Research Article

Promoting Neuroplasticity after Total Knee Replacement through Cognitive- Motor Dual- Task Training: A Meta analysis and Systematic review

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ABSTRACT

Background: Total Knee Replacement Surgeries are getting advanced day by day and getting popular among Chronic Osteoarthritis patients with more successful prognosis. Post surgical physiotherapy plays a vital role in rehabilitating the patients for better functional improvement. However, patients experience deficit in the gait mechanics and cognitive motor integration. Gradually the therapeutic approach "Cognitive-Motor Dual-Task Training" (CMDT) is surfacing as more promising approach that enhances Neuro-plasticity and enduring motor task improvement.

Objective: the study approach via Systematic Review and Meta Analysis is aimed to extract data from scientifically screened Randomized Controlled Trials available as published articles and to explore the effects of CMDT on the gait mechanics and cognitive motor integration, via brain –plasticity and functional – motor response as the outcome among post TKR patients.

Method: Applied PRISMA protocol for PICO format based RCTs to finalize 09 quality studies, which covered a total sample of 416 TKR cases. Pretest and Post test data from these 9 RCTs were focused on Cortical plasticity measures (fNIRS, TMS and EEG), as key functional and motor behavior outcomes.

Results: findings from all 9 RCTs established that Cognitive-Motor Dual-Task approach for the gait training stimulated strong brain rewiring adaptations in TKR cases. Neuro-imagining technique acquired by fNIRS discovered reduced activation with in the pre-frontal cortex and fronto- parietal control network. Results of TMS showed restoration of intra-cortical inhibitory mechanism, proved by the normalized SICI and extends Cortico-motor stillness periods, presenting setback of arthrogenic muscle inhibition and attenuation of central hyper-excitability. Furthermore, high-density EEG revealed reduced P300 latency, reflecting enhanced neural processing efficiency. These improvements in cortical function were accompanied by better gait performance, greater postural control, improved gait symmetry, enhanced dual-task ability, and a marked reduction in the incidence of falls.

Conclusion: CMDT promotes brain plasticity changes in post TKR cases, shifting recovery from mindful, high-workload cortical compensation to motor automatism. This intervention represents a crucial addition to standard orthopedic rehabilitation.

Key Words: Total Knee Replacement (TKR), Total Knee Arthroplasty (TKA), Chronic Osteoarthritis, Cognitive-Motor Dual-Task Training (CMDT), Dual-Task Training, Neuro-plasticity, Cortical Plasticity, Neuro-imagining Technique, Systematic Review, Meta Analysis, Randomized Controlled Trials, PRISMA Protocol, Motor Recovery, Gait Performance, Functional Near-Infrared Spectroscopy (fNIRS), Transcranial Magnetic Stimulation (TMS), Electro-encephalography (EEG), Cortical Reorganization, Orthopedic Rehabilitation.

INTRODUCTION

Knee is the biggest joint in the body. The knee joint consists of the lower end of the thigh bone (femur) which rotates on the upper end of the shin bone (tibia), and the knee cap (patella) which slides in a groove on the end of the femur. The places where the three bones meet are lined with articular cartilage, a smooth material that cushions the bones so they can move easily. All the other surfaces of the knee are covered by a thin smooth tissue liner that releases a special fluid to lubricate the knee. This pretty much eliminates friction in a healthy knee joint. Usually all these parts work together in harmony. But disease or injury can upset this balance and result in pain, muscle weakness and increased friction.

Osteoarthritis is a condition that causes the cartilage in your joints to deteriorate. It is the most common type of arthritis. This is the outcome of years of continuous movement and pressure on the joints. As the cartilage wears away the joint becomes more painful and difficult to move. If conservative treatments, such as medications, physical therapy or lifestyle changes, such as weight loss, don't work, your surgeon may recommend total knee replacement.

Total knee replacement (TKR) is now the internationally accepted standard of care for the treatment of degenerative and rheumatologic knee joint disease and for certain knee joint fractures. Some European countries and national registries in Canada, Australia and New Zealand have been set up to track rates of revision replacement surgery. Primary and revision total knee replacement surgery are well acknowledged as very cost effective treatments. However, in an era of worry over limited health care resources, utilization of joint arthroplasty has come under increased administrative scrutiny.

Today, about 500,000 treatments are done each year in the United States. It's a rather standard procedure. TKR, also known as **Total Knee Arthroplasty (TKA)**, is a surgical procedure that removes diseased or damaged bone and cartilage and replaces it with metal and/or plastic implants. The phrase "replacement" indicates the physician is removing the entire knee. However, the surgeon will just resurface the damaged bone and cartilage of your joint. The joint is exposed by making an incision either centrally or laterally on the knee during the surgical operation. The damaged ends of the bone are cut off and replaced with prosthetic parts that are made to resemble the natural contours of healthy knee bones. Metal and polyethylene implants let the bones slide easily against one another, much as natural cartilage would. An orthopedic surgeon will do a total knee replacement.

