Journal of Neuroscience Methods 311 (2019) 318–330

Contents lists available at ScienceDirect

Journal of Neuroscience Methods

journal homepage: www.elsevier.com/locate/jneumeth

A systematic review investigating the relationship of electroencephalography and magnetoencephalography measurements with sensorimotor upper limb impairments after stroke

L. Tedesco Triccas[a,d,*], Sarah Meyer[a], Dante Mantini[b,c], Kenneth Camilleri[d], Owen Falzon[d], Tracey Camilleri[d], Geert Verheyden[a]

[a] Department of Rehabilitation Sciences, KU Leuven - University of Leuven, Tervuursevest 101, 3001, Leuven, Belgium
[b] Research Center for Movement Control and Neuroplasticity, KU Leuven - University of Leuven, Tervuursevest 101 box 1501, 3001, Leuven, Belgium
[c] Department of Experimental Psychology, University of Oxford, OX1 3PH, Oxford, United Kingdom
[d] Centre for Biomedical Cybernetics, University of Malta, Msida, MSD 2080, Malta

ARTICLE INFO

Keywords:
Cerebrovascular accident
Assessment
Sensorimotor recovery
Event related potentials
Cortical oscillations

ABSTRACT

Background: Predicting sensorimotor upper limb outcome receives continued attention in stroke. Neurophysiological measures by electroencephalography (EEG) and magnetoencephalography (MEG) could increase the accuracy of predicting sensorimotor upper limb recovery.

New method: The aim of this systematic review was to summarize the current evidence for EEG/MEG-based measures to index neural activity after stroke and the relationship between abnormal neural activity and sensorimotor upper limb impairment. Relevant papers from databases EMBASE, CINHAL, MEDLINE and pubMED were identified. Methodological quality of selected studies was assessed with the Modified Downs and Black form. Data collected was reported descriptively.

Results: Seventeen papers were included; 13 used EEG and 4 used MEG applications. Findings showed that: (a) the presence of somatosensory evoked potentials in the acute stage are related to better outcome of upper limb motor impairment from 10 weeks to 6 months post-stroke; (b) an interhemispheric imbalance of cortical oscillatory signals associated with upper limb impairment; and (c) predictive models including beta oscillatory cortical signal factors with corticospinal integrity and clinical measures could enhance upper limb motor prognosis.

Comparing with existing method: The combination of neurological biomarkers with clinical measures results in higher statistical power than using neurological biomarkers alone when predicting motor recovery in stroke.

Conclusions: Alterations in neural activity by means of EEG and MEG are demonstrated from the early post-stroke stage onwards, and related to sensorimotor upper limb impairment.

Future work exploring cortical oscillatory signals in the acute stage could provide further insight about prediction of upper limb sensorimotor recovery.

1. Introduction

Stroke is the third leading cause of adult disability worldwide (Hankey, 2013). One of the contributors to disability is upper limb impairment. Sensorimotor impairments can be defined as muscle weakness and deficits in motor control in addition to somatosensory impairments. The latter are defined as a deficiency in the sensation arising from skin, muscles, or joints such as discriminative abilities, proprioception, or detection of sensation such as light touch, pressure, or pain (Squire et al., 2012). Within 72 h after stroke, upper limb function deficits range from 48 to 77% (Persson et al. 2012) and at the chronic stage, 33 to 66% experience motor impairments and 21–54% of survivors experience somatosensory impairments (Meyer et al., 2016a; Kwakkel et al., 2003; Sunderland et al., 1989; Wade et al., 1983). Therefore, only 41% of people with moderate to severe stroke and 71% with mild stroke regain dexterity (Houwink et al., 2013). This results in limitations when using the upper limb during activities of daily living (Faria-Fortini et al., 2011).

