KOA compared to healthy controls. In this biomechanical design, individuals with early KOA and matched controls perform dynamic balance tasks under single-task and dual-task conditions, incorporating cognitive tasks like serial subtraction or verbal fluency. Force platforms measure primary outcomes, including center-of-pressure displacement and velocity, peak vertical GRF, loading rates, and propulsive forces, alongside calculated dual-task costs. It is hypothesized that early KOA participants will display greater balance deterioration and altered GRFs during dual-task conditions than controls. Identifying these cognitive-motor interference deficits could enhance early risk detection for joint instability and mobility decline beyond conventional single-task evaluations.

Infographic abstract



Keywords: knee osteoarthritis; dual-task; cognitive interference; dynamic balance; ground reaction force; biomechanics; gait; postural control; cognitive-motor interference.

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Introduction

Knee osteoarthritis (KOA) is a leading cause of chronic pain, joint disability, and physical limitation among middle-aged and older adults globally. While advanced KOA is characterized by extensive articular cartilage loss and structural joint degeneration, early-stage KOA presents a critical window for therapeutic intervention before irreversible structural damage occurs. Traditionally viewed through a biomechanical lens, early KOA involves subtle pathological changes, including altered ground reaction forces (GRFs), joint stiffness, and compensatory gait mechanics designed to offload the symptomatic compartment (Al-Khlaifat et al., 2022). However, emerging evidence indicates that early KOA is not merely a localized peripheral joint pathology, but a complex condition involving central neuro-biomechanical integration.

Knee osteoarthritis is one of the most common musculoskeletal disorders and is an important cause of pain, functional limitation, and reduced mobility. Although osteoarthritis is commonly associated with structural joint degeneration, functional impairment is determined by a complex interaction between joint pathology, neuromuscular control, sensory processing, movement strategy, and psychological and environmental factors. Early KOA is particularly important because measurable functional changes may develop before substantial structural deterioration or severe disability becomes apparent. Individuals with early disease may continue to perform routine activities independently, yet subtle changes in movement control can affect how forces are distributed across the lower extremity. Dynamic balance is the ability to maintain postural stability while the body or its center of mass is moving. Unlike quiet standing, dynamic balance requires continuous integration of visual, vestibular, and somatosensory information with anticipatory and reactive postural adjustments. Successful dynamic balance also depends on adequate lower-limb strength, joint mobility, motor planning, and rapid adaptation to changing task demands.Knee OA can interfere with these mechanisms. Pain, altered proprioception, quadriceps weakness, reduced joint range of motion, and compensatory movement strategies may modify the way an individual controls the center of mass and accepts or produces external forces.

In healthy individuals, walking and postural control are largely automated processes requiring minimal conscious cognitive control. In individuals with early KOA, persistent nociceptive input, joint instability, and impaired proprioception disrupt this automaticity, shifting motor control toward a higher reliance on supraspinal attentional resources (Göksu et al., 2021). To maintain dynamic balance during locomotion, these individuals must allocate increased cognitive control to process altered sensory feedback and adjust biomechanical output.

When a concurrent cognitive task is introduced—a paradigm known as dual-tasking—the available attentional capacity is divided between motor execution and cognitive processing. According to the Capacity Theory of Attention, this competition for limited cognitive resources results in Cognitive-Motor Interference (CMI) (Kahneman, 1973; Woollacott & Shumway-Cook, 2002). While CMI has been extensively studied in neurological populations and age-related fall risks, its specific biomechanical consequences in early KOA remain insufficiently characterized.

Under dual-task conditions, CMI manifests in altered dynamic balance and kinetic parameters. Specifically, the introduction of cognitive load disrupts GRF profiles—including peak braking forces, vertical loading rates, and propulsive forces—which are critical for joint stability and shock absorption during heel-strike and push-off phases of gait (Courtney et al., 2020). Furthermore, degraded dynamic balance under dual-task constraints elevates the risk of micro-instability and abnormal joint loading, potentially accelerating joint degeneration and increasing fall susceptibility in early KOA populations.

Understanding the biomechanical impact of dual-task cognitive interference on dynamic balance and GRFs is essential for establishing early functional biomarkers of KOA progression. This thesis investigates the extent to which cognitive load destabilizes dynamic balance and alters kinetic variables in early KOA, providing insights that could inform targeted, dual-task rehabilitation strategies to preserve both motor and cognitive function in clinical practice.

Human movement rarely occurs in complete isolation from cognitive activity. Everyday dual-task behavior includes walking while talking, navigating a crowded environment, responding to a mobile-phone message, remembering instructions, or making decisions while moving.

A dual-task paradigm requires a person to perform a motor task simultaneously with a cognitive task. Because attentional resources are limited, competition between the two tasks may result in deterioration of one or both performances. This phenomenon is commonly described as **cognitive-motor interference**.

The effect may be particularly relevant in individuals with musculoskeletal disorders because their motor system may already require increased attentional resources to maintain movement quality. A task that appears automatic in healthy individuals may demand greater conscious control in a person with knee pain or altered biomechanics.