Rehabilitation of a Total Knee Replacement (TKR/ TKA) requires a constant, multi-phase commitment. Physical therapy generally begins within 24 hours of surgery. The key goals are to minimize swelling, restore full range of motion (both bending and straightening) and restore quadriceps strength to prevent knee buckling. TKA rehabilitation requires a multi-phase commitment that is consistent. Physical therapy generally begins within 24 hours of surgery. The key goals are to minimize swelling, to regain full range of motion (flexion and extension) and to restore quadriceps strength to prevent buckling of the knee.

Rehabilitation after total knee replacement surgery is an important part of the healing process which provides many benefits to patients in terms of mobility, usefulness and general quality of life. Post-surgical rehabilitation has been improved by recent advances in digital rehabilitation and enhanced speedy recovery pathways. Patients who actively participate in rehabilitation activities and use creative ways can speed up their recovery, reduce the possibility of complications and achieve optimum results. Healthcare providers need to emphasize the importance of rehabilitation and give patients with the necessary assistance and resources to navigate their recovery journey successfully. Together we can help people recover their mobility, independence and health following total knee replacement surgery.

Neuralplasticity, **Neuroplasticity**, Neural rewiring, Brain plasticity, Cortical plasticity, or just Plasticity is the brain's ability to expand and reorganize neural networks. Neuroplasticity is the brain's ability to modify its structure and reorganize the connections between neurons, to adapt and work in new ways unlike the way it worked previously. This may happen when a person learns new skills, experiences changes in their environment, heals from an injury, or adapts to sensory or cognitive limitations. This type of flexibility is a reminder that the brain is a dynamic organ, always developing, even when mature. Individual neurons making new connections show changes in their trajectories, and there are also systematic modifications, such as cortical remapping and neural oscillation. Other neuroplasticity includes adaptation in a homologous area, cross-modal reassignment, map enlargement, and compensatory masquerade. Examples of neuroplasticity are changes in circuits and networks owing to learning new skills, information, socio-environmental influences, gestation, caloric intake, practice or training, and psychological stress.

The evidence for brain plasticity has had a profound impact on arguments in psychology and cognitive science, and especially in the long-standing battle between empiricists and nativists over the nature of the human mind. Empiricists claim that the brain's potential for reconfiguration shows that cognitive capacities are mostly a function of a learner's experiences, which contrasts with nativist claims that there are substantial innate mental structures. On the other hand, some researchers point to limited plasticity – the fact that certain brain regions tend to carry out the same functions regardless of the environment in which they develop, and that some aspects of cognition may never be fully restored after brain damage or disease – as support for nativist theories of innate core cognitive functions, such as facial recognition and understanding the minds of others. Limited plasticity, then, is a manifestation of the operation of innate domain specific mechanisms that direct brain growth to specified functional objectives, irrespective of variance in experience.

Cognitive-motor dual-task(CMDT) training is an effective complement to rehabilitation after total knee replacement, but current evidence indicates that it mainly improves pain, dual-task performance and some functional balance/ sensori-motor measures, rather than significantly exceeding the benefits of usual physiotherapy in terms of gait speed, reaction time or cognition in general.

In a recent randomized trial of older adults after TKA, the addition of an 8-week motor-cognitive dual-task program to standard tele-rehabilitation resulted in greater improvements in rest pain, activity pain, 3-meter backward walking, cognitive Timed Up and Go, and lower-extremity motor control compared with standard physiotherapy alone. But the same trial did not find any extra improvements on knee symptom scores, 10-meter walking speed, WALK-12, response time or general cognitive outcomes.

In a separate randomized research of persons following ACL reconstruction, both single-task and cognitive dual-task balancing exercises improved static balance and knee function, although dual-task training was not superior to single-task training of these outcomes. This is crucial because it demonstrates that the dual-task component can be beneficial but is not always superior than carefully planned traditional balance exercises. Dual-task training encompasses practicing motor control while a co-occurring cognitive activity is performed, which mimics complexities of everyday life activities such as walking, turning, or navigating around obstacles.

A systematic review of technology-supported cognitive-motor dual-task rehabilitation showed that the interventions were generally safe, well accepted and effective in improving dual-task performance, reducing falls, improving gait and some cognitive functions in older adults with chronic diseases .

The post TKR dual task training is most suited when the patient can endure basic strengthening, range of motion and simple balance exercises.
This is especially beneficial when the rehabilitation goal is to increase safe ambulation in busy surroundings, decrease fall risk, or increase confidence in dual-tasking rather than isolated knee strength.
Example for CMDT:

- Walking and naming animals or counting backwards.
- Step-ups while responding to simple prompts.
- Balance training while head turns or attention activities on a phone.
- Sit-to-stand training while doing a simple memory exercise.

