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RESEARCH ARTICLE

Corticospinal and spinal adaptations following lower limb motor skill training: a meta-analysis with best evidence synthesis

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Abstract
Motor skill training alters the human nervous system; however, lower limb motor tasks have been less researched compared to upper limb tasks. This meta-analysis with best evidence synthesis aimed to determine the cortical and subcortical responses that occur following lower limb motor skill training, and whether these responses are accompanied by improvements in motor performance. Following a literature search that adhered to the PRISMA guidelines, data were extracted and analysed from six studies ($n = 172$) for the meta-analysis, and 11 studies ($n = 257$) were assessed for the best evidence synthesis. Pooled data indicated that lower limb motor skill training increased motor performance, with a standardised mean difference (SMD) of 1.09 being observed. However, lower limb motor skill training had no effect on corticospinal excitability (CSE), Hoffmann's reflex (H-reflex) or muscle compound action potential (M_{MAX}) amplitude. The best evidence synthesis found strong evidence for improved motor performance and reduced short-interval cortical inhibition (SICI) following lower limb motor skill training, with conflicting evidence towards the modulation of CSE. Taken together, this review highlights the need for further investigation on how motor skill training performed with the lower limb musculature can modulate corticospinal responses. This will also help us to better understand whether these neuronal measures are underpinning mechanisms that support an improvement in motor performance.

Keywords Lower limb · Motor skill training · Corticospinal excitability · Motor performance · Meta-analysis · Best evidence synthesis

Abbreviations

CI	Confidence interval
CSE	Corticospinal excitability
EEG	Electroencephalogram
EMG	Electromyography
FDI	First dorsal interosseous
fMRI	Functional magnetic resonance imaging
GABA	Gamma aminobutyric acid
H-reflex	Hoffmann reflex
ISI	Interstimulus interval
LTP	Long-term potentiation
M1	Primary motor cortex
MEP	Motor-evoked potential
M_{MAX}	Muscle compound action potential
SICI	Short-interval intracortical inhibition
SMD	Standardised mean difference
STP	Short-term potentiation
TA	Tibialis anterior
TMS	Transcranial magnetic stimulation

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Introduction

Motor skill training alters the human nervous system (Mooney et al. 2019; Paparella et al. 2020) with adaptations often attributed to structural and functional reorganisation of the primary motor cortex (M1) (Muellbacher et al. 2001;

Kleim et al. 1996). Acute responses following motor skill training provides evidence towards a highly modifiable M1, which manifest as an alteration of spinal (Perez et al. 2005; Ung et al. 2005) and supraspinal circuits (Mooney et al. 2019; Pascual-Leone et al. 1995). Defined as the acquisition and refinement of novel movement sequences (Adkins et al. 2006), skill training has both functional and clinical relevance and forms an essential part of neurorehabilitation programmes (Fimland et al. 2010). Following brain trauma or lesions on the brain, fundamental motor skills can be negatively affected; this has an impact on the ability of an individual to perform day-to-day activities (Hatem et al. 2016). Therefore, a primary goal of sporting and clinical practitioners is to support the learning (or re-learning) of motor skills which will, in turn, facilitate an improved level of performance or quality of life (Tallent et al. 2021).

Transcranial magnetic stimulation (TMS) is a non-invasive brain stimulation technique based on the principle of electromagnetic induction, first described by Faraday in 1831, that states a rapidly changing magnetic field induces a concomitant electrical current which in turn activates underlying neural tissue (Terao and Ugawa 2002). This results in the production of multiple descending volleys (i.e., action potentials) that activates corticospinal and intracortical neurones (Berardelli et al. 1990; Edgley 1997; Rossini et al. 2015). Through the integration of electromyography (EMG), the muscle activity generated as a result of magnetic stimulation can be recorded, monitored, and used to indicate the corticospinal response (Kobayashi and Pascual-Leone 2003). When a single TMS pulse is applied to the M1, an electrical recording at the targeted muscle contralateral to the site of stimulation is captured, which is referred to as a motor-evoked potential (MEP) and provides a measure of corticospinal excitability (CSE) (Abbruzzese and Trompetto 2002). Paired pulse TMS involves the delivery of two consecutive stimuli interspersed with a selected interstimulus interval (ISI), providing researchers with a measure of intracortical inhibition or facilitation (Brownstein et al. 2018). Different ISI are manipulated to investigate the cortical networks facilitated by glutamate and gamma aminobutyric acid (GABA) neurotransmitters (Zhen and Chen 2011). Specifically, GABA-$_A$-mediated inhibition represents the measure of short-interval intracortical inhibition (SICI), GABA-$_B$ mediated inhibition indicates long-interval intracortical inhibition (LICI) and intracortical facilitation (ICF) is contingent on glutamate mediation (Kujirai et al. 1993). Taken together, TMS is a vital tool used to assess the integrity of the M1 and corticospinal pathway with many applications in the sporting, clinical, and research settings (Hallett 1996; Brownstein et al. 2017; Tallent et al. 2017).

Upper limb motor skill training has been assessed via visuomotor tracking (Tracy 2007), ballistic movements (Lee et al. 2010; Dickins et al. 2015), and sequential tasks (Takeo et al. 2021), with the corticospinal responses assessed across distal and proximal muscles (Poh et al. 2012; Mason et al. 2019; Mooney et al. 2019). Increases in CSE (i.e., peak-to-peak MEP amplitude) and reductions in SICI (i.e., conditioned MEP amplitude calculated as a percentage of the unconditioned MEP) have been reported following just a single session of upper limb motor skill training (Jensen et al. 2005; Leung et al. 2015; Mason et al. 2019), with others reporting the same responses after multiple weeks of training (Jensen et al. 2005; Leung et al. 2017). Manipulation of task demands and feedback have also been shown to shape the corticospinal response, namely in the form of external pacing (Ackerley et al. 2011), progressive increases in task difficulty (Christiansen et al. 2018, 2020), and altered feedback frequencies (Smyth et al. 2010). However, non-skill-based simple movements without external pacing, such as self-paced single-limb resistance exercises have no effect on CSE after a single session (Leung et al. 2015) with reductions in CSE being observed after 4 week resistance training (Jensen et al. 2005). This shows that skill-based complex tasks are more centrally demanding (i.e., movements with a requirement for motor acuity or precision) and provide a clear stimulus for training-induced adaptations along the neuroaxis, compared to those without additional demands.

In addition to concomitant increases in CSE and reductions in SICI, skill acquisition has also been inferred via an improvement in motor performance of the task (Smyth et al. 2010). Visuomotor tracking error has been shown to reduce following 4 weeks of motor skill training in the elbow flexors (Jensen et al. 2005; Leung et al. 2017); however, a recent meta-analysis has questioned the association between the corticospinal responses that are induced after a period of motor skill training, and the behavioural response specific to the trained task (Berghuis et al. 2017; Hortobágyi et al. 2021). It was reported by Berghuis et al (2017) that the TMS parameters assessed (CSE and SICI) were unrelated to the changes in motor skill acquisition, despite finding an increase in CSE after visuomotor but not ballistic training in young adults, and no change in SICI in either task. Despite the lack of association between corticospinal responses and changes in motor performance, for which several reasons are responsible (Bestmann and Krakauer 2015), it could be suggested that the increased CSE and reduced SICI observed following motor skill training are mediating factors which contribute towards an improvement in motor performance. However, the aforementioned changes in corticospinal responses do result from the training task itself, but are not a prerequisite of skill acquisition. It is important to also note that Berghuis et al. (2017) assessed responses in the upper limbs, making it difficult to draw any conclusions regarding lower limb responses.

Compared to the upper limb, the corticospinal responses and associated performance outcomes following lower limb motor skill training has received considerably less empirical investigation. Researchers have investigated the cortical and subcortical responses after balance and ballistic training (Schubert et al. 2008), although assessment of motor performance/behaviour was not recorded. This failure to measure motor performance was also apparent in cross-sectional comparisons of non-trained and well-trained athletes, where improved corticospinal adaptations were evident following long-term training (Saito et al. 2014; Grosprêtre et al. 2019). Improvement in lower limb motor performance has, however, been reported by Perez et al (2004) who showed that, following a single session of completing a visuomotor tracking task, there was a reduction in motor error alongside an increase in CSE and reduced SICI in the tibialis anterior (TA). However, the relative lack of further motor performance data following lower limb motor skill training makes it difficult to draw firm conclusions as to whether the corticospinal responses induced are related to motor skill acquisition.