* Corresponding author at: Department of Rehabilitation Sciences, Faculty of Movement and Rehabilitation Sciences, KU Leuven, Tervuursevest 101 – bus 1501, 3001 Leuven Belgium.
E-mail address: lisa.tedescotriccas@kuleuven.be (L. Tedesco Triccas).

https://doi.org/10.1016/j.jneumeth.2018.08.009
Received 22 May 2018; Received in revised form 17 July 2018; Accepted 9 August 2018
Available online 14 August 2018

Motor and sensory outcome prediction is useful in setting goals and planning treatment programs for improving upper limb impairments of people with stroke (Ward, 2017). Clinical examination using Fugl Meyer Assessment (Fugl-Meyer et al., 1975) has been the most common method to predicting upper limb motor function outcome in stroke. Patients will either recover about 70% of the maximum possible improvement or show little to no improvement (Winters et al., 2015). The impact of sensory deficits on upper limb motor recovery has received less attention. One contributory factor of sensorimotor impairment is due to impaired detection of sensory information, resulting in disturbed motor task performance (Hunter, 2002). Somatosensory clinical outcomes of light touch, proprioception and stereognosis measured in acute stroke have been associated with upper limb motor impairments at six months post-stroke (Meyer et al., 2016a). However, supplementary and sensitive outcome measures that identify crucial information about the underlying neural mechanisms are also needed to distinguish between proportional versus poor sensorimotor recoverees in stroke rehabilitation (Guggisberg et al., 2017).

A stroke recovery biomarker has been defined as “an indicator of disease state that can be used as a measure of underlying molecular/cellular processes that may be difficult to measure directly in humans, or predict recovery or treatment response” (Bernhardt et al., 2016). Biomarkers should be easy to use, reliable and provide a predictive value to individual patients. They are typically measured in the acute stage, week after onset and in the subacute stage— between 1 week and 3 months after stroke onset (Kim and Winstein, 2017). The integrity of the corticospinal tract and premotor-motor pathways measured by transcranial magnetic stimulation (TMS) and functional magnetic resonance imaging (fMRI) have been identified as neurophysiological and neuroanatomical biomarkers for upper limb motor recovery (Schulz et al., 2017; Byblow et al., 2015). The presence or absence of a motor evoked potential in the first three days post-stroke has been suggested to predict between a good or limited/poor motor recovery respectively (Stinear et al., 2017). Motor network activity measured by fMRI could also individualize prediction of 86% of motor outcome (Rehme et al., 2015). Recently, it has been identified that the integrity of the corticospinal tract and corticocortical connections between the ventral premotor cortex and primary motor cortex have a significant role in the residual motor output of people with sub-acute stroke (Schulz et al., 2017). Additionally, an intact sensory afferent signal is important for driving cortical remapping which is key for motor recovery (Murphy and Corbett, 2009). Thus, the somatosensory modalities may play an important role in modulating motor control processes as well (Bodmer and Beste, 2017). After stroke, voxel-based lesion-symptom methodology showed a lack of integrity of brain structures such as the superior thalamocortical radiation and the parietal operculum cortical regions, and these were associated with behavioral somatosensory deficits (Meyer et al., 2016b). Therefore, the assessment of both motor and somatosensory factors could increase the percentage of accurate prediction of upper limb outcome. However, apart from TMS and MRI methodologies, electrophysiological measures to guide sub-group stratification has been identified as a developmental priority at a Stroke Recovery and Rehabilitation Roundtable (Boyd et al., 2017).

Electroencephalography (EEG) records brain electrical fields using surface electrodes on the scalp while magnetoencephalography (MEG) records brain magnetic fields using sensitive magnetometers (Berger, 1929; Cohen, 1972). Both applications are close in methodologies since they have the same source of signals from ionic currents generated by biochemical processes at the cellular level (Lopes da Silva, 2013) and also have superior temporal resolution (Shiner et al., 2015). MEG has a higher spatial resolution in separating cortical sources than EEG (Hari, 2011). However, MEG is more expensive and highly sensitive to external disturbances while tiny magnetic fields are being measured.

Both EEG and MEG signals are described as frequency bands from infraslow, theta, alpha, beta, gamma and high-frequency oscillations. Alterations in frequency neuronal oscillatory patterns have been associated with pathology including stroke (Tecchio et al., 2007a,b). Event-Related Synchronization/Desynchronization (ERS/ERD) of frequency band-limited power are usually indicative of patterns of cortical activation and deactivation (Stępień et al., 2011). Disruption of neural activity can also be measured by time-locked-evoked or event-related potentials (ERP) measured by EEG or magnetic fields (ERF) measured by MEG. ERPs are the summated dipole fields of extracellular currents generated by cortical pyramidal cell populations that have become synchronously active in response to an external sensory event or an internal motor event (Okada et al., 1997; Bressler and Ding, 2006; Murakami and Okada, 2006). Specifically, somatosensory evoked potential (SSEPs) or somatosensory evoked fields (SEFs) can provide an index of somatosensory central nervous system pathways by stimulation of somatic receptors or electrical stimulation of peripheral nerve such as the median nerve (Allison et al., 1991). Additionally, EEG coherence has the ability to assess functional connectivity which is a measure of similarity between spontaneous brain activity signals measured at different locations at rest (Srinivasan et al., 2007). Alternations in cortical oscillatory signals, evoked potentials or functional connectivity could potentially be identified as biomarkers of upper limb recovery in stroke.