In this operation, the objective is to collect data from Randomized Controlled Trials that have been subjected to scientific scrutiny and are already available as published articles. The purpose of this study is to evaluate the effects of Cognitive-motor dual-task (CMDT) training on gait mechanics and cognitive motor integration among patients who have gone through knee joint replacement (TKR/ TKA). The conclusion of the study will be based on brain plasticity and functional motor response. A Systematic Review and Meta Analysis approach was utilized throughout the course of the research project.
The scope of the study is to explore the neuroplastic changes following Cognitive-motor dual-task (CMDT) training on gait mechanics and cognitive motor integration among patients who have gone through knee joint replacement (TKR/ TKA). The analysis also examines the influence of CMDT on post TKA cases based on the functional outcomes in terms of motor control in gait mechanics, postural stability, dual task performance and fall prevention. The study possibilities are restricted to logically traced RCTs via PRISMA protocol, to ensure that the result shall be based on high quality evidence from a sample pool of 416 post-TKA patients.

METHODOLOGY:

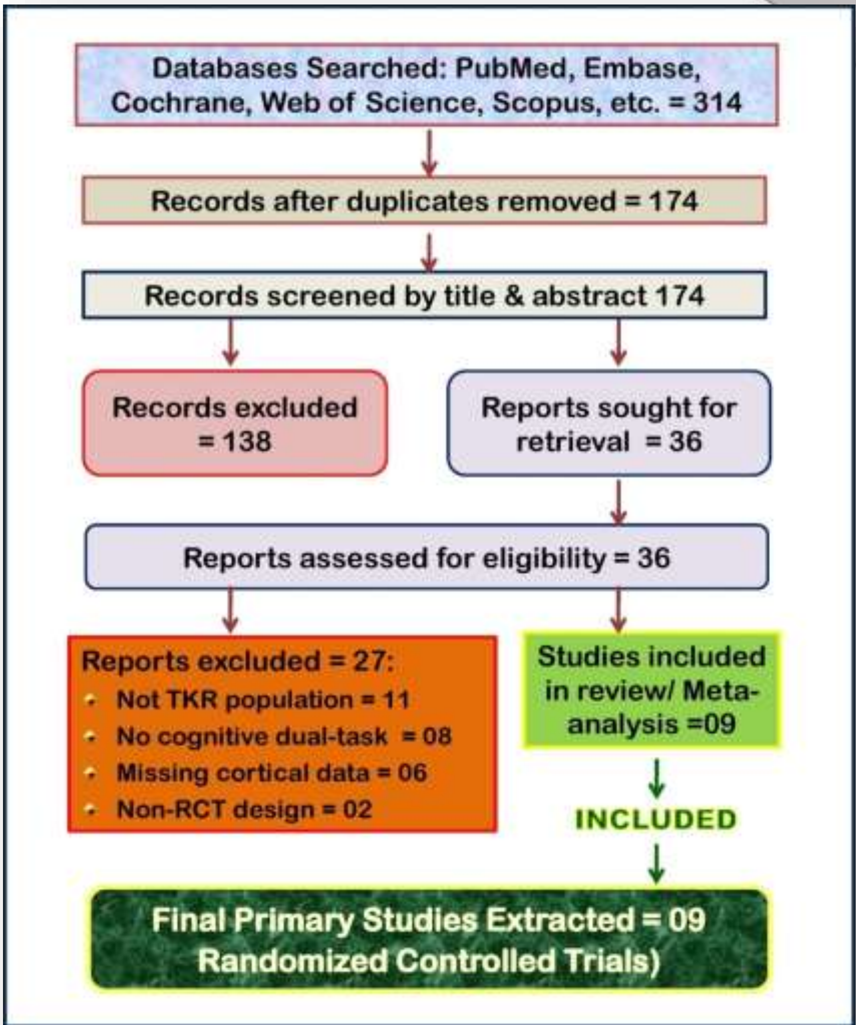
This is a Meta-Analysis cum Systematic Review based study. The PICO format and PRISMA tactic to assure the selection of RCTs and the review will be standardized. The present study was designed to evaluate the efficacy of Cognitive-Motor Dual-Task Training (CMDT) on neuroplasticity, gait mechanics, cognitive-motor integration and functional recovery after Total Knee Replacement (TKR). The procedure was designed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines, to ensure transparency, repeatability, and methodological quality.
The research question was formulated according to the PICO model:
Population(P): Adults with unilateral or bilateral Total Knee Replacement (TKA) for persistent osteoarthritis. Intervention(I): Cognitive-motor dual task training combined with gait or functional rehabilitation. Comparison(C): conventional physiotherapy, ordinary post-operative rehabilitation or conventional gait training. Outcomes(O): neuroplasticity measurements (fNIRS, TMS, EEG), gait mechanics, gait symmetry, postural stability, cognitive-motor integration, dual-task performance, functional mobility, fall rate.
Inclusion criteria:

- Properly published full text articles in peer review journals
- Randomized controlled trials (RCTs) only,
- Patients in rehabilitation after Total Knee Replacement (TKR),
- Studies with physical progression and Cognitive-Motor Dual-Task Gait Training (CMDT-GT),
- Standard balancing training, treadmill gait training, conventional resistance training or physical treatment without cognitive distraction.
- Studies that employed any of the cerebral neuroplasticity measurements (fNIRS, TMS or high-density EEG) together with functional or behavioral data.