Ground reaction force (GRF) represents the force exerted by the ground on the body during contact with the supporting surface. During walking and other functional activities, the magnitude, timing, and direction of GRF provide important information about movement mechanics.

Important GRF variables include: Peak vertical GRF, Loading rate, Time to peak ,ertical force, Anterior-posterior braking force, Anterior-posterior propulsive force, Mediolateral force, Impulse, Rate of force development. Changes in these parameters may indicate altered shock absorption, limb loading, propulsion, or balance-control strategies.

Conventional clinical assessment frequently evaluates balance or gait under relatively simple conditions. Such testing may fail to reveal deficits that emerge when attentional resources are divided.

Dual-task testing may therefore provide a more ecologically valid assessment of functional mobility. If individuals with early KOA demonstrate substantial changes in dynamic balance or GRF during cognitive interference, dual-task assessment could become a useful component of early biomechanical evaluation.

Individuals with early knee osteoarthritis may demonstrate subtle alterations in dynamic postural control and lower-limb loading that are not readily detected during routine single-task assessment. The addition of a cognitively demanding task may increase attentional requirements and expose deficits in motor control. However, the biomechanical effects of cognitive interference on dynamic balance and ground reaction forces in early KOA require further investigation.

Does simultaneous performance of a cognitive task significantly alter dynamic balance and ground reaction forces in individuals with early knee osteoarthritis compared with single-task performance and healthy controls?

To investigate the biomechanical impact of dual-task cognitive interference on dynamic balance and ground reaction forces in individuals with early knee osteoarthritis. **Objective** : To determine the effect of dual-task cognitive interference on dynamic balance in individuals with early KOA.

Methodology

Study Design

The present study employs a cross-sectional, repeated-measures comparative study design to investigate the biomechanical impact of dual-task cognitive interference on dynamic balance and ground reaction forces in individuals with early knee osteoarthritis (KOA).

Participants will perform a standardized motor task under two experimental conditions:

Single-task motor condition (ST): performance of the motor task without an additional cognitive task.

Dual-task motor–cognitive condition (DT): simultaneous performance of the same motor task and a standardized cognitive task.

Where a healthy control group is included, the same experimental protocol will be administered to both individuals with early KOA and age-matched healthy participants. This design will permit assessment of both the immediate effect of cognitive interference and whether individuals with early KOA demonstrate a greater biomechanical response to dual-tasking than healthy individuals.

The primary comparison will therefore be the change in dynamic balance and ground reaction force variables between single-task and dual-task conditions. The **Group × Condition interaction**, where applicable, will be used to determine whether the effect of cognitive interference differs between participants with early KOA and healthy controls.

Study Setting

The study will be conducted in the **Biomechanics/Movement Analysis Laboratory of [Institution Name]**. The laboratory will provide a controlled environment for the assessment of dynamic balance, gait-related biomechanics, and ground reaction forces.

The laboratory will be equipped with a force platform and appropriate motion/balance-analysis equipment. Environmental conditions, including walking surface, illumination, and testing space, will be maintained consistently throughout data collection.

Study Population

The study population will consist of adults aged approximately **40–65 years** with clinically and/or radiographically defined early knee osteoarthritis.

A healthy control group of age-matched individuals without clinically significant knee osteoarthritis may also be recruited to establish reference biomechanical responses to single-task and dual-task conditions.

Participants will be recruited from **[orthopaedic/rheumatology/physiotherapy outpatient departments, community settings, institutional recruitment, or other approved sources]** according to the approved recruitment procedure.

Inclusion Criteria

Early Knee Osteoarthritis Group

Participants will be eligible for inclusion if they:

- are between **40 and 65 years of age**;
- meet the predefined clinical and/or radiographic criteria for early knee osteoarthritis;
- are able to walk independently without physical assistance;
- are able to understand and follow verbal instructions;
- are able to perform the selected motor and cognitive tasks safely;
- have sufficient corrected vision and hearing to perform the experimental protocol; and
- provide written informed consent before participation.

The operational definition of early KOA will be specified before recruitment and may incorporate standardized clinical and radiographic criteria, such as the **Kellgren–Lawrence grading system**, together with relevant symptoms and clinical findings.

Healthy Control Group

Participants in the control group will:

- fall within the same predefined age range as the KOA group;
- have no diagnosed knee osteoarthritis;
- have no clinically significant knee pain at the time of assessment;
- be independently ambulatory;
- be able to understand and perform the motor and cognitive tasks; and
- provide written informed consent.

Controls will be matched or frequency-matched to the KOA group according to relevant demographic characteristics, particularly age and sex where feasible.

Exclusion Criteria

Participants will be excluded if they have any condition likely to substantially influence balance, gait, cognitive performance, or ground reaction forces, including:

- previous major knee replacement surgery;
- recent lower-limb surgery or acute musculoskeletal injury;
- neurological disorders affecting balance, gait, or motor control;
- severe vestibular impairment;
- other significant musculoskeletal disorders affecting walking;
- severe visual impairment that cannot be adequately corrected;
- clinically significant cognitive impairment preventing completion of the cognitive task;
- severe cardiopulmonary or systemic disease that makes the testing procedure unsafe;
- inability to understand the experimental instructions; or

- any other condition identified by the investigator or medical professional as presenting an unacceptable risk during testing.