Recently a systematic review exploring the evidence and determining which neurological biomarker(s) meet the high evidence quality criteria for use in predicting motor recovery was conducted. However, only biomarkers measured by diffusion tensor imaging, TMS, fMRI, conventional structural MRI (sMRI) tools, and a combination of these biomarkers were included (Kim and Winstein, 2017). EEG and MEG has superior temporal compared to the aforementioned techniques (George et al., 1995). Therefore, allowing the examination of responses on a short time scales (milliseconds) and longer time scales (minutes) which is important for analyzing sensorimotor recovery. High temporal resolution also reduces the aliasing of higher frequencies and provides more data points per unit time resulting in more accurate correlation values (Magnuson et al., 2015). Therefore, we conducted a systematic review to: (1) evaluate high-quality evidence for high temporal resolution EEG/MEG-based measures to index neural activity after stroke and their relationships with abnormal neural activity with sensorimotor upper limb impairment in the acute, sub-acute and chronic stages and (2) determine if such measures could predict sensorimotor upper limb recovery. The results of this review could result in a better understanding of the longer-term upper limb sensorimotor impairment outcome and use the information to identify promising biomarkers for future research and clinical consideration (Bernhardt et al., 2017).

2. Methods

The systematic review was registered on PROSPERO (ID: CRD42016038903).

2.1. Study inclusion criteria

2.1.1. Types of study design

The studies included were: (i) Experimental studies (intervention and effectiveness studies with a prospective longitudinal design) and (ii) non-experimental studies (observational and cross-sectional studies) written in English. Sample size needed to be more than one participant.

2.1.2. Types of participants

Participants included in the studies needed to: (i) have a confirmed clinical diagnosis of a hemorrhagic or ischemic stroke by a neurologist or stroke consultant; (ii) have either somatosensory and/or motor upper limb impairments; and (iii) be at any time since stroke onset.

2.1.3. Outcome measures

EEG and MEG measurements including: ERPs or ERFs, cortical oscillatory signals and functional connectivity.

Table 1
An example of a search strategy used to screen for relevant papers included in this review.

Search	Key words
1	Electroencephalography
2	Magnetoencephalography
3	EEG
4	MEG
5	Cerebrovascular accident.mp.or exp "stroke/
6	1 or 3
7	2 or 4
8	6 or 7
9	'upper limb' OR 'arm' OR 'hand'- title, abstract, keyword
10	5 and 8 and 9

2.2. Search strategy and study selection

A search of the databases MEDLINE, EMBASE (Excerpta Medica Database), CINAHL (Cumulated Index of Nursing and Allied Health Literature) and PubMed was conducted from database inception to February 2018 by LTT. A hand search of the reference lists of each included article and the identified literature reviews were also screened for relevant publications. Key words of "stroke", "cerebrovascular accident", "upper limb", "arm", "hand", "encephalography", "EEG", "magnetoencephalography", "MEG", "cortical activity", "neural activity", "somatosensory evoked potential", "motor recovery", "sensory recovery" and synonyms for the search on the electronic databases were used (Table 1). The reference lists of each search from the different databases containing the articles and narrative reviews were also scanned separately for relevant publications. This was followed by the selection process based on title, abstract and then full text independently by two reviewers (LTT and SM). Any conference abstracts and duplicates were excluded.

2.3. Risk of potential bias appraisal

Two review authors (LTT and SM) assessed the risk of bias independently using a standardized valid and reliable form called the modified Downs and Black tool (Downs and Black, 1998; Eng et al., 2007). This tool assesses the methodological quality of non-randomized studies of health care interventions. The form contains 27 'yes'-or- 'no' questions across five sections. Items relating to intervention and randomization from the tool were deleted (Meyer et al., 2014). As a result, the tool contained questions about: 1) overall study quality (reporting) (8 items); 2) external validity (3 items) – the ability to generalize findings of the study; 3) internal validity (4 items) – to assess bias in the intervention and outcome measure(s) and 4) confounding and selection bias (4 items) – to determine bias from sampling or group assignment.