The difficulty (or risk) in drawing conclusions on how lower limb muscles respond to motor skill training based on findings from research employing upper limb tasks may be explained using their physiological characteristics. Assessing the strength of corticospinal projections, Brouwer and Ashby (1990) observed a smaller compound muscle action potential (CMAP) in the lower limb, which also required a much stronger stimulus compared to the upper limb. The leg muscles, in particular the quadriceps, are predominantly involved in gross motor control, with a greater proportion of motor units driven by larger motoneurons, with higher activation thresholds (Smith et al. 2017; Kesar et al. 2018). Due to the lower evoked amplitude and stronger stimulus needed, it is conceivable to assume the corticospinal projections from the M1 to spinal motoneurons which innervate the skeletal muscle of the lower limbs may be weaker in comparison to the upper limb. However, Brouwer and Ashby (1990) also reported similar CMAP amplitudes between the TA and first dorsal interosseous (FDI), which are lower and upper limb muscles, respectively. This is particularly interesting given the TA is also implicated in human locomotion and linked to the activation of the corticospinal tract during walking (Capaday et al. 1999). Given this similarity in amplitudes, the specific nuances must be taken into consideration when comparing the corticospinal responses between muscles, and simply generalising the upper and lower limb muscles may overlook potential differences within each isolated region of the body.

Lower limb motor skill training and its effect on neuromuscular function require further empirical investigation to support the mechanisms that have thus far been observed. Therefore, this meta-analysis with best evidence synthesis aims to determine the cortical and subcortical responses that occur following lower limb motor skill training, and whether these responses are accompanied by improvements in motor performance. Enhancing our understanding of the mechanisms underpinning motor skill training in the lower extremities will enable us to provide some much-needed clarity and ascertain where the responses occur along the neuroaxis.

Methods

This systematic review and meta-analysis were conducted in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al. 2021).

Eligibility criteria

Studies were included for analysis if they fulfilled the following criteria: (i) recreationally trained or untrained healthy adults (males and females) between the ages of 18 and 45; (ii) motor skill training performed in the lower limb that was restricted to a single session or completed across multiple weeks; (iii) training intervention compared to a control group; (iv) stimulation of the M1 at baseline and post-training to quantify changes in corticospinal responses using single-and paired-pulse TMS indicators, as well as variables assessed through electrical stimulation (H-reflex and M-wave responses) between an experimental and control group; and (v) motor performance of the training task quantified prior to and after the intervention. Studies were considered eligible if at least one of the above variables assessed via either form of neurostimulation was measured.

Exclusion criteria included: (i) diseased populations or older adults (mean age > 45 years); (ii) studies that utilised an element of strength training in the skill training task, ballistic movements, or motor tasks performed at an intensity > 30% MVC; (iii) no comparison to a control group would exclude studies from the meta-analysis, but were included in the best evidence synthesis; (iv) no post-intervention assessment of neural responses or motor performance; (v) participants that received additional treatments or factors (i.e., supplementation, transcranial direct current stimulation) that may have affected the neurological response; and (vi) non-English publications, non-peer reviewed documents or theses.

Information sources

An electronic search of the literature was conducted in the following databases from inception until 12th April 2022: PubMed, Sports Discus, Web of Science, PsycINFO, CINAHL, and Cochrane Library. To ensure the entire field of literature had been reached, a final search was conducted via Google Scholar by all authors using the relevant key terms. Following these processes, the reference lists of all included studies were screened for additional relevant papers.

Search strategy

Electronic databases were searched using an extensive list of key terms (i.e., "motor skill training", "neural plasticity", and "TMS") and its associated synonyms. The key terms that were applied to each specific database are outlined in Table 1.

Selection process

All studies identified as a result of the literature search were exported onto a custom-built Microsoft Excel document (Microsoft Excel, Version 16.55). One of the authors (AW) performed the initial search and screened all retrieved articles to remove duplicates and any items that were deemed outside the scope of the meta-analysis. Two authors (AW and JT) then independently screened and reviewed the remaining titles and corresponding abstracts. Full-text articles that satisfied the inclusion criteria were read in full, with eligible studies then included within the meta-analysis. Next, these authors met to discuss and agree on any discrepancies in included studies. A full list of included studies within the meta-analysis and best evidence synthesis are shown in Tables 2 and 3, respectively.

Data collection process and data items

Data from included studies were extracted from the available text (AW and JT) onto a custom-made Excel document. Information on the study intervention, participant characteristics (age and sex), target muscle from stimulation, sampling method, key measures, and results were extracted from all included studies. In addition, the following outcome measures were retrieved: motor performance (specific to the training task), corticospinal excitability (peak-to-peak motor-evoked potential (MEP) waveform expressed as raw amplitude, normalised as a percentage of peripheral M-wave amplitude, relative to motor threshold, MEP_{MAX} or arbitrary units extracted from a stimulus–response curve), Hoffmann's reflex (H-reflex (expressed in mV, μV, % M_{MAX} or H_{MAX}/M_{MAX})) and maximal muscle compound action potential (M_{MAX}; mV, μV), and SICI (quantified as the size of the conditioned paired-pulse MEP expressed relative to the size of the unconditioned MEP). Data were extracted as means and standard deviation at pre-training and post-training time points for each outcome measure in both the experimental and control groups. Where post-intervention means ± standard deviations were not reported within the available text, raw data (means ± standard deviations) were converted from the number of participants (*N*), standard error, 95% confidence intervals, *P* values, *t* values, or *F* values. Where standard deviations were presented across multiple time points, data were pooled into a single value and subsequently used for analysis. For studies that presented results in figures, publicly available software (WebPlotDigitizer, Version 4.5) was used to extrapolate the required data. All extracted data were checked for accuracy independently by two authors (AW and JT). Where agreements could not be reached regarding data extraction from the included studies, two further researchers were consulted (JN and CM).

Study risk-of-bias assessment

Two authors (AW and JT) assessed the quality of included studies using a modified version of the Downs and Black checklist (Downs & Black 1998). Eleven items (4, 8, 9, 13, 15, 17, 19, 22, 23, 24 and 27) were not deemed relevant for this review and subsequently excluded from the quality assessment. Previous systematic reviews and meta-analyses

Table 1 Search terms

Term	Search strategy
OR	1. "motor learning" OR "motor skill learning" OR "motor training" OR "motor skill training" OR "motor skill acquisition" OR "motor performance" OR "motor behaviour" OR "motor memory consolidation" OR "lower limb" OR "lower extremities" OR "lower body" OR "leg" OR "single session" OR "multiple sessions" OR "training programme" OR "task learning" OR "sequential learning" OR "balance task" OR "task-specific improvement" OR "visuomotor task" OR "force tracking task"
WITH	2. "neural adaptations" OR "neuronal plasticity" OR "corticospinal plasticity"
OR	3. "transcranial magnetic stimulation" OR "TMS" OR "TMS measures" OR "TMS parameters" OR "motor cortex" OR "corticospinal excitability" OR "motor evoked potential" OR "corticospinal inhibition" OR "silent period" OR "voluntary activation" OR "SICI" OR "short-interval intracortical inhibition" OR "intracortical inhibition" OR "H-reflex" OR "V-wave" OR "F-wave"