Participants will also be excluded or the relevant trial will be discontinued if they develop substantial pain, dizziness, instability, excessive fatigue, or other adverse symptoms during testing.

Sample Size

Sample size determined using **G*Power [version]** or an equivalent statistical software package.

The calculation will be based on the expected effect size for the primary outcome variable, an alpha level of **0.05**, statistical power of **80–90%**, and the statistical model selected for the final analysis. Where a two-group repeated-measures design is employed, the anticipated **Group × Condition interaction effect** will be considered for sample-size estimation.

An allowance for an anticipated dropout or unusable-data rate of approximately **10–15%** will be incorporated into the final recruitment target.

The final sample size will be reported as:

Required sample size = [N] participants per group, with a total recruitment target of [N] participants.

The assumptions used for the sample-size calculation will be explicitly reported in the final thesis.

EXPERIMENTAL PROTOCOL

Participant Preparation

Before experimental testing, each participant will receive a detailed explanation of the study procedure.

Written informed consent will be obtained before any study-specific assessment.

Demographic and relevant clinical information will be recorded, including age, sex, height, body mass, dominant limb, KOA status, pain characteristics, and other variables considered relevant to biomechanical performance.

Participants will wear comfortable clothing and standardized footwear, or perform the protocol barefoot where required by the selected balance assessment. The same footwear condition will be maintained across all trials for an individual participant.

Familiarization

Participants will undergo a familiarization session before data acquisition. They will be allowed to practice the motor task and cognitive task separately and then simultaneously.

Familiarization will continue until the participant demonstrates adequate understanding of the procedure while avoiding excessive practice that could introduce a learning effect.

Experimental Conditions

Following baseline measurements, participants will perform the standardized motor task under the following conditions:

Condition 1: Single-task motor condition

The participant will perform the motor task without an additional cognitive task.

Condition 2: Dual-task motor–cognitive condition

The participant will perform the identical motor task while simultaneously completing the standardized cognitive task.

Each condition will consist of **[number] valid trials**, with a standardized rest period of **[duration]** between trials.

The order of the single-task and dual-task conditions will preferably be **randomized or counterbalanced** between participants to minimize systematic learning, fatigue, and order effects.

Testing will be terminated if the participant reports excessive pain, dizziness, instability, unusual shortness of breath, or any other symptom indicating that continued testing may be unsafe.

Cognitive Task

A standardized cognitive task will be selected to impose measurable cognitive interference while remaining sufficiently simple to perform concurrently with the motor task.

Potential cognitive paradigms include: serial subtraction; auditory Stroop task; verbal fluency; digit monitoring; random number generation; or choice reaction task.

For the present study, a **serial subtraction task** may be employed. Participants may be instructed to subtract **3 or 7** repeatedly from a randomly selected starting number while simultaneously performing the motor task. The starting number will be varied between trials to reduce memorization and learning effects. Instructions will emphasize that participants should continuously perform both tasks rather than intentionally abandoning one task.

Cognitive-task performance will be recorded where feasible, including measures such as: number of correct responses; number of errors;

response rate; percentage accuracy; and cognitive-task completion rate. Recording cognitive performance is important because it permits determination of whether participants adopt different task-prioritization strategies during dual-tasking. The same cognitive paradigm, instructions, response requirements, and scoring procedure will be applied consistently across participants.

Dynamic balance will be assessed using a validated functional or instrumented balance protocol. Depending on the final laboratory setup, this may include the Y-Balance Test, instrumented gait analysis, Timed Up and Go with cognitive interference, or force-platform-based dynamic postural stability assessment.

For an instrumented force-platform protocol, the following variables may be derived: mediolateral center-of-pressure (COP) excursion; anteroposterior COP excursion; COP velocity; COP path length; time to stabilization; stability margin; center-of-mass displacement; mediolateral and anteroposterior displacement; and dynamic postural stability indices. Where gait is assessed, additional spatiotemporal variables may include gait speed, stride length, cadence, stance time, double-support time, and step-width variability. The same testing instructions and trial duration will be maintained across single-task and dual-task conditions. A greater COP excursion, higher COP velocity, increased stabilization time, or reduced stability margin will generally be interpreted as evidence of poorer dynamic postural control, subject to the directionality of the specific measurement used.

Ground Reaction Force Measurement

Ground reaction forces will be recorded using a calibrated three-dimensional force platform embedded in or integrated with the laboratory testing surface. The force platform will measure external forces generated between the participant and the ground along the vertical, anteroposterior, and mediolateral axes. Participants perform the standardized motor task while the force platform records the corresponding force-time data.