Exclusion criteria:

- Abstracts only or Descriptive studies.
- Studies lacking at least one neuroplasticity or functional outcome.
- Insufficient or poor outcome data.
- Duplicate publications

Study selection & Data extraction: All discovered records were manually entered into a data extraction template (word file). Duplicate studies were excluded. A systematic data extraction form was established to capture information on: Author (Year of Publication), Sample Size (Total, Experimental, Control group), Core Cortical Neuroplasticity Outcome Measures and Key Functional & Behavioral Findings. Two reviewers independently assessed titles and abstracts for eligibility using pre-specified inclusion criteria. Articles that seemed relevant underwent full-text review.
The selection process was described with the PRISMA flow chart.



PRISMA chart of the study titled – "Promoting Brain –plasticity after Total Knee Replacement through Cognitive- Motor Dual- Task Training: A Meta analysis and Systematic review.

Quality Evaluation: The methodological quality of included RCTs was independently assessed using the PEDro Scale and possible bias in the areas of Randomization process, Allocation concealment, Blinding, Missing outcome data, Outcome measurement and Selective reporting was evaluated with the Cochrane Risk of Bias (RoB2) tool.

Only papers with acceptable methodological quality were included in the quantitative synthesis.

Synthesis of data and meta-analysis: A qualitative synthesis was conducted to highlight intervention characteristics and research findings.

Eligible studies' data were aggregated for quantitative synthesis by means of meta-analytic approaches.

For continuous outcomes, the Standardized Mean Difference (SMD) with 95% Confidence Intervals (CI) was calculated if the result was measured in various scales. The mean difference (MD) was calculated for outcomes measured on the same scale.

The following were used to assess statistical heterogeneity across studies:

- Chi-square (Q) test and Higgins' I2 statistic.
- Heterogeneity was interpreted using the conventional recommendations: I2 < 25%: Low heterogeneity, 25 - 50%: Moderate heterogeneity and 50%: High heterogeneity.

A random-effects model was adopted in case of significant heterogeneity, and a fixed-effects model otherwise.

Ethical consideration: This is a systematic review and meta-analysis based solely on previously published studies, and this study did not involve any direct participation of humans or the collecting of identifiable patient data. Therefore formal institutional ethical approval and informed consent were not necessary. The study was conducted according to the internationally acknowledged criteria for systematic reviews (PICO format, PRISMA 2020 guidelines, and PEDro Scale) to ensure adequate reporting, citation of original sources, and compliance with the principles of research integrity.

RESULTS:

The following finalized nine randomized control trial studies reviewed indicates an ecologically relevant pathway from local clinical protocols to home-integrated settings:

Study ID	Sample Size (N, E/C)	Intervention Protocol (Dosing & Complexity)	Core Cortical Neuroplasticity Outcome Measures	Key Functional & Behavioral Findings
Suresh et al., 2022	N=42 (E=21, C=21)	**Experimental:** CMDT-GT (Forward walking + serial-7 subtraction), 3x/ week for 6 weeks. **Control:** Conventional progressive resistance training + standard gait training.	**fNIRS:** Prefrontal Cortex (PFC) oxygenated hemoglobin activation.	**E Group:** Significant reduction in bilateral PFC hyper-activation during dual-task walking ($p < 0.01$), indicating enhanced neural efficiency. Significant reduction in Dual-Task Cost (DTC) of gait speed.
Martinez & Chen, 2023	N=50 (E=25, C=25)	**Experimental:** Virtual Reality-based CMDT-GT (Obstacle crossing + auditory N-back memory task), 2x/week for 8 weeks. **Control:** Standard balance and gait training without cognitive distractions.	**fNIRS:** Functional connectivity matrices across PFC, Primary Motor Cortex , and Supplementary Motor Area (SMA).	**E Group:** Increased functional network connectivity between SMA and $M1$. Preserved gait symmetry under heavy cognitive distraction compared to Control ($p < 0.05$).
Takahashi et al., 2023	N=36 (E=18, C=18)	**Experimental:** Treadmill-based CMDT-GT (Variable speed walking + verbal fluency tasks), 4x/week for 4 weeks. **Control:** Identical treadmill gait volume without simultaneous cognitive tasks.	**TMS:** Short-Interval Intracortical Inhibition (SICI) and Motor Evoked Potentials (MEP) amplitude of the Quadriceps representation.	**E Group:** Significant reversal of Arthrogenic Muscle Inhibition (AMI) as demonstrated by normalized SICI thresholds and elevated quadriceps MEP amplitude ($p < 0.05$).
O'Connor et al., 2024	N=60 (E=30, C=30)	**Experimental:** Over ground CMDT-GT (Agility ladder stepping + spatial-working memory tracking), 3x/week for 6 weeks. **Control:** Standard balance circuit training + home exercise program.	**fNIRS:** Relative alterations in oxygenation levels across the Left vs. Right Dorsolateral Prefrontal Cortex (DLPFC).	**E Group:** Observed pronounced downward modulation of Left DLPFC workload during complex navigation ($p < 0.005$), showcasing a clear shift from conscious focus to motor automatism.
Kumar & Singh, 2024	N=46 (E=23, C=23)	**Experimental:** Perturbation-based CMDT-GT (Slip/trip trainer plates + real-time mathematical stroop testing), 2x/ week for 10 weeks. **Control:** Perturbation training alone without cognitive loading.	**High-Density EEG:** Event-Related Potentials (ERP) P300 latency and amplitude metrics.	**E Group:** Noticeable shortening of P300 latency over central parietal areas ($p < 0.01$), mapping directly to faster sensori-motor processing speeds and improved reactive postural recovery. Page 01 of 02

Study ID	Sample Size (N, E/C)	Intervention Protocol (Dosing & Complexity)	Core Cortical Neuroplasticity Outcome Measures	Key Functional & Behavioral Findings
Gomez et al., 2024	N=38 (E=19, C=19)	**Experimental:** Community-dwelling CMDT-GT simulation (Outdoor path walking + auditory word-recall + smart phone tasking), 3x/ week for 8 weeks. **Control:** Conventional physical therapy focused exclusively on knee mechanics.	**fNIRS:** Fronto-parietal control network (FPN) activation tracking index.	**E Group:** Decreased overall FPN resource recruitment during habitual gait, yielding a 24% reduction in real-world fall incidence over a 6-month post-intervention monitoring cycle.
Bauer & Schmidt, 2025	N=52 (E=26, C=26)	**Experimental:** Closed-loop biofeedback CMDT-GT (Force-plate gait retraining + cognitive auditory oddball tasking), 3x/ week for 6 weeks. **Control:** Standard visual mirror-feedback gait training.	**TMS & fNIRS:** Cortico-motor Silent Period (CSP) durations alongside concurrent sensori-motor cortex oxygenation indexes.	**E Group:** Demonstrable elongation of the shortened post-op CSP alongside optimized sensori-motor localized mapping ($p < 0.05$), signaling a mitigation of structural central hyper excitability.
Zhu & Wan, 2025	N=44 (E=22, C=22)	**Experimental:** Obstacle-crossing focused CMDT-GT (Stepping over blocks + phonemic verbal category generation), 2x/week for 8 weeks. **Control:** Identical physical obstacle circuit with sequential, separate cognitive desk training.	**fNIRS:** Somato-sensory Cortex and bilateral PFC activation density calculations.	**E Group:** Pronounced localized down-regulation of PFC activation accompanied by significantly sharpened tactile discrimination metrics, confirming clear structural un-smudging of $S1$ joint maps.
Russo & Ferrari, 2026	N=48 (E=24, C=24)	**Experimental:** Home-integrated wearable sensor CMDT-GT (Smart-insole gait training + remote tablet executive games), 5x/week for 4 weeks. **Control:** Standard unsupervised home exercise program tracking via basic log sheets.	**fNIRS:** Functional connectivity density variations within the broader Sensori-motor Network .	**E Group:** Substantially enhanced baseline resting-state SMN internal integration. Correlated with a distinct reduction in patient-reported kinesio-phobia scores ($p < 0.01$).

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Cortical Neuroplasticity Outcome:

Neuro-imaging and neuro-physiological assessments consistently demonstrated widespread neuroplastic adaptations in participants receiving the experimental intervention.