Table 2 Study characteristics for included studies within the meta-analysis

Study	Intervention	Participant characteristics	Target muscle	Key DV	Key measures	Results	*D & B*
Giboin et al. (2019)	12 sessions over 6 weeks, slackline training 2 × per week	44 untrained healthy young adults. Trained (*n* = 22, 22 ± 2 years, 8M & 14F). Control (*n* = 22, 25 ± 4 years, 12M & 10F)	Soleus	Spinal excitability, balance performance	H-reflex (% M_{MAX}), Number of steps	↓ H-reflex, ↑ Number of steps	12/17
Gruber et al. (2007)	16 sessions over 4 weeks, postural stabilisation tasks of the right leg, 4 × per week	20 untrained healthy young adults. SMT (*n* = 11, 26 ± 5 years, 7M & 4F). Control (*n* = 9, 26 ± 3 years, 5M & 4F)	Soleus	H-reflex, balance performance	H_{MAX}/M_{MAX} Ratio, Cumulative sway path	↓ H_{MAX}/M_{MAX} Ratio, ↓ Cumulative sway path	13/17
Keller et al. (2012)	10 sessions over 4 weeks, 90 min slackline training, 2–3 × per week	24 healthy young adults. Trained (*n* = 12, 6M & 6F). Control (*n* = 12, 6M & 6F)	Soleus	Spinal excitability, balance performance	H_{MAX}/M_{MAX} Ratio, Sway path	↑ H_{MAX}/M_{MAX} Ratio, ↓ Sway path	13/17
Taube et al. (2007)	16 sessions over 4 weeks, postural stabilisation tasks of the right leg, 4 × per week	23 healthy young adults. SMT (*n* = 13, 25 ± 3 years, 8M & 5F). Control (*n* = 10, 27 ± 5 years, 6M & 4F)	Soleus	Spinal excitability, balance performance	H_{MAX}/M_{MAX} Ratio, Cumulative sway path	↓ H_{MAX}/M_{MAX} Ratio, ↓ Cumulative sway path	14/17
Perez et al. (2004)	Single session (32-min) of visuomotor training, ankle dorsi-and plantar flexions	25 healthy young adults (28 ± 7 years, 14M & 11F). Motor skill (*n* = 10), non-skill (*n* = 10) and passive training (*n* = 10)	TA	Corticospinal excitability, SICI, tracking error	MEP amplitude (% M_{MAX}), Conditioned MEP (% control MEP), Tracking error	↑ MEP amplitude, ↓ SICI, ↓ Visuomotor tracking error	13/17
Bakker et al. (2021)	Single session (30-min) of balance skill training	36 healthy young adults. BT (*n* = 12, 20.67 ± 1.07 years, 6M & 6F). NC (*n* = 12, 21.58 ± 2.50 years, 6M & 6F)	TA	Corticospinal excitability, SICI, balance performance	MEP amplitude (mV), SICI (% MEP sitting), balance board–time in balance (%)	↔ MEP amplitude, ↔ SICI, ↑ time to balance	13/17

BT balance training, *D & B* downs and black quality assessment, *F* female, H_{MAX} maximum H-reflex, *M* male, M_{MAX} maximum M-wave, *mV* millivolts, *NC* no-intervention control group, *SICI* short-interval intracortical inhibition, *SMT* sensorimotor training, *TA* tibialis anterior

↑ increase, ↓ decrease, ↔ no change. *Keller et al. (34) shows an increase H-reflex response after pooled across multiple conditions

Table 3 Study characteristics for included studies within the best evidence synthesis

Study	Intervention	Participant characteristics	Muscle	Key DV	Key measures	Results	*D & B*
Giboin et al. (2020)	Two sessions separated by 24 h (experimental and retention)	18 untrained healthy young adults ($n=18$, 27 ± 8 years, 8M & 10F)	Soleus	Balance performance	Tilt-board performance (s)	↑ Time spent on tilt-board	13/17
Hirano et al. (2018)	Single session of visuomotor tracking ankle dorsi-plantar flexions	28 healthy right-footed young adults ($n=28$, 23 ± 1.2 years, 23M & 5F)	TA	Corticospinal excitability, M_{MAX}, visuomotor performance	I–O curves of MEP amplitude, M_{MAX} amplitude (mV), visuomotor error	↑ I-O curve, ↓ M_{MAX} amplitude, ↓ visuomotor error	12/17
Kubota et al. (2015)	Single session of visuomotor tracking ankle dorsi-plantar flexions	8 healthy young adults ($n=8$; 22.37 ± 1.59 years, 6M & 5F)	Soleus	M_{MAX}, visuomotor performance	M_{MAX} amplitude (mV), motor error	↑ M_{MAX} amplitude, ↓ motor error	12/17
Hirano et al. (2015)	Two sessions on consecutive days (visuomotor tracking on day 1)	20 young adults. SMT ($n=20$, 22.5 ± 2.5 years, 16M & 4F)	TA	Corticospinal excitability, M_{MAX}, visuomotor performance	I-O slope, M_{MAX} amplitude (mV), visuomotor performance (au)	↔ I-O slope, ↓ M_{MAX} amplitude, ↓ visuomotor error	12/17
Tatemoto et al. (2019)	Single session of skillful cycling training on a recumbent ergometer	11 healthy young adults ($n=11$, 25.4 ± 2.5 years, 8M & 3F)	TA	Corticospinal excitability, SICI, tracking error	MEP amplitude (mV), SICI (ratio), tracking error (au)	↔ CSE, ↓ SICI, ↓ tracking error	13/17

CSE corticospinal excitability, Downs and Black Quality Assessment, *F* female, *I-O* input–output, *M* male, M_{MAX} maximal M-wave, *SICI* short-interval intracortical inhibition, *TA* tibialis anterior

↑ increase, ↓ decrease, ↔ no change

have utilised a similar modified version (Alibazi et al. 2020; Maniar et al. 2016). In addition, the Cochrane Risk-of-Bias tool was used which categorised the included studies as "high risk", "low risk", or "unclear risk" across six independent criteria: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting, and other sources of bias (Higgins and Green 2011).

Statistical analysis

Post-training data after lower limb motor skill interventions in the experimental and control groups from included studies were used for the following outcome measures: motor performance, CSE, H-reflex, M_{MAX}, and SICI. Meta-analysis was performed using a random effects model to compare the overall pooled effect for each outcome measure. This was deemed appropriate considering the differences in researchers, methods, and interventions between included studies (Borenstein et al. 2010). Standardised mean difference (SMD) with 95% confidence intervals (CIs) were used to measure the intervention effect as the included studies presented data in several different ways. The SMD values of $0.2 \leq 0.49$, $0.5 \leq 0.79$, and ≥ 0.8 indicated small, medium, and large comparative effects, respectively (Cohen 1998). The results for each outcome measure are reported as SMD, 95% CIs, and the associated *P* value. This approach provides information on both the existence of an effect, as well as the size and direction of the effect following the intervention. Heterogeneity between included studies was assessed using the I^2 statistic, with cut-off points indicating low (25%), moderate (50%), and high (75%) heterogeneity. Statistical analyses were performed in RevMan 5.4 using an alpha level of $P < 0.05$ to determine statistical significance.

Where it was deemed that reported data from included studies were insufficient for meta-analysis (i.e., no comparison to a control condition) and could not be obtained via additional methods (e.g., through email communication with authors), a best evidence synthesis was employed to assess the remaining data. Data were extracted from 11 studies using the following outcome measures: Motor performance (quantified as the within-group difference from pre- to post-training specific to the task), MEP amplitude (peak-to-peak motor-evoked potential waveform expressed as raw amplitude, normalised as a percentage of peripheral M-wave amplitude, relative to motor threshold, MEP_{MAX} or arbitrary units extracted from a stimulus–response curve), and SICI (quantified as the size of the conditioned paired-pulse MEP expressed relative to the size of the unconditioned MEP). The level of evidence used to rank the available data was consistent with previous systematic reviews (Alibazi et al.

2020; Maniar et al. 2016) and is defined using the following criteria:

- Strong evidence: two or more studies of high quality and generally consistent findings (≥ 75% of studies showing consistent results).
- Moderate evidence: one high-quality study and two or more low-quality studies and generally consistent findings (≥ 75% of studies showing consistent results).
- Limited evidence: one low-quality study.
- Conflicting evidence: inconsistent findings (< 75% of studies showing consistent results).
- No evidence: no supportive findings.

Studies with a risk-of-bias score of ≥ 70% and < 70% were considered as high-quality and low- quality studies, respectively (Maniar et al. 2016). Cohen's *d* effect size and 95% CIs were displayed in forest plots using Prism 9 for Mac (GraphPad Software, Inc, La Jolla, California). Effect sizes were quantified as small (≤ 0.20), moderate (0.50), and large (≥ 0.80) (Cohen 1988).