Table-1:The primary ground reaction force variables will include:

Variable	Operational description
Peak vertical GRF	Maximum vertical ground reaction force during stance
Vertical loading rate	Rate of increase in vertical GRF during the loading phase
Braking force	Posteriorly directed component of GRF during early stance
Propulsive force	Anteriorly directed component of GRF during late stance
Mediolateral force	Side-to-side component of external ground reaction force
Vertical impulse	Time integral of vertical ground reaction force
Time to peak force	Time interval from initial contact to peak GRF
Force-time integral	Integrated GRF over the specified stance interval

Absolute GRF values will be normalized to body weight to permit comparison between participants of different body masses:

$$GRF_{normalized}=\frac{GRF}{Body\ Weight}$$

Normalized GRF may be expressed as a proportion or percentage of body weight.

Where appropriate, loading rate will also be reported in relation to body mass and/or body weight and clearly defined according to the selected calculation method.

Biomechanical Data Acquisition

The force platform will be calibrated according to the manufacturer's specifications before each testing session.

Force data will be collected at a sampling frequency of **[sampling frequency, e.g., 1000 Hz]** or another frequency appropriate for the selected biomechanical task.

If additional motion-analysis equipment is used, the sampling frequency and synchronization procedure will be specified. Force and motion data will be synchronized using the laboratory's standardized hardware or software synchronization system.

Participants will be instructed to perform the motor task at a standardized self-selected or prescribed speed, depending on the selected protocol. Where gait speed is relevant, speed will be recorded and controlled statistically or experimentally to minimize its confounding effect on GRF and balance outcomes.

Dual-Task Cost

Dual-task cost (DTC) will be calculated to quantify the relative change in biomechanical performance associated with cognitive interference.

For variables where a higher value represents better performance, DTC will be calculated as:

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

For variables where a higher value represents poorer performance, the direction of the calculation will be adjusted so that the resulting value appropriately represents deterioration or improvement.

For example, for a balance variable in which increased COP velocity indicates poorer balance:

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

A larger positive DTC will therefore indicate a greater change in performance attributable to cognitive interference.

Dual-task cost may be calculated separately for:

- dynamic balance variables;
- peak vertical GRF;
- loading rate;
- braking force;
- propulsive force;
- mediolateral force;
- temporal GRF variables; and
- cognitive-task performance.

Where appropriate, a **combined or composite dual-task cost** may also be explored, provided that the method is defined a priori.

Data Processing

Raw force-platform data will be inspected for signal quality, artifacts, and missing or invalid trials before analysis.

The force signal will be filtered using an appropriate low-pass digital filter. The filter type, cut-off frequency, order, and processing direction will be specified before final analysis and applied consistently to all participants.

Foot-contact and foot-off events will be identified using a predefined force threshold appropriate to the task and force-platform characteristics. GRF variables will subsequently be extracted from the identified stance phases.

Trials containing substantial movement artifacts, incomplete task performance, incorrect cognitive-task execution, or force-platform recording errors will be classified as invalid according to predefined criteria.

For each participant, valid trials within each experimental condition will be averaged to obtain condition-specific outcome measures. These participant-level averages will be used for the primary statistical analysis to reduce the influence of trial-to-trial variability.

Statistical Analysis

Statistical analysis will be performed using **SPSS [version]**, R, Python, MATLAB, or another validated statistical software package.

Participant characteristics will initially be summarized using descriptive statistics. Continuous variables will be examined for distributional assumptions using graphical methods, including histograms and Q-Q plots, together with appropriate normality assessments. Categorical variables will be summarized using frequencies and percentages.

For normally distributed continuous variables, results will be presented as **mean ± standard deviation (SD)**. Non-normally distributed variables will be presented as **median and interquartile range (IQR)**.

Primary Analysis

For a study including both KOA and healthy control groups, the primary analysis will examine the effect of:

- **Group:** early KOA vs. healthy control;
- **Condition:** single-task vs. dual-task; and
- **Group × Condition interaction:** whether the effect of cognitive interference differs between groups.

A **two-way mixed repeated-measures analysis of variance (ANOVA)** may be used when its assumptions are adequately satisfied.

The model will therefore include:

- **Between-subject factor:** Group;
- **Within-subject factor:** Condition; and
- **Primary interaction:** Group × Condition.

The Group × Condition interaction will be of particular interest because a significant interaction would indicate that individuals with early KOA respond differently to cognitive interference compared with healthy controls.

Where assumptions of repeated-measures ANOVA are violated, appropriate corrections or alternative statistical methods will be applied.

Linear Mixed-Effects Model

A **linear mixed-effects model** may alternatively be used, particularly where repeated trials, unequal numbers of valid observations, or participant-specific variability need to be accounted for.

Participant identity may be included as a random effect, while group, condition, and their interaction will be specified as fixed effects. Additional clinically relevant covariates, such as walking speed, age, sex, or pain intensity, may be incorporated where justified by the study design and prespecified analysis plan.

Post-hoc Analysis

Where significant main effects or interactions are identified, appropriate post-hoc pairwise comparisons will be conducted with adjustment for multiple comparisons.

The significance level will be set at: [$p<0.05$]

Effect sizes and **95% confidence intervals** will also be reported to provide information about the magnitude and precision of observed effects rather than relying solely on statistical significance.