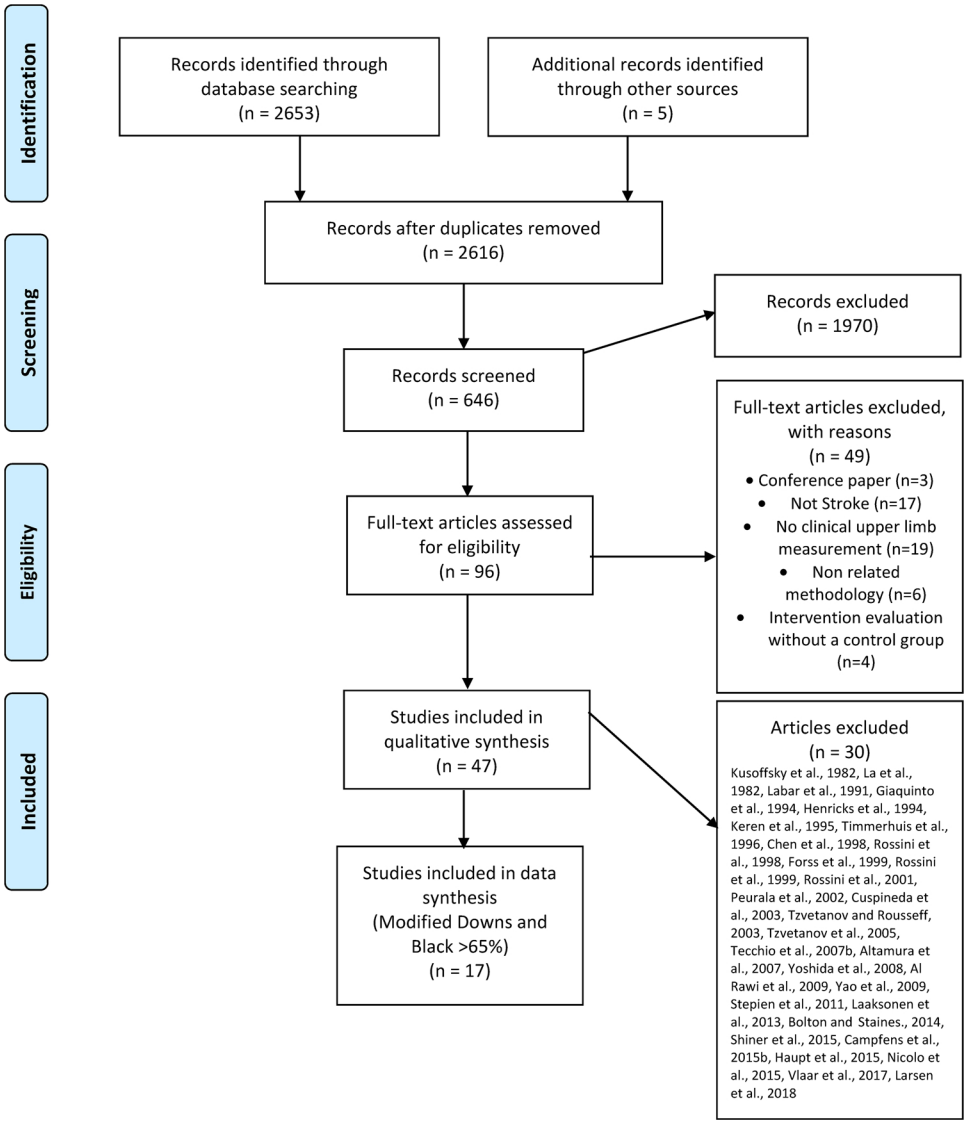

Fig. 1. Prisma flow diagram showing the selection process for included studies in the review (Al-Rawi et al., 2009; Altamura et al., 2007; Bolton and Staines, 2014; Chen et al., 1998; Coupar et al., 2012; Cuspineda et al., 2003; Forss et al., 1999; Giaquinto et al., 1994; Haupt et al., 2015; Hendricks et al., 1994; Keren et al., 1995; Kusoffsky et al., 1982; La et al., 1982; Laaksonen et al., 2013; Labar et al., 1991; Larsen et al., 2018; Nicolo et al., 2015; Peurala et al., 2002; Rossini et al., 1998, 1999, 2001; Stępień et al., 2011; Timmerhuis et al., 1996; Tzvetanov and Rousseff, 2003; Tzvetanov et al., 2005; Vlaar et al., 2017; Yao et al., 2009; Yoshida et al., 2008).