Results

Study selection

The PRISMA flowchart (Fig. 1) outlines the process involved in study identification, screening, and evaluation of the eligibility of included studies. The initial search returned 6,011 articles from all electronic databases, plus a further eight articles identified via additional sources. These were reduced to 5,333 articles after the removal of duplicates. Further screening of titles and abstracts left 143 full-text articles. Searching the reference lists of included studies did not retrieve any additional papers. On the basis of inclusion criteria, 137 articles were removed from the 143. In turn, 11 papers were included in the final sample. Six papers were assessed as part of the meta-analysis, and 11 papers were assessed under the best evidence synthesis.

Study characteristics

The six studies included in the meta-analysis had recruited a total of 172 participants (84 males & 76 females), with an age range between 22 and 28 years. Four studies assessed the effect that motor skill training has on lower limb musculature in the soleus (Giboin et al. 2019; Gruber et al. 2007; Keller et al. 2012; Taube et al. 2007), whereas two studies assessed responses in the TA (Bakker et al. 2021; Perez et al. 2004). The motor training task employed varied between studies, with five examining balance (Bakker et al. 2021; Giboin et al. 2019; Gruber et al. 2007; Keller et al. 2012; Taube et al. 2007) and one utilising a visuomotor tracking task (Perez et al. 2004). The duration of the intervention ranged from a single session (Bakker et al. 2021), 4 weeks (Gruber et al. 2007; Keller et al. 2012; Taube et al. 2007) to 6 weeks (Giboin et al. 2019) in those employing a balance task. The study employing a visuomotor tracking task examined the corticospinal response before and after a single session (Perez et al. 2004). In addition, two studies included a third experimental group consisting of a ballistic strength training (Gruber et al. 2007) and a cycling training intervention (Bakker et al. 2021), both of which were excluded from the analysis. A detailed summary of all studies included within the meta-analysis is presented in Table 2, with a further summary of the additional included studies for the best evidence synthesis presented in Table 3.

Quality assessment

A modified version of the Downs and Black checklist was used to assess the quality of included studies (Alibazi et al. 2020; Maniar et al. 2016) (Tables 2 and 3). This checklist revealed that studies meeting the inclusion criteria ranged between 12 (71%) and 14 (82%) out of a possible 17 points, with a mean score of 13 ± 0.63. The Cochrane risk-of-bias tool showed that all included studies demonstrated high risk of allocation concealment, blinding of participants and personnel, and blinding of outcome. The risk-of-bias graph is displayed in Fig. 2a, b.

Motor performance

Changes in motor performance were extracted from six studies that assessed balance parameters or visuomotor tracking error post-training ($n = 80$) compared to a control ($n = 75$). The pooled data showed an increase in performance after lower limb motor skill training (SMD 1.09; 95% CI 0.74, 1.43, $P < 0.00001$). There was also low heterogeneity across these studies ($\tau^2 = 0.00$; $\chi^2 = 1.47$; $df = 5$; $P = 0.92$; $I^2 = 0\%$). Figure 3a displays the forest plot showing the effect of lower limb motor skill training on measures of motor performance.

Corticospinal excitability

Data from two studies were used to assess changes in CSE post-training ($n = 22$) compared to a control ($n = 22$). Pooled data indicated that lower limb motor skill training did not alter CSE (SMD 0.56; 95% CI −0.78, 1.90, $P = 0.41$), with high heterogeneity across these studies ($\tau^2 = 0.73$; $\chi^2 = 4.50$; $df = 1$; $P = 0.03$; $I^2 = 78\%$). Figure 4a displays the forest plot

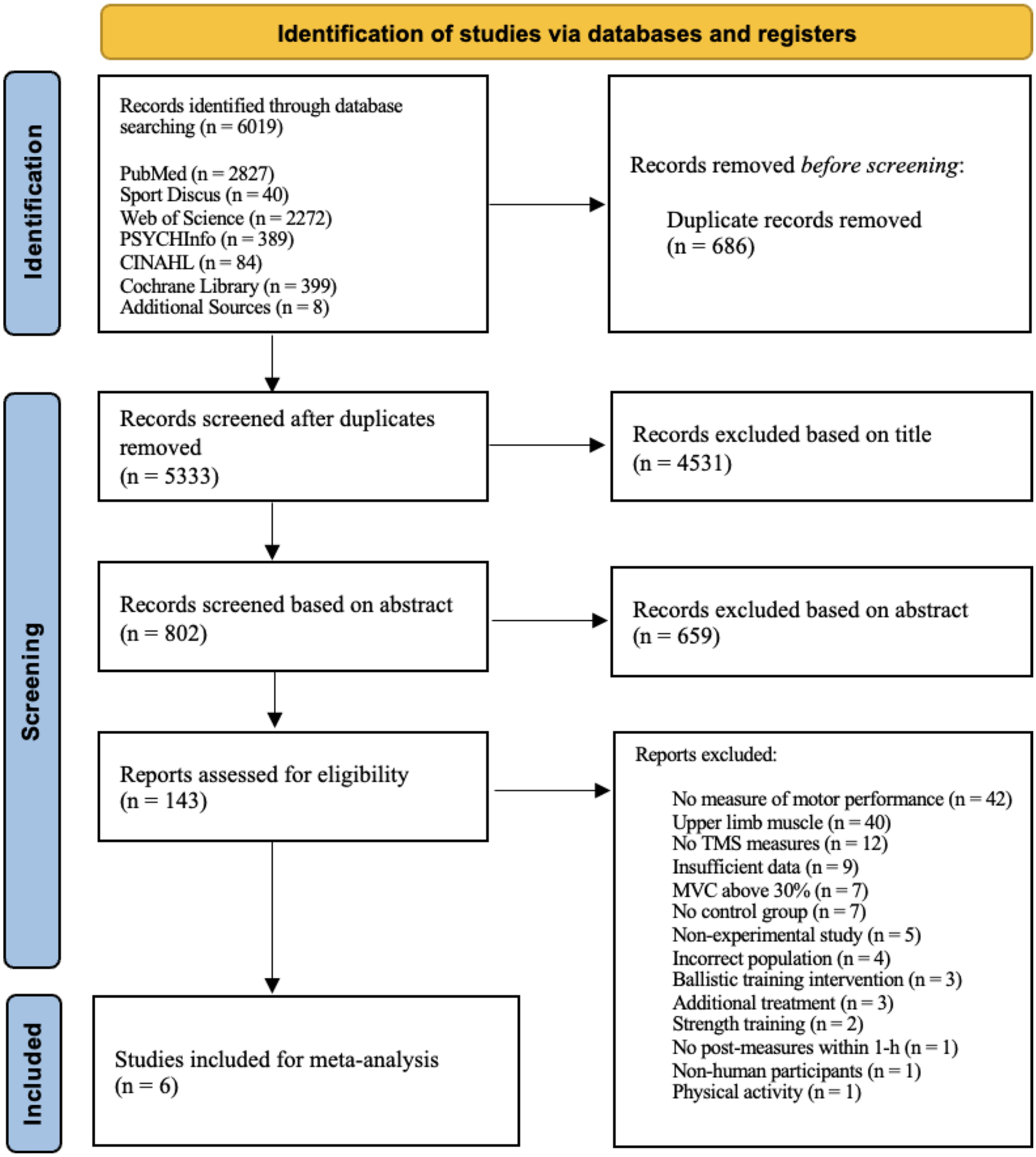


Fig. 1 The process of identifying, screening, and assessing the included studies according to the PRISMA 2020 guidelines

demonstrating the effect of lower limb motor skill training on CSE.

H-reflex

Post-training data were extracted from four studies ($n = 52$) that examined the H-reflex response compared to a control ($n = 44$). Pooled data showed that lower limb motor skill training had no effect on the H-reflex (SMD 0.34; 95% CI −0.44, 1.11, $P = 0.39$), with high heterogeneity across these studies ($\tau^2 = 0.44$; $\chi^2 = 10.09$; $df = 3$; $P = 0.02$; $I^2 = 70\%$). Figure 5 displays the forest plot showing the effect of lower limb motor skill training on the H-reflex response.

M_{MAX}

Changes in M_{MAX} were extracted from two studies post-training ($n = 28$) compared to a control ($n = 25$). Pooled data demonstrated that lower limb motor skill training had no effect on M_{MAX} amplitude (SMD 0.97; 95% CI −1.07, 3.00, $P = 0.35$), with high heterogeneity ($\tau^2 = 1.95$; $\chi^2 = 10.53$; $df = 1$; $P = 0.001$; $I^2 = 91\%$). Figure 6 shows the forest plot demonstrating the effect of lower limb motor skill training on M_{MAX} amplitude.