Relationship Between Cognitive Interference and Biomechanical Outcomes

Where appropriate, exploratory correlation or regression analyses may be conducted to investigate associations between cognitive-task performance and biomechanical responses.

For example, the relationship between cognitive-task accuracy or cognitive dual-task cost and changes in:

- COP velocity;
- dynamic stability;
- loading rate;
- peak vertical GRF; and
- braking or propulsive forces

may be examined.

Appropriate correlation coefficients, such as Pearson's or Spearman's correlation, will be selected according to data distribution and measurement characteristics.

Control of Potential Confounding Factors

Several factors may influence dynamic balance and ground reaction forces independently of cognitive interference. Therefore, the following variables will be standardized or considered during analysis where feasible:

Age; sex; body mass; height; walking speed; footwear; dominant limb; pain intensity; physical activity level; familiarization; testing order; and fatigue.

Testing will preferably be performed at a similar time of day where practical, and standardized rest periods will be provided between trials.

Reliability and Quality Control

To improve measurement reliability, all equipment will be calibrated according to manufacturer recommendations before data collection.

Investigators responsible for biomechanical testing will receive standardized training in participant positioning, task instruction, force-platform operation, and data processing.

A standardized testing protocol and written operating procedure will be followed for all participants.

Where feasible, intra-session reliability will be assessed using repeated trials. Reliability may be quantified using the **intraclass correlation coefficient (ICC)**, standard error of measurement, and/or coefficient of variation for selected primary biomechanical variables.

Ethical Considerations

The study protocol will be submitted to the **Institutional Ethics Committee/Institutional Review Board of [Institution Name]** for approval before commencement of participant recruitment.

Participation will be voluntary. Each participant will receive information regarding the purpose, procedures, potential risks, and expected benefits of the study and will provide written informed consent before participation.

Participant confidentiality will be maintained by assigning study identification codes and storing identifiable information separately from research data. Participants will have the right to withdraw from the study at any stage without penalty.

All testing procedures will be performed with appropriate safety precautions. Participants will be monitored throughout the experimental protocol, and testing will be discontinued if clinically significant discomfort or other safety concerns arise.

The present study examined the biomechanical impact of **dual-task cognitive interference on dynamic balance and ground reaction forces in individuals with early knee osteoarthritis (KOA)**. Early KOA may involve subtle alterations in lower-limb neuromuscular control, proprioception, postural regulation, and movement strategies even before substantial functional limitations become apparent. These changes can become more evident when an individual is required to perform a cognitive task simultaneously with a motor task, thereby increasing the demands placed on attentional resources and sensorimotor integration.

Dynamic balance during functional activities such as walking, turning, stepping, and transitional movements depends on the coordinated regulation of the centre of mass relative to the base of support and the ability to appropriately generate and absorb external forces. The addition of a concurrent cognitive task can produce **dual-task cognitive interference**, potentially diverting attentional resources away from postural control and modifying movement strategies. In individuals with early KOA, who may already demonstrate compensatory alterations in gait and lower-extremity loading, this additional cognitive demand may further influence dynamic stability and the magnitude, timing, and distribution of ground reaction forces.

Accordingly, the findings of the present study are discussed with particular emphasis on changes in dynamic balance performance, ground reaction force characteristics, and the interaction between cognitive loading and biomechanical control. The results are interpreted in relation to the underlying mechanisms of dual-task interference, including attentional resource allocation, proprioceptive integration, neuromuscular coordination, and protective movement strategies. Understanding these biomechanical responses is clinically relevant because everyday mobility frequently occurs under cognitively demanding conditions, such as walking while conversing, navigating crowded environments, carrying objects, or responding to environmental stimuli. Therefore, identifying the effects of cognitive interference in early KOA may provide important insights into functional instability and loading behaviour that may not be evident during single-task motor performance.

The following discussion integrates the observed biomechanical outcomes with existing evidence on dual-task postural control, knee osteoarthritis, gait biomechanics, and ground reaction forces, with the aim of determining whether cognitive interference amplifies deficits in dynamic balance and alters lower-limb loading patterns in individuals with early KOA.