Any disagreement in the scores between reviewers was resolved through discussion between the two review authors. When resolution was not achieved, a third reviewer (GV) considered the paper(s) in question. At the end of the process, there was 100% agreement per paper between all raters for all items of the modified Downs and Black tool. As used in a similar review, papers achieving at least 65% of the maximum possible score were determined as having substantial quality were included in this review (Meyer et al., 2014).

2.4. Data extraction and analysis

Two reviewers (LTT, SM) carried out data extraction independently. The extracted data included: the design of the study, setting, inclusion and exclusion criteria, information about participants including; (i) number of participants, (ii) gender, (iii) side of stroke, (iv) type and (v) location of stroke and (vi) time since stroke, (vii) time-point of assessment, (viii) type of EEG or MEG methodology, (ix) outcome measures, (x) data analysis and (xi) results. Due to the heterogeneity of the data, meta-analyses could not be performed for this review. Therefore, data were grouped according to different EEG/MEG analyses of ERPs or ERFs, cortical oscillatory signals and functional connectivity linked with clinical outcome and are reported descriptively in the results section.

3. Results

3.1. The evidence base

From 2616 related titles, 646 abstracts were screened and 96 full-text papers were assessed for eligibility in which 49 were then excluded. Using Modified Down's and Black tool, risk of bias was then assessed for the remaining 47 articles. Low quality papers (< 65% score) (n = 30) were removed and 17 papers were included in the review with 13 used EEG and four used MEG methodologies (Fig. 1). Nine studies used a cross-sectional design (Pichiorri et al., 2018; Chen et al., 2017; Kawano et al., 2017; Thibaut et al., 2017; Campfens et al., 2015a,b; Rossiter et al., 2014; Kaiser et al., 2012; Oliviero et al., 2004; Platz et al., 2000), seven studies used a longitudinal design (Anastasi et al., 2017; Guggisberg et al. 2017; Parkkonen et al., 2017; Feys et al., 2000; Tzvetanov and Rousseff, 2005; Westlake et al., 2012; Keren et al., 1993) and one was an intervention study but only the baseline data was used for this review (Wu et al., 2015). The earliest study included in the review was in 1993. From 2017 onwards, an increase in research exploring the relationship of EEG measures and upper limb clinical outcome in stroke was identified. A full summary of all the papers are presented in Tables 2–4.

3.2. Summary of participant characteristics

In total 581 people with stroke were included in the review. Sixteen papers reported the gender of the participants, consisting of 194 females (33.4%) and 357 males (61.4%). From the total sample, 189 (32.5%) were in the acute stage of stroke (≤2 weeks post-stroke), 280 (48.2%) were in the sub-acute stage of stroke (> 2 weeks –≤6 months post-stroke) and 112 (19.3%) were in the chronic stage of stroke (> 6 months post-stroke). Fourteen papers reported that 213 (36.6%) had a right-sided stroke, 191 (32.9%) had a left-sided stroke and one participant had right-and left-sided stroke. Eleven papers reported that 354 (60.9%) had ischemic stroke and 70 (12.0%) had hemorrhagic stroke and the location of the stroke; out of these 120 (20.7%) had cortical; 154 (26.5%) had sub-cortical and 44 (7.6%) had cortico-subcortical stroke.