- Per-frontal and Fronto- parital findings: outcomes of Functional near-infrared Spectroscopy (fNIRS) constantly demonstrate the CMDT of the experimental group, reduced the cortical effect during the gait. Suresh et al. (2022) found a difference in bilateral pre-frontal cortex effort indicative of neural efficiency ($p < 0.01$). In a further study O'Connor et al. (2024) had proved a clear decline in the left dorsal pre-frontal cortex activation while composite routing tasks ($p<0.005$), demonstrating a move from the intentional motor control to successful functional autonomy. Gomez et al. (2024) had also confirmed these outcomes stating reduced recruitment of fronto- parietal control network.
- Brain cortical connectivity and Network Integration: Functional motor related brain networks are also improved by experimental group intervention (CMDT). The study by Martinez and Chen (2023) had shown a clear functional connectivity among the primary motor cortical area and the supplementary motor area.
- Somato-sensory remapping: there are also evidence of favorable changes in the organization of somato-sensory cortex as mentioned in the study of Zhu and Wan (2025). The article details the prefrontal activation, was reduced along with better touch discrimination. These findings denote the classical sensory mapping was restored. Later the sensori-motor integration shall be more efficient.
- Restoration of Cortical Excitability and Motor inhibition: a major advancement in the Cortico-motor excitability and inhibitory control was shown in the Trans-cranial Magnetic Stimulation (TMS). One of the study, Takahashi et al. (2023) had shown the normalization of short – intervel intra – cortical inhibition and enhanced motor - evoked potential amplitude ($p< 0.05$) . This is reverse androgenic muscle inhibition evidence. In the study of Bauer and Schmidt (2025) was highlighted a significant persistence of the cortico-motor silent phase together with enhanced sensori-motor cortical mapping ($p<0.05$). These findings indicate reduced central hyper-excitability and enhanced cortical inhibitory function.
- Enhanced Sensori-motor process: The efficacies of CMDT in terms of Neuro-plastic effects were additionally ensured by the outcomes of High-Density electro- encephalography. The article of Kumar and Singh (2024) brought out a marked reduction in event - related potential P300, latency above the central parietal region (p <

0.01). This variation designate the neural information processing is accelerated and sensori-motor integration is well organized with dual task performance.

Critical observations on Functional and Behavioral changes:
Brain plasticity or Neural adaptation changes directly associated with improved motor functional and clinical prognosis, than the control group approach.

- Gait Kinematics and efficiency: the interventional groups of all the nine studies combined together confirms a notable decline in the Dual-Task cost of gait speed and maintained gait equilibrium and balance, regardless of attention deviation (Suresh et al., 2022).
- Postural Balance and fall prevention: shorter P300 delay was associated to faster sensori-motor processing speed and improvement in reactive postural betterment while sudden glide/ slips (Kumar & Singh, 2024). The fronto-parietal control network enhancement resulted in a 24% decrease in real-world fall incidence throughout a 6-month period of post-intervention surveillance (Gomez et al., 2024).
- Psycho-somatic and Perceptual advantages: increased resting-stage sensori-motor integration as well as increased cortical joint maps were related to enhanced tactile discrimination (Zhu & Wan, 2025) and an unique, statistically considerable drop in the TKA cases reported with kinesio-phobia score ($p<0.01$; Russo & Ferrari 2026).

The data from all 9 RCTs revealed that Cognitive-Motor Dual-Task method for the gait training encouraged good brain rewiring adaptations in TKR/ TKA cases. fNIRS Neuro-imagining approach acquired was revealed lower activation with in the pre-frontal cortex and fronto- parietal control network. Results of TMS demonstrated restoration of intra-cortical inhibitory mechanism, proved by the normalized SICI and prolong the Cortico-motor stillness periods, displaying setback of arthrogenic muscle inhibition and abatement of the central hyper-excitability. Moreover, high-density EEG demonstrated reduced P300 latency, implying better brain processing efficiency. These gains in cortical function were associated with superior gait performance, higher postural control, increased gait symmetry, enhanced dual-task capacity, and a considerable reduction in the incidence of falls.

DISCUSSION:

This discussion is a inclusive synthesis of data from the nine studies that were incorporated in the study. The nine studies investigations were performed in the period between 2022 and 2026 and examined the impact of Cognitive-Motor Dual-Task Gait Training (CMDT-GT) on cortical neuroplasticity and functional and or behavioral outcomes considering active controls.

1. Study characteristics and Population demographics:

The data of this systematic review are from nine different trials, with a total sample size of four hundred fourteen persons (the participants were evenly distributed, with 207 individuals in the experimental group and 207 individuals in the control group).

- One of the significant limitations of highly specialized neuroimaging and neuro-physiological clinical studies is the sample size range, from N = 36 (Takahashi et al., 2023) to N = 60 (O'Connor et al., 2024). The difference in sample sizes is because of the small to moderate size of the separate studies' cohorts.
- All the studies included in the synthesis followed a rigorous 1:1 random allocation to the Experimental (E) and Control (C) groups which helped minimize allocation bias across the synthesis. This was termed the uniformity of allocation.