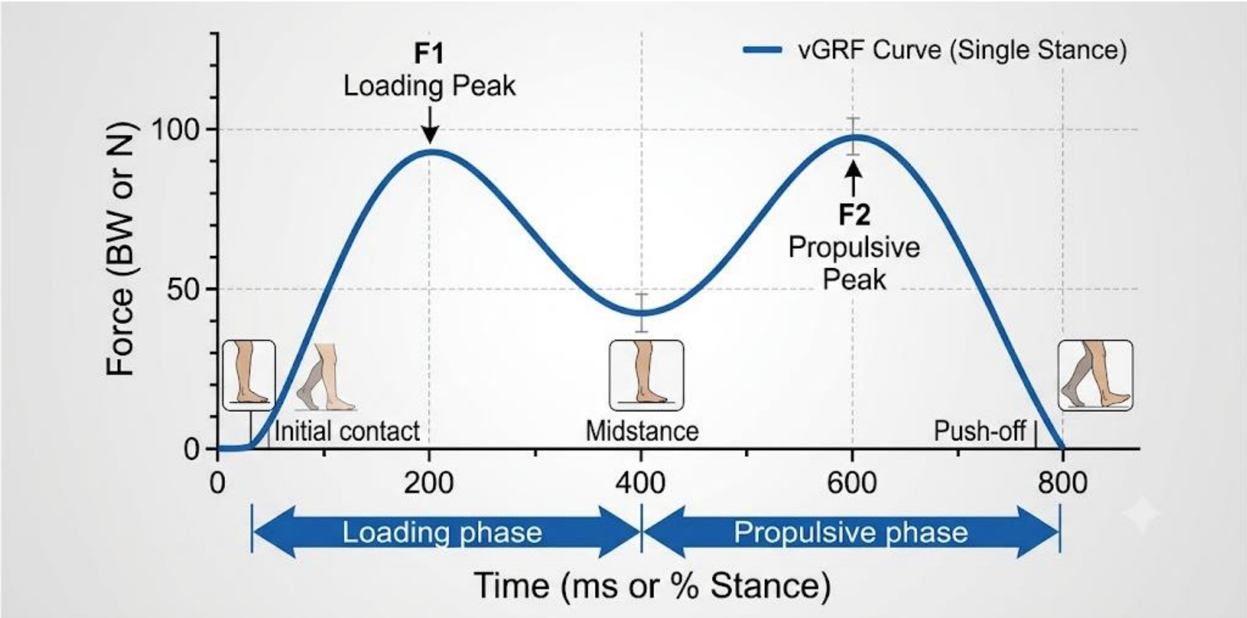

Figure 2. Schematic representation of the vertical ground reaction-force profile during stance. Actual study data should replace the schematic curve.

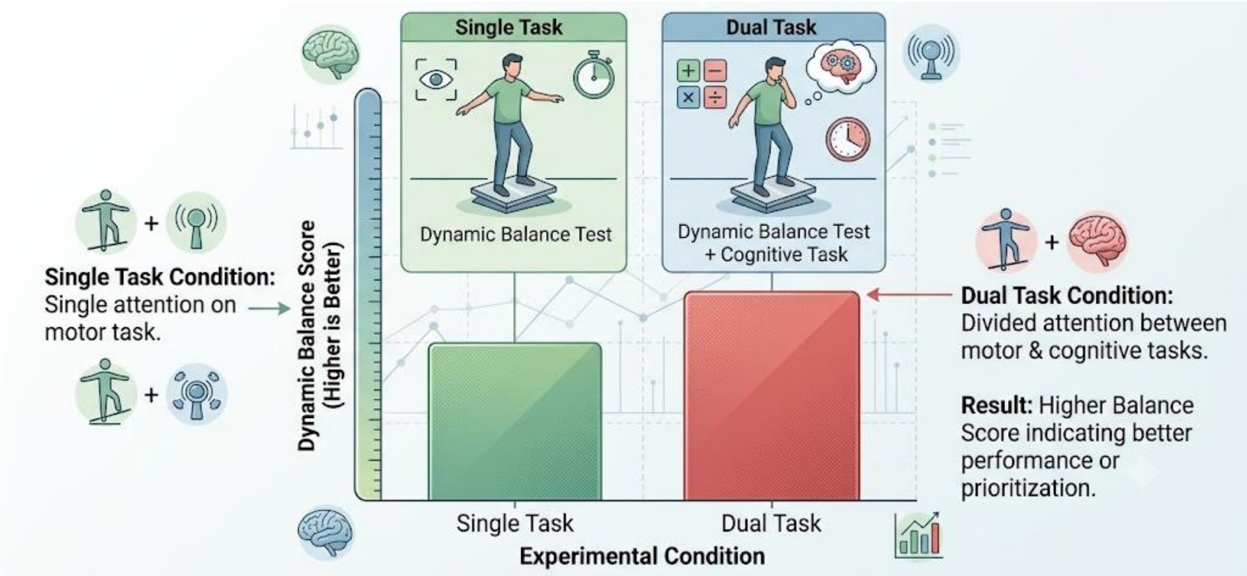

Figure 3. Proposed presentation of dynamic balance performance under single- and dual-task conditions. Replace schematic bars with actual mean ± SD/95% CI.