Best evidence synthesis

Motor performance (single session)

Six studies (Bakker et al. 2021; Hirano et al. 2015, 2018; Kubota et al. 2015; Tatemoto et al. 2019) were assessed, with strong evidence that a single session of lower limb motor skill training improved motor performance. The magnitudes of the intervention effect were moderate to large, with an effect size ranging between 0.71 and 3.00 (Fig. 3b).

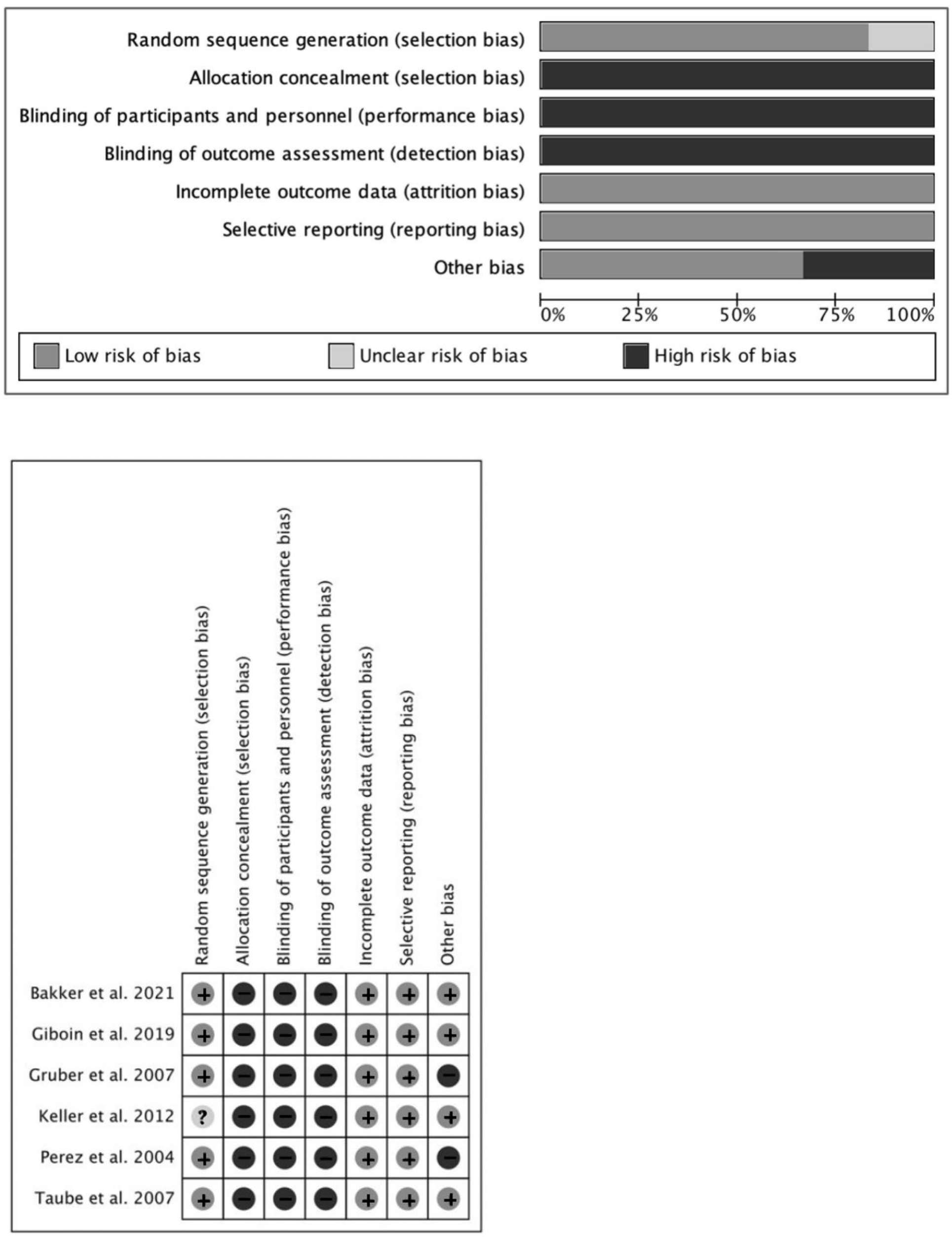
Motor performance (multiple weeks of training)

Four studies (Giboin et al. 2019, 2020; Gruber et al. 2007; Keller et al. 2012) were assessed, with strong evidence that lower limb motor skill training performed across multiple weeks improved motor performance. The magnitudes of the intervention effect were large, with an effect size ranging between 0.90 and 3.07 (Fig. 3c).

Corticospinal excitability

Five studies (Bakker et al. 2021; Hirano et al. 2015, 2018; Perez et al. 2004; Tatemoto et al. 2019) examined CSE from

Fig. 2 Risk of bias: review authors' judgements about each risk-of-bias item presented as **a** percentages across all included studies and **b** risk-of-bias summary for each included study



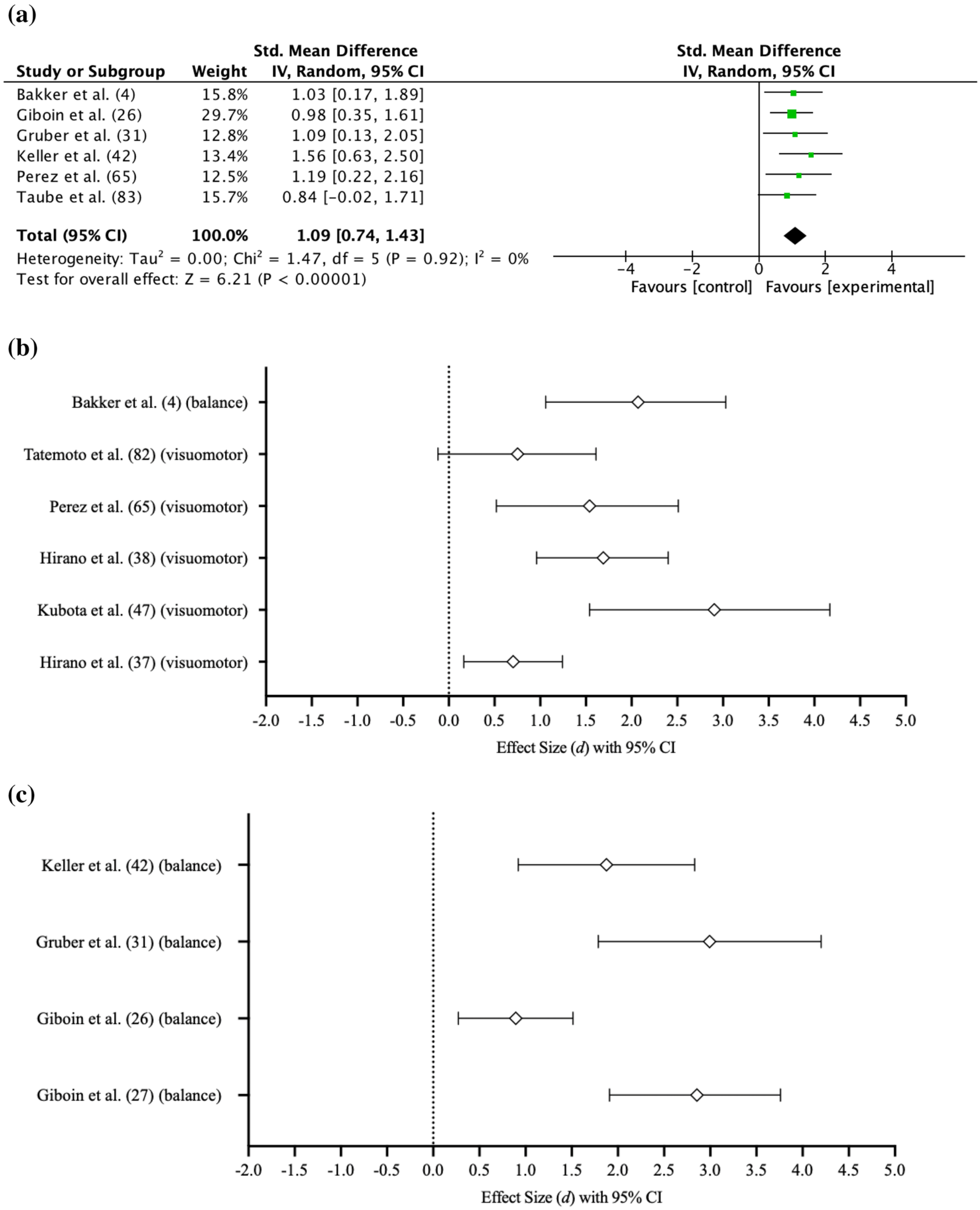


Fig. 3 Forest plots showing the **a** pooled effect of lower limb motor skill training on measures of motor performance (six studies, 155 participants), **b** effect sizes following a single session and **c** multiple weeks of lower limb motor skill training. *Std* standardised mean difference, *IV* inverse variance, *Random* random effect model, *CI* confidence interval, *df* degrees of freedom, I^2 inconsistency statistic. Statistical significance set at $P<0.05$. Effect size, Cohen's *d*; 95% CI confidence intervals