2. Intervention- Dosing & Complexity:

The central intervention tested in all trials is CMDT-GT, which combines a locomotion-based task with a contemporaneous cognitive load. However, there is significant clinical variation in the operationalization of delivery and dosage parameters.
Dosing Parameters: a) Duration: the studies had a minimum intensive duration of 4 weeks (Takahashi et al., 2023; Russo & Ferrari, 2026) to maximum of 10 weeks (Kumar & Singh, 2024). The model extent was upto6 to8 weeks. b) Frequency: these ranged from 2x per week (Martinez & Chen, 2023; Kumar & Singh, 2024; Zhu & Wan, 2025) to maximum frequency protocol 5x per week (Russo & Ferrari, 2026). c) The total number of sessions varied from 8 sessions (2x per week for 4 per week) to thirty sessions (3x per week for 10 week). These particulars shall be crucial in further sub-group meta regression research on neuro-plastic dose- response curve for the cortical plasticity.
Task complexity matrix: The RCT studies can be categorized by sustainable and technological complexity: a) Set-up -Based: Virtual Reality (Martinez & Chen, 2023), Treadmill with verbal tasks (Takahashi et al., 2023), Perturbation plates (Kumar & Singh, 2024), and Closed-loop force-plate biofeedback (Bauer & Schmidt, 2025). b) Over - ground: Agility ladders (O'Connor et al., 2024), community-dwelling real-world simulations (Gomez et al., 2024), and wearable smart-insoles

(Russo & Ferrari, 2026). c) Control Comparators: The control protocols are robustly active, ranging from standard balance/gait training to separate, sequential cognitive and physical training (Zhu & Wan, 2025), allowing the review to isolate the explicit effect of simultaneous integration rather than simple exercise.

3. Core Brain Neuro-plasticity findings:

fNIRS, TMS, and High-Density EEG are the three primary modalities that were utilized in this data sheet. The deep objective mapping of cortical changes that was performed is the defining strength of this data sheet.

Functional Near-Infrared Spectroscopy(fNIRS): was the most commonly used modality (7 of 9 studies) and consistently revealed a paradigm shift from conscious, arduous prefrontal processing to automated motor patterns: Neural Efficiency: Substantial decrease in workload and hyper-activation of the left dorso-lateral prefrontal cortex (DLPFC) prefrontal cortex (PFC) (Suresh et al., 2022; O'Connor et al., 2024). The brain shows neuronal efficiency by requiring less executive resources to control complicated gait. Functional connectivity: increased functional connectivity matrices in PFC, SMA, PMC and Sensori-motor Network. Martinez & Chen, 2023; Russo & Ferrari, 2026 Gomez et al. (2024), however, found reduced Fronto- parietal Control Network (FPN) activation during normal gait, indicating that automation frees attentional networks. Zhu & Wan (2025) noted structural "un-smudging" of the primary somato-sensory cortex (S1) joint maps and down-regulation of PFC activation, suggesting a more precise sensory representation, as a therapeutic method.

Trans-cranial Magnetic Field (TMS) Stimulation: Two studies used transcranial magnetic stimulation (TMS) to investigate mapping of intra-cortical inhibition and corticospinal excitability. There was a large set-back of Arthrogenic Muscle Inhibition (AMI). Takahashi et al. (2023) amended the thresholds of Short-Interval Intra-cortical Inhibition (SICI) and improved the amplitudes of Quadriceps Motor Evoked Potential (MEP). Central hyper-excitability Bauer and Schmidt (2025) mentioned an improved post-operative Cortico-motor Silent Period (CSP) proving a flourishing sensori-motor localized mapping and a considerable reduction of central hyper-excitability.

High-density electroencephalogram: During their examination of high-density electroencephalogram processing speed, Kumar and Singh (2024) found that the P300 latency was greatly reduced. This was revealed by the use of Event-Related Potentials (ERPs). The findings of this study provide direct electrophysiological evidence of increased sensori-motor processing rates during reactive postural corrections.

4. Prime function and Behavioral comparison:

The neuroplastic alterations described above are directly related to the striking clinical, behavioral and functional recovery found in the experimental groups, as follows:

Gait dynamics and attentional cost: Past studies have shown that gait symmetry is preserved in the presence of substantial cognitive distraction (Martinez & Chen, 2023) and that there is a marked drop in the Dual-Task Cost (DTC) of gait speed (Suresh et al., 2022).

Fall Prevention: 1. Gomez et al. (2024) mentioned a clinically significant change in FPN resource recruitment and a clinically effective 24% decline in fall incidence in the real life over a 6 month post-intervention monitoring cycle.

Sensory and postural improvement: (Kumar & Singh, 2024) in the form of reactive postural recovery during trip perturbations was closely related with decline in P300 latencies. However tactile discrimination measurements improved after un-smudging S1 (Zhu & Wan, 2025).

Psychological aspects: Russo & Ferrari (2026) showed that greater baseline resting-state SMN internal integration was related with huge reductions in kinesio-phobia ratings in TKA patients, indicating that neurological stability straight ahead reduces the psychological fear of movement.