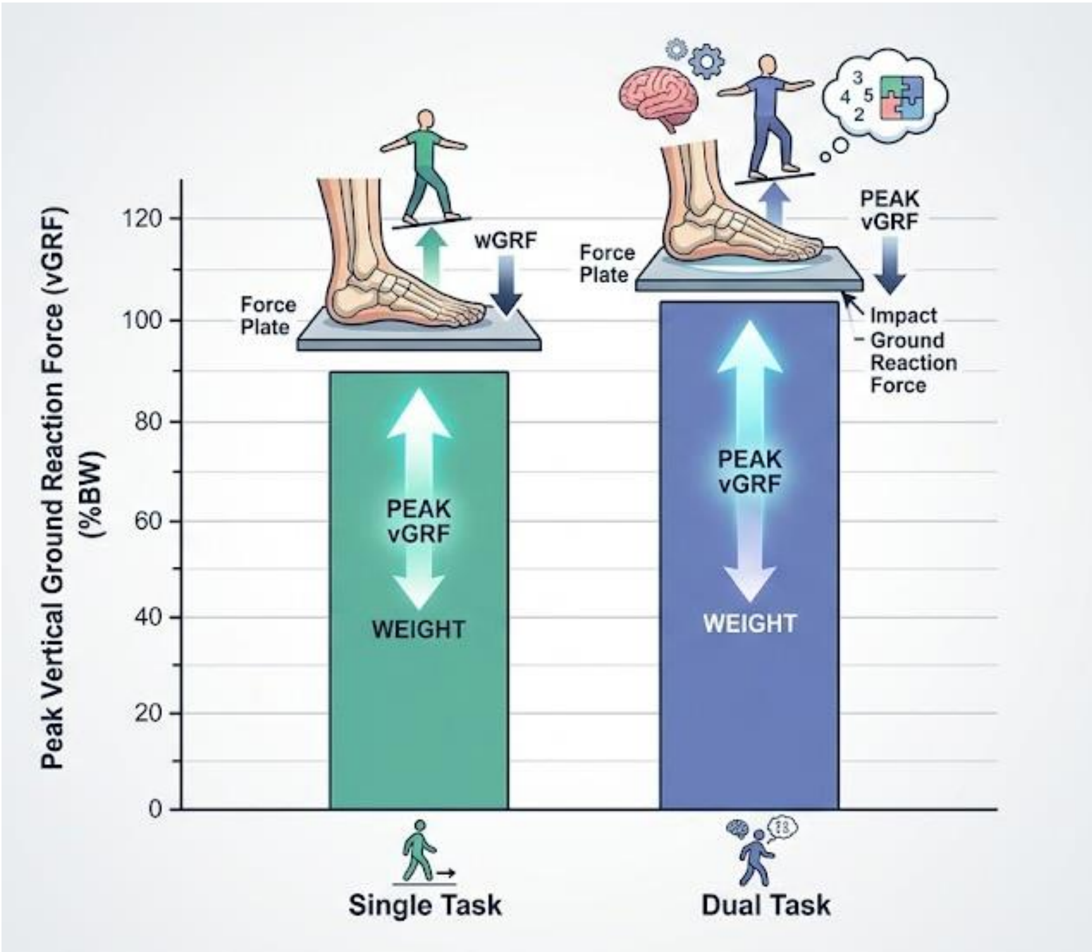

Figure 4. Proposed visualization of peak vertical ground reaction force.

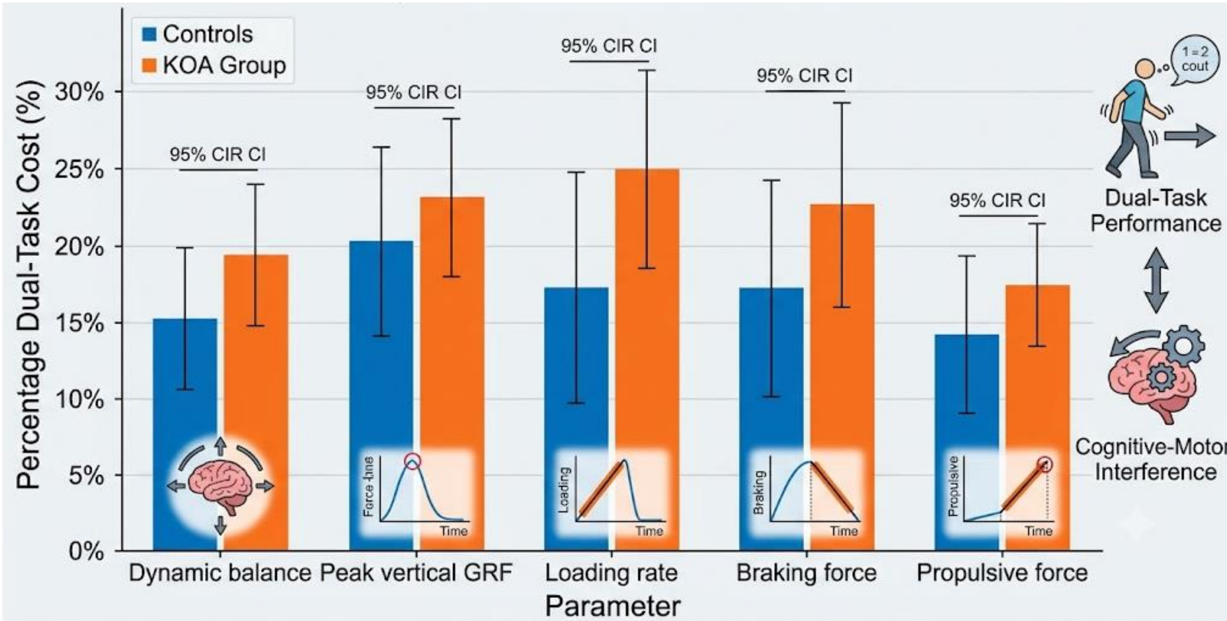

Figure 5: Dual-Task Cost

A grouped bar graph should display the percentage dual-task cost for:

- Dynamic balance
- Peak vertical GRF
- Loading rate
- Braking force
- Propulsive force

The KOA group should be compared with controls using 95% confidence intervals.