either a resting or active leg muscle. There was conflicting evidence for modulating CSE following lower limb motor skill training. The magnitudes of the intervention effect were small to moderate, with an effect size range between −0.15 and 0.59 (Fig. 4b).

Short-interval intracortical inhibition

Three studies (Bakker et al. 2021; Perez et al. 2004; Tatemoto et al. 2019) assessed SICI following lower limb motor skill training. There was strong evidence showing a

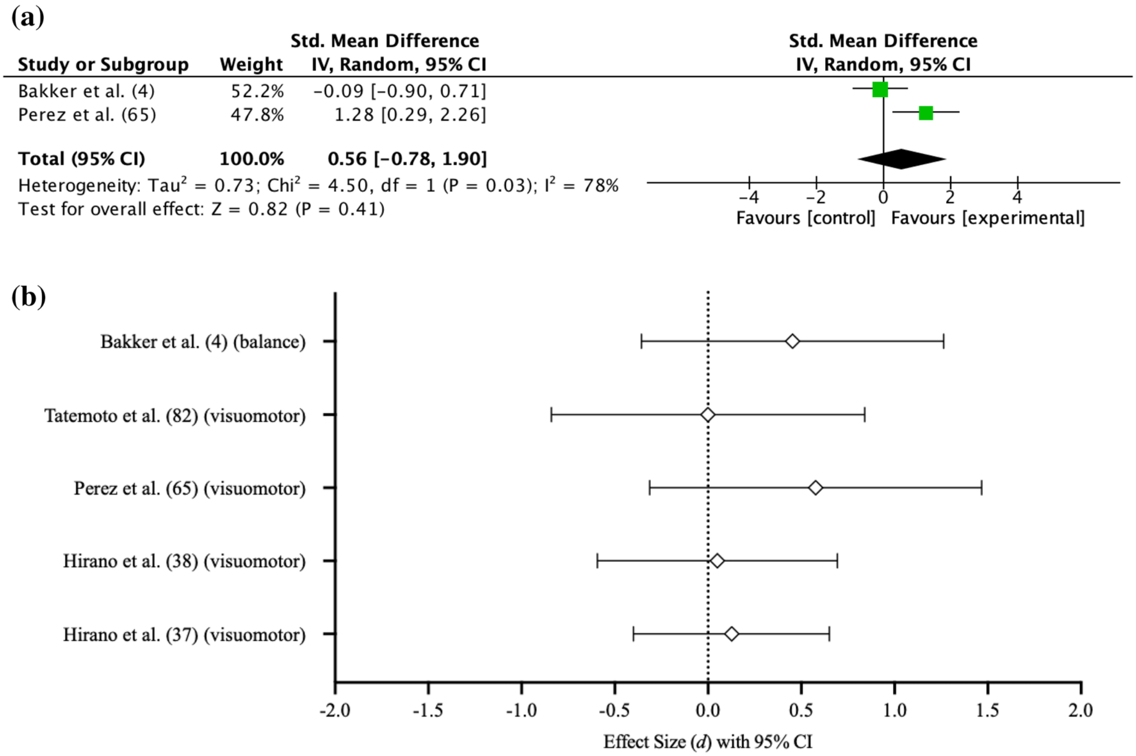


Fig. 4 Forest plots showing the **a** pooled effect of lower limb motor skill training on corticospinal excitability (two studies, 44 participants), and **b** effect sizes for corticospinal excitability following lower limb motor skill training. *Std* standardised mean difference, *IV* inverse variance, *Random* random effect model, *CI* confidence interval, *df* degrees of freedom, I^2 inconsistency statistic. Statistical significance set at $P < 0.05$. Effect size, Cohen's *d*; 95% *CI* confidence intervals

reduction in SICI, suggesting that the intrinsic intracortical circuitry is altered as a result of motor skill training performed in the lower limb. The magnitudes of the intervention effect were small to large, with effect sizes ranging from 0.13 to 2.59 (Fig. 7).

Discussion

The aim of this meta-analysis with best evidence synthesis was to determine the cortical and subcortical responses following lower limb motor skill training, and to assess the effect on motor performance. Overall, there was a large effect towards an improved performance (SMD, 1.09), showing that both visuomotor and balance interventions resulted in successful motor skill acquisition. This meta-analysis also found that lower limb motor skill training did not affect CSE,

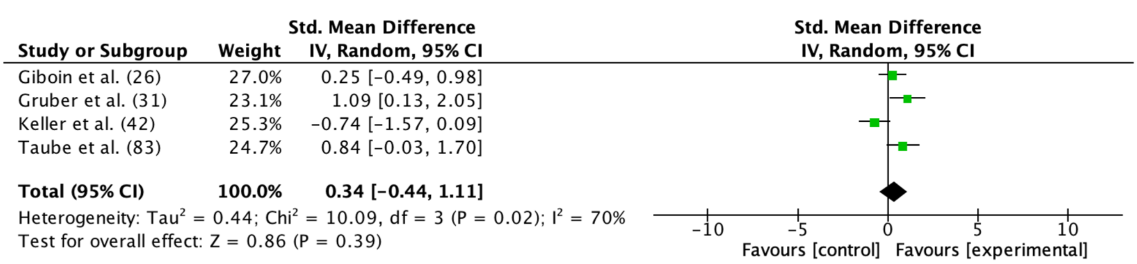


Fig. 5 Forest plots showing the effect of lower limb motor skill training on the H-reflex response (four studies, 96 participants). *Std* standardised mean difference, *IV* inverse variance, *Random* random effect model, *CI* confidence interval, *df* degrees of freedom; $I.^2$, inconsistency statistic. Statistical significance set at $P < 0.05$

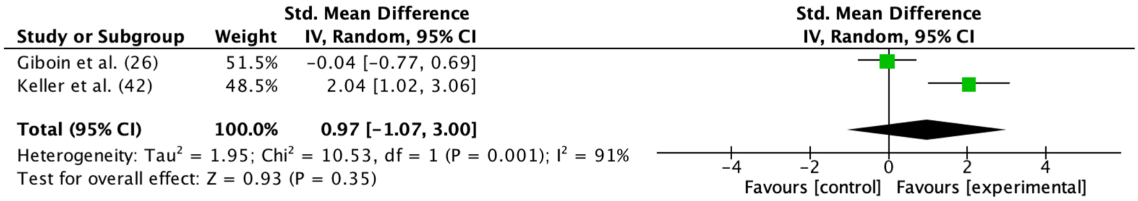


Fig. 6 Forest plots showing the effect of lower limb motor skill training on M_{MAX} amplitude (two studies, 53 participants). *Std* standardised mean difference, *IV* inverse variance, *Random* random effect model, *CI* confidence interval, *df* degrees of freedom, I^2 inconsistency statistic. Statistical significance set at $P < 0.05$. *Keller et al. (2012) had a lower M_{MAX} at baseline in the experimental compared to control group

H-reflex or the M_{MAX} response, suggesting that mechanisms underpinning an improvement in task performance are not supported by changes along the corticospinal pathway, spinal cord, or maximal muscle membrane excitability. The best evidence synthesis assessed corticospinal responses, finding strong evidence towards an improved motor performance and reduced SICI, but conflicting evidence for the modulation of CSE.