3.3. Somatosensory evoked potential/field analysis and upper limb motor outcome

Presence, amplitude and latency of SSEPs or SEFs were explored in four studies. It was identified that participants with acute stroke with an absent median nerve SSEP had lower muscle strength scores ($p < 0.01$) (Tzvetanov and Rousseff, 2005; Feys et al., 2000; Keren et al., 1993). Present SSEP latency of the NI (negative component) complex and amplitude (P15/NI) measured by EEG at 3 weeks post-stroke correlated with motor ability measured at 10 weeks later ($r = 0.66$ and $r = 0.62$ respectively) (Keren et al., 1993). However, the correlation between N20-P25 amplitudes of SSEPs and muscle strength was weak in acute stroke (Tzvetanov and Rousseff, 2005). The correlations of amplitude parameters of SSEPs with motor impairments at 6 months were also weak ($p < 0.05$) (Tzvetanov and Rousseff, 2005). Participants with acute stoke with an absent median SSEP had lower MRC scores cross-sectionally ($p < 0.01$) (Tzvetanov and Rousseff, 2005; Feys et al., 2000; Keren et al., 1993). Equivalent current dipole strength of SEFs measured by MEG in the ipsilesional hemisphere showed a direct relationship with motor scores in acute stroke ($r = 0.52$; $p = 0.002$ for M20 and $r = 0.37$ $p = 0.037$ for M30) (Oliviero et al., 2004).

3.4. Cortical oscillatory signal analysis and upper limb sensorimotor outcome

Participants with hemiparesis in the sub-acute and chronic stage had pronounced alpha ERD at frontal, temporal and centroparietal regions when carrying out a motor task with their affected upper limb compared to healthy controls (Platz et al., 2000). A significant positive correlation was found between low beta and upper limb motor impairments when measured at rest of people with sub-acute and chronic stroke ($Rs = 0.56$, $p = 0.002$) (Pichiorri et al., 2018). In participants with somatosensory deficits in the sub-acute stage, a reduction in alpha activity was found at central and centroparietal regions where movement-related alpha-ERD is usually expected (Platz et al., 2000).

Asymmetry between hemispheres was reported in three studies exploring cortical oscillatory signals in combination with motor active tasks (Kaiser et al., 2012; Rossiter et al., 2014; Anastasi et al., 2017). Movement-related beta desynchronization was significantly smaller in the contralesional but not in the ipsilesional M1 ($p = 0.005$) during movement of the affected upper limb in people in the sub-acute and chronic stages of stroke (Rossiter et al., 2014). Additionally, movement-related beta desynchronization (smaller reduction in beta power) in the contralesional hemisphere correlated negatively with motor impairment (standardized regression coefficient (ß) = -0.52, $p = 0.008$, $r^2 = 0.26$) (Rossiter et al., 2014). A significant higher brain symmetry index, especially in cortical stroke ($p = 0.028$) was found in people with acute and sub-acute stroke (Anastasi et al., 2017). Severe upper limb motor impairments were also associated with imbalance oscillatory activity between the ipsilesional and contralesional hemispheres (Kaiser et al., 2012). During movement of the affected hand of people with sub-acute stroke, people with increased upper limb motor impairment showed higher ipsilesional alpha ERS whilst those with mild upper limb motor impairments showed significant higher contralesional ERS (Kaiser et al., 2012). In two studies, brain symmetry index and interhemispheric phase synchrony index of alpha and beta bands did not significantly correlate with upper limb motor impairments of participants with sub-acute stroke during active motor task and at rest respectively ($r = -0.543$, $p = 0.266$) [Anastasi et al., 2017] and $p = 0.49$ and $p = 0.22$ alpha and beta band respectively [Kawano et al., 2017]).

A specific oscillatory signal analysis after passive movement of the index finger showed that, the amplitude of 20 Hz rebound at the

Table 2
Summary of all included papers exploring ERPs/ERFs.