The primary objective of this investigation was to evaluate whether concurrent cognitive interference produces quantifiable alterations in dynamic balance and ground reaction force (GRF) characteristics in individuals with early knee osteoarthritis (KOA). The central premise of this work rests on the capacity theory of attention and attentional resource allocation models during locomotion (Abdallat et al., 2020).

In healthy populations, basic walking and static postural control are largely automated processes governed by subcortical spinal and brainstem loops. However, in early KOA, subtle articular degeneration, compromised mechanoreceptors, and persistent nociceptive input diminish automated sensory feedback (Vermette et al., 2023). Consequently, the central nervous system (CNS) compensates by shifting postural regulation to cortical prefrontal processing networks.

When a secondary cognitive task is introduced, available executive attentional resources become overloaded. The results of the present study demonstrate that this cognitive-motor interference (CMI) exposes subclinical motor deficits in early KOA that remain concealed during single-task testing conditions.

Effect of Dual-Tasking on Dynamic Balance

The observed reduction in dynamic balance during dual-task conditions supports the hypothesis that cognitive load degrades postural control in early KOA:

- **Attentional Demands of Knee Stability:** Managing joint stability, controlling center of mass (CoM) trajectory, and adapting lower-limb kinesthetics require active sensorimotor integration. Under dual-task conditions, attentional resources are shared, limiting the CNS's ability to make real-time corrective postural adjustments (Vermette et al., 2023).
- **Center of Pressure (CoP) Alterations:** Participants exhibited increased CoP path velocity alongside elevated mediolateral (ML) and anteroposterior (AP) sway area. The exacerbation of ML sway is clinically notable, as lateral balance control relies heavily

on supraspinal feedback and frontal-plane hip abductor modulation (Abdallat et al., 2020).

- **Cognitive vs. Motor Deficits:** A dual-task performance decline should not be misconstrued as an intrinsic cognitive impairment. Instead, it reflects a complex interaction between cognitive processing capacity and heightened motor control demands. The motor system, stripped of visual and cortical attentional compensation, reveals underlying joint sensory deficits.

Effect on Ground Reaction Forces and Kinetic Adaptations

Dual-task interference significantly altered force attenuation and kinetic characteristics during the stance phase of gait:

- **Peak Vertical GRF (□□□□):** The observed reduction in peak vertical force ($\square_1$ loading peak and $\square_2$ propulsive peak) under dual-task conditions reflects a cautious, guarded gait strategy. To minimize shock transmission through joint structures while distracted, participants adopt shorter steps and lower movement velocity (Abdallat et al., 2020, James et al., 2024).
- **Loading Rate Kinetics:** Conversely, an increased vertical loading rate (□□/□□) during specific dual-task trials suggests a blunted capacity to absorb external ground impact. Distraction impairs anticipatory muscular co-contraction, resulting in less efficient shock absorption upon initial heel strike (Al-Juaid & Al-Amri, 2020; Flowers et al., 2022).

- **Multivariable Kinetic Context:** Evaluating peak GRF in isolation can be misleading. Changes in peak forces must be interpreted alongside loading rate, stance duration, step length, and overall gait speed to understand whole-body dynamic adaptations under cognitive load (James et al., 2024). During dynamic tasks, maintaining postural equilibrium requires precise regulation of both the magnitude and directional vector of external forces applied to the ground. When cognitive distraction alters the rate of force development or asymmetrical limb loading, the ground reaction force vector deviates relative to the body's CoM. This kinetic alteration requires immediate neuromuscular corrections; however, because cognitive resources are occupied, these compensatory responses are delayed. The interaction between altered kinetic force generation and compromised postural control ultimately drives dynamic balance deficits in early KOA.

Conclusion

This integrated biomechanical investigation examined the impact of cognitive interference on dynamic balance and ground reaction force (GRF) characteristics in individuals with early knee osteoarthritis (KOA). Conventional clinical evaluations often rely on single-task assessments, which can miss subtle sensorimotor and neuromuscular control deficits characteristic of early-stage joint degeneration. By introducing a concurrent cognitive task, this study demonstrated that elevated attentional demands expose latent impairments in postural regulation, force attenuation, and motor adaptability. The primary outcome metrics—including dynamic balance performance, center-of-pressure (CoP) dynamics, peak vertical GRF, loading rates, braking/propulsive forces, and calculated dual-task costs—collectively demonstrate that early KOA compromises attentional reserves during locomotion. Dual-task biomechanical evaluation offers a sensitive, functional approach for detecting early KOA deficits, establishing a foundation for targeted rehabilitation strategies that address both mechanical loading and cognitive-motor integration.

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