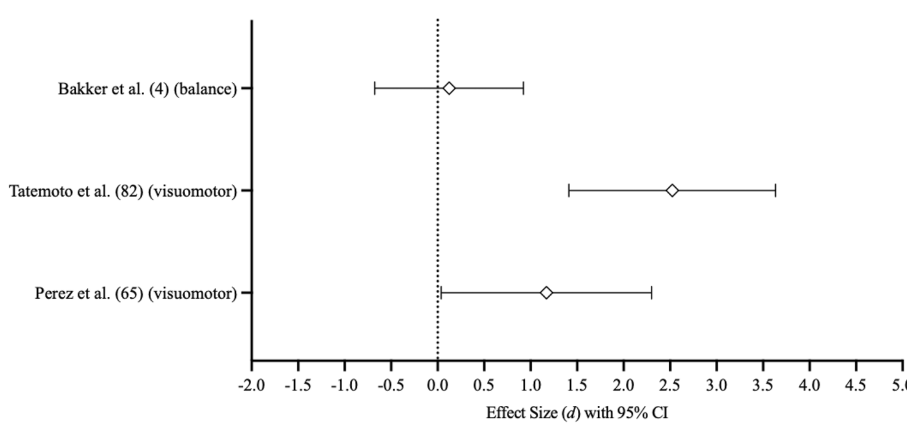
Motor performance

Motor performance following lower limb motor skill training was assessed in six studies, with five studies investigating balance performance (Bakker et al. 2021; Giboin et al. 2019; Gruber et al. 2007; Keller et al. 2012; Taube et al. 2007) and one study utilising visuomotor tracking (Perez et al. 2004). The pooled estimate revealed a large increase (SMD, 1.09) in motor performance, with improved behavioural outcomes specific to the trained task often observed after a single session of visuomotor ankle dorsi/plantar flexion movements (Perez et al. 2004) and skilful cycling (Tatemoto et al. 2019), as well as short-term interventions (Christiansen et al. 2020; Jensen et al. 2005; Leung et al. 2017). Similarly, a meta-analysis by Berghuis and colleagues demonstrated improved motor performance following visuomotor and ballistic training in the upper limb muscles of young adults (Berghuis et al. 2017). However, the present study excluded ballistic interventions from the analyses, due to the involvement of strength in the task, and instead examined only visuomotor and balance assessments. Continuing this notion of improved behavioural outcomes, the best evidence synthesis found strong evidence towards an improvement in motor performance after balance tasks performed over a 4–6-week duration (Giboin et al. 2019; Gruber et al. 2007; Keller et al. 2012; Taube et al. 2007) and visuomotor tracking movements during a single session (Perez et al. 2004). Much of the previously published literature has been conducted in the upper limb and has shown clear evidence for improved motor-performance and by-proxy an improvement in motor skill acquisition. The results of the current meta-analysis and best evidence synthesis indicate that, despite reported physiological differences between upper and lower limbs (see Brouwer and Ashby 1990) and their typical differential involvement in fine and gross motor tasks, respectively, improved motor performance following a motor skill training intervention is not confined to the upper limbs alone and extends the body of evidence to the lower limbs.

Corticospinal excitability

The present meta-analysis pooled data from two studies which utilised a visuomotor tracking (Perez et al. 2004) and balance task (Bakker et al. 2021), respectively, finding that lower limb motor skill training did not have an effect on CSE

Fig. 7 Forest plot showing effect sizes for short-interval intracortical inhibition following lower limb motor skill training. Effect size, Cohen's *d*; 95% *CI* confidence intervals



(SMD, 0.56). The best evidence synthesis, which is able to assess within-group differences, found conflicting evidence towards the modulation of CSE following motor skill training in the lower extremities. Collectively, four of the studies included within the best evidence synthesis utilised a visuomotor tracking paradigm as the training task, with a further study assessing balance performance, and both of which measured the associated corticospinal responses in the immediate time period post-exercise. Two of these studies reported an increase in CSE (Hirano et al. 2018; Perez et al. 2004), whilst the remaining three studies found no differences in CSE after the training intervention (Bakker et al. 2021; Hirano et al. 2015; Tatemoto et al. 2019). These contrasting results are surprising, as a large body of evidence has reported transient elevations in CSE following motor training (Jensen et al. 2005; Leung et al. 2015; Mason et al. 2019; Perez et al. 2004). Early research from Jensen et al. (2005) found an increased CSE after the first session and a decrease at the cessation of training. Specifically, tasks involving a greater degree of external feedback have demonstrated a consistent facilitation in CSE, with visuomotor skill training and metronome-paced movements increasing CSE to a larger extent than self-paced movements (Leung et al. 2015). Based on these findings, it appears the demands, novelty, complexity, application of visual feedback, and degree of somatosensory feedback implicated within the task are likely key contributing factors which lead to greater modulations of the corticospinal pathway. However, it is important to highlight that the aforementioned studies assessed the corticospinal responses in the upper limbs, as opposed to the lower limbs.

Despite the lack of difference in CSE reported within the present meta-analysis, of the five studies included within the best evidence synthesis, two found an increase in CSE (Hirano et al. 2018; Perez et al. 2004). This disparity in CSE could be attributed to the methodology during the stimulation protocol, in which background muscle activation has been shown to influence TMS measures of CSE (Hand et al. 2020; Zoghi et al. 2003). Due to the inclusion of studies assessing the responses in either a resting or active muscle, this may account for the differences observed following lower limb motor skill training. Further, there is little information on how the lower limb muscles respond after the performance of skilled movements, with the majority of researchers choosing to select the wrist, upper limb digits or elbow flexors as a more appropriate medium to assess the corticospinal response (e.g., Dickins et al. 2015; Poh et al. 2012). The increase in CSE reported by two included studies suggests that tasks in which the visual and motor systems are sufficiently challenged, the corticospinal responses may, to some degree, follow the same trend as those reported in the literature which have employed upper limb tasks (Jensen et al. 2005; Leung et al. 2015; Mason et al. 2019). This is an important finding given the differences in physiological characteristics between the upper and lower limbs. Corticospinal neurons which project from the M1, onto spinal motoneurons and subsequently innervate lower limb musculature may be weaker compared to the upper limbs (Brouwer and Ashby 1990). Therefore, despite a lower projection strength, the present study presents an initial basis to suggest the corticospinal responses may be, in part, modulated following lower limb motor skill training. However, this should be interpreted with caution due to the lack of difference found within the meta-analysis and conflicting support following the outcomes of the best evidence synthesis. The inclusion of only two studies meeting the eligibility criteria demonstrates that to resolve the lack of consensus regarding the corticospinal responses of the lower limbs, that further studies are required which will allow for more substantive conclusions to be drawn.

H-reflex

This meta-analysis pooled the statistical effects from four studies assessing the H-reflex response, demonstrating no difference (SMD, 0.34) after lower limb motor skill training. However, the intervention utilised across each of these four studies were all balance tasks, performed across 4–6 weeks with 2–4 sessions per week. Balance training typically involves the use of a slackline or the requirement to complete a range of postural stabilisation tasks, which has normally resulted in a reduced H-reflex response and has been consistently observed in individual studies (e.g., Gruber et al. 2007; Taube et al. 2007). This reduction in H-reflex following balance training is attributed to a series of neurophysiological processes, which begins via a suppression of Ia afferent transmission that in turn inhibits reflex mediation joint oscillations and subsequently allows for an improved balance performance (Trimble and Koceja 1994). It is surprising, therefore, that the present meta-analysis did not detect the same trend in H-reflex response that has been observed in discrete studies. Some of the included papers measured the H-reflex responses across a number of different conditions; for example, Keller et al. (2012) used four separate surfaces (stance, cushion, Posturomed, slackline). To circumvent this potential issue, the extracted data were pooled across these conditions to determine through a holistic approach whether lower limb motor skill training modulates the H-reflex. It is possible that our method may have contributed to the disparate results between the present meta-analysis and those consistently reported by individual studies. There are several different methods that can be used to assess the H-reflex response, which include the calculation of the raw amplitude, H/M_{MAX} or H_{MAX}/M_{MAX}. In turn, the H-reflex can be evoked at different parts of the recruitment curve, as well as potentially with respect to the M-wave recruitment curve. Given the nuances in H-reflex assessment, it is possible that different methodologies employed across studies may have contributed to the disparate outcomes observed. Of note, each included study assessed the H-reflex response across short-term training durations (i.e., 4–6 weeks) with pre–post-measurements taken. As observed with other neurophysiological variables, it is possible that transient changes in H-reflex amplitude may occur on an acute basis immediately after a single training session but, in the context of the present study, be missed due to inclusion of longer training studies and lack of data on acute responses.