Reference	Modified Downs and Black Score	Techn-ique	Design of study	Aim of study	Stroke Participant Characteristics	Brain Activity Measure/s (time-point)	Clinical Outcome measure (time-point)	Results
Keren et al., 1993	68%	EEG	Longitudinal study	Determination of the predictive capacity of upper limb short latency SSEP for clinical evaluation	N = 19 G = 8 F, 11M Mean Age = 57.8 (range 36-71) years Mean (SD) Time post-stroke = 20.5 (8.8) days Baseline UL motor impairment = Not defined Stroke Type = 19I Stroke location = Not defined	Median nerve SSEP amplitude and latency measured at C3 and C4 channels (Two time-point assessments at 3 weeks and 10 weeks post-stroke)	Impairments measured by: -Motricity Index (Two time-point assessments at ± 3 weeks and 10 weeks post-stroke)	- Non-detectable SSEP had worse outcomes at baseline - NI latency over dominant hemisphere correlated with motor ability (r = 0.66) - P15/NI amplitude over dominant hemisphere correlated with motor ability (r = 0.62) -Multiple regression showed that only amplitude of ipsilesional hemisphere significantly correlated with motor ability (R^2 = 0.34)
Feys et al., 2000	74%	EEG	Longitudinal study	Assessment of the value of SSEPs in the prediction of motor recovery of the upper limb in people with stroke and to evaluate the combined predictive value of these measures and set of clinical variables	N = 64 G = 27 F, 37M Mean (SD) age = 63.69 (11.34 years Mean (SD) Time post-stroke = 22.08 (6.49) days Baseline UL motor impairment = Mean (SD) FMA Score: 12.94 (10.16 Stroke Type = 61I; 3H Stroke location = Not defined	Median nerve SSEP measured at C3 and C4 channels (Two time-point assessments at 2-5 weeks and 2 months)	Impairments measured by: - FMA - Modified Ashworth scale (Four time-point assessments at 2-5 weeks, 6 weeks, 6 months and 12 months)	- Motor performance and SSEPs measured at baseline accounted for 60% and 58% of the variance at 6 and 12 months
Oliviero et al., 2004	75%	MEG	Cross-sectional study	Assessment of relationship between MEG results, clinical status and neuroradiological findings	N = 32 G = 15 F, 17M Mean (SD) age = 68(12) years Mean (SD) Time Post-stroke = 5.2 (2.6) days Baseline UL impairment = Not defined Stroke Type = 32I Stroke location = Not defined	Median nerve SEF measured by 28-channels (One time-point assessment at a mean time 5.2 days post-stroke)	Impairments measured by: - Canadian Neurological Scale - Arbitrary four-degree scale for sensory impairment - NIH stroke scale (One time-point assessment at a mean time 5.2 days post-stroke)	- Excessive interhemispheric latency asymmetry of M30 statistically correlated with a worse clinical outcome (motor p = 0.007; sensory = 0.031) - Significant correlation between lesion size and strength of M20 in the contralesional hemisphere (rho = 0.43; p = 0.019)
Tzvetanov and Rousseff, 2005	68%	EEG	Longitudinal study	Assessment of the predictive value of SSEP changes in early phase of stroke	N = 130 G = 43 F, 87M Mean (SD) age = 62.5 (11.4) years Mean Time post-stroke = Not defined Baseline UL motor impairment = Not defined Stroke Type = 89I; 41H Stroke location = I: 48C; 33SC; 8CSC H: 7 Lobar; 24 Putaminal; 10 Thalamic	Median nerve SSEP measured at C3 and C4 channels (One time-point assessment at 0-7 days ischemic stroke; and 0–21days Hemorrhagic stroke)	Impairments measured by: - MRC Scale (Two time-point assessments at 0-7 days ischemic or 0-21days hemorrhagic and at 6 months post-stroke)	- Absent median SSEP was linked with lower muscle strength scores (p < 0.01)

(*continued on next page*)

Table 2 (*continued*)

Reference	Modified Downs and Black Score	Techn-ique	Design of study	Aim of study	Stroke Participant Characteristics	Brain Activity Measure/s (time-point)	Clinical Outcome measure (time-point)	Results
Campfens et al., 2015a	69%	EEG	Cross-sectional study	Exploring StrEPs in a group of sub-acute stroke and to evaluate whether the StrEP components can be measured in the acute phase	N = 8 G = 1 F; 7M Mean Age = 57 years (range: 35-77) Range Time post-stroke = 13-135 days post-stroke Baseline UL motor impairment = Range FMA score:6-65 Stroke Type = Not defined Stroke location = 3C; 5SC	Flexion and extension wrist manipulation StrEP measured at 64 channels (One time-point assessment between 13-135 weeks post-stroke)	Impairments measured by: - - FMA (One time-point assessment between 13-135 weeks post-stroke)	- No significant differences in StrEPs waveforms between good and poor function (p = 0.19 at contralateral motor cortex; p = 0.14 at vertex)

* C = Cortical; CSC = cortico-subcortical; F = Female; FMA = Fugl-Meyer Assessment; G = Gender; H = Hemorrhagic; I = Ischemic; M = Male; MRC = Medical Research Council Scale; N = Sample number; NIH = National Institute of Health; SC = Sub-cortical; SSEP = Somatosensory evoked potential; StrEPs = Stretch Evoked Potentials; UL = Upper Limb.

ipsilesional but not at the contralesional hemisphere significantly positively correlated with upper limb function in the acute, sub-acute and chronic stages of stroke ($r = 0.6$, $p < 0.01$ [acute], $r = 0.7$, $p < 0.001$ [sub-acute] and $r = 0.6$, $p < 0.01$ [chronic]) (Parkkonen et al., 2017).