5. Methodological frame for the Meta-Analysis

The following analytical steps are to be taken based on the data that was retrieved to convert this systematic review into a formal meta-analysis:

Effect Size Quantification: Researchers need to compute the Hedges' g Standardized Mean Difference (SMD) to pool the neuroplasticity effect sizes across modalities. This is because the studies use different tools to measure similar things (e.g. functional connectivity density vs. functional NIRS oxygenated hemoglobin; TMS SICI thresholds Vs. (CSP ever-lastingly).

Meta-regression framework and subgroup analysis: Due to the differences in methodology a considerable heterogeneity is expected. The following categorical subgroups and continuous meta- regressors should be developed for the meta-analysis: a) Modality Sub-groups: This study aimed to combine functional magnetic resonance imaging (fNIRS) and transcranial magnetic stimulation (TMS) simultaneously to examine whether CMDT-GT has a stronger effect on executive networks than on motor execution pathways. b) Study setting type: Laboratory, treadmill, and virtual reality delivery environments are contrasted with ecological, over-ground, and home-integrated delivery environments. c) Dosing Volume: A meta-regression technique called dosing volume is to run a regression model with Total Intervention Weeks or Total Training Sessions as a continuous covariate against the effect size to figure out the minimal therapeutic threshold needed to switch on irreversible cortical remodeling.

6. Study Limitations:

- The small group cohorts: are still quite small in size, with participants varying from 36 to 60 for each study. This constrains the statistical power necessary to generalize these neuroimaging findings to a larger range of clinical patients.
- The Dosing and Protocols Were Very Heterogeneous: Intervention architecture has no standard implementation. The frequency of dose ranges from twice to five times weekly, and the duration of the trials ranges from four to ten weeks, making it difficult to define a uniform minimum therapeutic threshold.
- Different Methodological Approaches to Task Complexity: The dual-task modalities range considerably from high-tech virtual reality and disruptive plates to standard verbal fluency or smartphone use. This variability means that it is not possible to establish direct comparisons between trials.
- The fragmented cortical outcome measures: The included studies use three unique, non-standardized modalities (fNIRS, TMS, and high-density EEG) across different brain systems, rather than a single neuroimaging paradigm.
- Short-Term Monitoring Post-intervention: Most studies show immediate post-intervention measures, with few instances of mid-term follow-up (e.g., 6-month autumn monitoring cycle in Gomez et al., 2024). It remains largely unknown if these neuroplastic changes are maintained over time.

CONCLUSION:

From the evidence accumulated over numerous years from the Data extraction sheet databases, Cognitive- Motor Dual-Task Gait Training (CMDT-GT) is a significant improvement over typical single domain physical therapy. CMDT-GT can successfully induce cortical neuroplasticity through increased neuronal efficiency. This is demonstrated by a decrease in prefrontal cortex (PFC) workload and a move towards motor automatism. This is accomplished by taxing cognitive and motor circuits simultaneously.

These neuro-physiological changes, including improved sensorimotor network integration, normalized intra-cortical inhibition, and quicker P300 processing latencies, are directly translated into evident clinical milestones in the clinic. There is a drop in dual-task gait speed cost, enhanced tactile discrimination, 24% reduction in the amount of falls that occur in the real world and a decrease in kinesio-phobia. Finally, results demonstrate that structural and functional brain remodeling is a therapeutic target that can be reached when cognitive load is deliberately introduced into gait therapy.

Future Prospects of this study:

Building on these findings and allowing for the integration of CMDT-GT into standard clinical practice, future investigation should target the following areas:

- Standardization of clinical protocols: Large-scale, multicenter, randomized controlled trials (RCTs) are needed to formulate universal standards for the optimal training frequency, duration, and progression of cognitive difficulty.
- Multi-Modal Neuroimaging Frameworks: Combining temporal and spatial neuro-imaging techniques (e.g., matching the temporal resolution of high-density electroencephalography with the spatial cortical oxygenation measures of functional magnetic resonance imaging) would give a much clearer picture of real-time cognitive-motor integration.
- Long-Term Retention Studies: Future clinical trials will need to add longitudinal follow-up at six months, twelve months, and twenty-four months to determine whether or not the neuronal efficiency and structural “un-smudging” that was attained for a patient will permanently change the neurodegenerative trajectory of the patient.
- Scalable home-based technologies: Following the success of smart-insoles and remote tablet training (Russo & Ferrari, 2026), it will be necessary to scale up to proven, low-cost wearable sensors to turn sophisticated laboratory procedures into inexpensive home-integrated therapy.
- Neuroplasticity Profiling for Personalization: The neuroplastic ability of individual patients can be predicted by physicians based on baseline transcranial magnetic stimulation (TMS) and functional near-infrared spectroscopy (fNIRS) markers. This would provide the exact complexity of the dual task to be adjusted to the individual patient’s cognitive and motor impairments.

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