M_{MAX}

The M-wave has been used extensively to provide quantitative information regarding changes in maximal muscle membrane excitability after fatiguing contractions, muscle damage protocols, and strength training interventions (e.g., Goodall et al. 2018; Place et al. 2010; Škarabot et al. 2021). However, its utility in response to motor skill training is limited and has not been investigated. The present meta-analysis pooled the estimate obtained from two studies, finding no change in M_{MAX} (SMD, 0.97) following lower limb motor practice and, more specifically, balance assessments (Giboin et al. 2019; Keller et al. 2012). Often within studies that utilise neurostimulation techniques, either in the form of TMS of electrophysiological reflex methods, assessing the M-wave response is typically used as a normalisation strategy to account for methodological and physiological issues (Rodriguez-Falces and Place 2017). However, in the context of fatiguing contractions, there is mixed evidence regarding the trend of M_{MAX} (Neyroud et al. 2013; Pageaux et al. 2013). Due to the relative intensity of motor skill tasks, particularly visuomotor and balance assessments, it is not surprising that M_{MAX} remained unchanged following motor skill training.

Short-interval intracortical inhibition

Paired-pulse TMS can be used to assess the degree of intracortical inhibition within the nervous system, which is synaptic in origin and mediated by GABAergic neurons acting via $GABA_A$ receptors (Di Lazzaro et al. 2000; Siddique et al. 2020; Ziemann et al. 1996). There is good evidence to show that the modulation of SICI is implicated in selective hand muscle activation (Stinear and Byblow 2003), and although this is prevalent in the upper limbs, it indicates that intracortical inhibition is implicit for motor performance (Ziemann et al. 2001). Previous literature has reported a reduction in SICI after learning a simple and complex motor task in young adults (Garry et al. 2004; Liepert et al. 1998; Perez et al. 2004). Of particular importance to the present review, Perez et al (2004) found a single session of visuomotor ankle dorsi/plantar flexion movements modified local intracortical networks (i.e., decreased SICI). Consistent with this, further support has found a reduced SICI within the lower extremities following low-intensity pedalling (Yamaguchi et al. 2012) and acute aerobic exercise (Yamazaki et al. 2019), with more recent evidence concluding that the GABAergic interneuronal circuits of the hand and leg representations are similar (Mrachacz-Kersting et al. 2021). The present best evidence synthesis revealed strong evidence that SICI is reduced after lower limb motor skill training, which builds on the findings of Berghuis et al. (2017) who observed that upper limb visuomotor training had no effect on SICI in young adults but the opposite in older adults. Due to the nature of the task, visuomotor movements require greater precision to accurately follow the intended direction (Zoghi et al. 2003). It is surprising that young adults did not have the same inhibitory response, and questions whether the removal of inhibition after motor practice is an important substrate for motor learning and M1 plasticity (Rantalainen et al. 2013). In light of the idea that the inhibitory networks are similar between the upper and lower extremities (Mrachacz-Kersting et al. 2021), the majority of literature to date has examined the effect of upper limb motor skill training on intracortical inhibition, which in turn is limiting the understanding of how the lower extremity musculature, given its role in gross motor function, interacts with GABAergic inhibitory networks.

Further considerations and limitations

Although beyond the scope of this paper, the low number of studies that satisfied eligibility criteria lends itself to a suggestion of potential publication bias. Whilst we can only comment tentatively upon this, it is perhaps somewhat surprising that there are not more studies which report no significant main effects. Publication bias is a well-recognised issue in science (DeVito and Goldacre 2018) with a tendency to favour publication of studies reporting significant over null effects (Fanelli 2013; Schmucker et al. 2014). Whether it is a case of journal editors being less inclined to publish null findings, or researchers not submitting such work for publication given the perception that it will be less well received, the (unintended) consequence is that the ability to accurately represent the body of evidence in a given area is impaired (Driessen et al. 2015). We therefore encourage replication studies of those published works that have been included in our review, and collectively highlight the importance of null effect studies being published.

Of 143 studies, 42 were excluded based on the lack of motor performance data. Despite evidence that TMS measures and motor skill acquisition is not correlated in the upper limbs (Berghuis et al. 2017), further research should assess the degree of skill acquisition and corticospinal responses to determine whether the two are related in the lower limb muscles, as currently there is little evidence to inform this conclusion beyond the upper limbs. Future studies should also apply a multi-focal approach combining techniques including functional magnetic resonance imaging (fMRI), electroencephalogram (EEG), TMS, and electrical nerve stimulation to increase the overall quality of research design and provide new information outside of the current body of literature. By understanding the mechanisms following lower limb motor skill training, it will enable targeted and effective prescription guidelines that can be easily translated into clinical practice.

All included papers within the meta-analysis and best evidence synthesis stimulated either the soleus or TA. This is most likely attributed to their physiological distinctions from other lower limb muscles, whereby the TA has been shown to demonstrate strong corticospinal projections which are similar to some upper limb muscles (Brouwer and Ashby 1990). It is clear that the TA has important functionality in the control of foot trajectory during the gait cycle and is known to be affected through foot drop in patients with cortical and spinal cord injuries (Thompson et al. 2018). However, the role of the quadriceps in gross motor control is not to be understated and, in turn, requires more investigation around the corticospinal responses. This is also related to the small number of studies employing lower limb tasks, which is further reflected in the discussions of Berghuis et al (2017) who did not return any lower limb studies despite not placing any restrictions on body region. A more comprehensive understanding on how the lower limb responds to motor skill training is needed, and this is clear from six studies returning from the literature search. To circumvent the low number, the best evidence synthesis presented alongside the meta-analysis accounts for within-groups differences and includes studies that may have previously been excluded based on no comparison to a control group. Although this provides a wider picture about the corticospinal responses following lower limb motor skill training, further empirical support is required to develop this area in line with the upper limb literature. It is also important to recognise that behavioural improvements and corticospinal responses may diverge at different stages of the motor learning process. For example, Dupont-Hadwen et al. (2019) investigated the profile of SICI dynamics before and in response to a thumb abduction task. Disinhibition in the M1, via a release of SICI, was observed during the movement preparation phase with no overall changes observed during the motor task. At the early stages of training, there was a correlation between behavioural improvements and increases in late pre-movement SICI, whereas later stage training-induced behavioural improvements were correlated to early changes in SICI. This indicates that as individuals prepare to move, and during the execution of the movement itself, there is a changing profile of inhibitory dynamics that acts to coordinate the muscle activity and perform the intended motor action (Dupont-Hadwen et al. 2019). Taken together, future work should consider the different shifts in corticospinal responses during each phase of motor learning when aiming to provide pooled effects.

Conclusions

This is the first meta-analysis and best evidence synthesis to provide quantitative information regarding lower limb motor skill training. The results of the meta-analysis revealed positive improvements in motor performance, but had no effect on CSE, H-reflex and M_{MAX}. The best evidence synthesis found strong evidence for improved motor performance and reduced SICI following lower limb motor skill training, with conflicting evidence towards the modulation of CSE. Taken together, this review highlights the need for further investigation on how motor skill training performed with the lower limb musculature modulates corticospinal responses. This will also help us to better understand whether these neuronal measures are underpinning mechanisms that support an improvement in motor performance.

Author's contribution All authors contributed to the study conception and design (AW, JSN, JH, CPM, DJK, and JT). Literature search and data extraction was performed by Alex Woodhead and Jamie Tallent. The first draft of the manuscript was written by Alex Woodhead and all authors (JSN, JH, CPM, DJK, and JT) commented on previous versions of the manuscript. All authors read and improved the final manuscript.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest, financial, or otherwise.

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