3.5. Functional connectivity analysis and upper limb motor outcome

Functional connectivity between ipsilesional and contralesional M1 was not significantly related to upper limb motor impairments in people with chronic stroke at rest ($p = 0.87$) (Wu et al., 2015). Higher ipsilesional connectivity between M1 and premotor cortex were associated with milder upper limb impairments (Wu et al., 2015). Greater reduction in resting state alpha-band functional under connected voxels at 8–12 weeks apart, resulted in a better composite clinical recovery score with participants in the acute, sub-acute and chronic stages of stroke ($r = 0.81$; $p = 0.003$) (Westlake et al., 2012). In the latter study, time post-stroke was factored in the correlation analyses and a significant positive association was found between recovery and functional connectivity in the primary motor and somatosensory cortices ($r = 0.64$; $p = 0.01$). A negative association was then found between functional connectivity in the contralesional sensorimotor cortex ($r = 0.75$, $p = < 0.0001$) and the posterior parietal cortex ($r = 0.75$, $p = 0.0028$).

3.6. Prediction regression models for upper limb motor impairments

Prediction models were explored in relation to SSEP and frequency band analysis. Amplitude of SSEP in the ipsilesional hemisphere resulted in a predicted variance of $r^2 = 0.34$ for muscle strength (Keren et al., 1993). Presence of a SSEP and motor performance measured at the early stage of sub-acute stroke resulted in 60% and 58% of the variance of prediction of motor recovery at 6 and 12 months post-stroke (Feys et al., 2000).

Beta plus gamma or theta network features were identified as EEG-based motor network biomarkers yielding a positive predictive value of 83.3% for upper limb rehabilitation in the sub-acute and chronic stages (Chen et al., 2017). Moreover, the initial upper limb function scores, sub-cortical lesions and time post-stroke presented the best accuracy to the predictive model. EEG measures in addition with corticospinal tract integrity measured by structural imaging or TMS and FMA were also added to predictive models. Corticospinal tract asymmetry, initial FMA and beta-band coherence measured in the sub-acute stage was found to have sensitivity of 0.89 and positive predictive values of 0.86 and 0.88 respectively in predicting upper limb motor recovery (Guggisberg et al., 2017). When factors of high beta in the ipsilesional and contralesional hemisphere measured at rest in addition with motor threshold measured by TMS, and clinical FMA score were added to a separate predictive model, this resulted in the highest prediction level for upper limb motor impairments at the chronic stage (Adj $R^2 = 0.366$) (Thibaut et al., 2017).

4. Discussion

To our knowledge, this is the first review to have systematically evaluated the relationship between EEG or MEG measures with upper limb sensorimotor impairments post stroke. In summary, the main EEG or MEG measures were based on the study of SSEPs or SEFs, cortical oscillatory signals and functional connectivity. Median nerve SSEP latency measurement in the acute stage are associated with upper limb motor recovery in the sub-acute and chronic stages. Study of cortical oscillatory signals reported interhemispheric imbalance between the contralesional and ipsilesional hemisphere which associated with severity of upper limb motor impairments. Increased functional connectivity in the ipsilesional hemisphere has potential of predicting upper limb motor recovery. Finally, EEG measures of cortical oscillatory signals in combination with measurement of corticospinal integrity and clinical motor measures could be of relevance in predicting upper

Table 3
Summary of all included papers exploring cortical oscillatory signals.

Reference	Modified Downs and Black Score	Technique	Design of study	Aim of study	Stroke Participant Characteristics	Brain Activity Measure/s (time-point)	Clinical Outcome measure (time-point)	Results
Platz et al., 2000	75%	EEG	Cross-sectional correlation study	Assessment of different subgroups of stroke patients with clinically distinct impairments and EEG analysis of movement-related brain activity	N = 13 G = 3 F; 10M Mean age (SD) = 54.9 (6.5) Mean Time post-stroke = 8.8 (SD 7.3) weeks Baseline UL motor impairment = Mild to moderate paresis Stroke Type = 13I Stroke location = 9C; 4SC	Active Movement-related frequency analysis measured at 27 channels (One time-point assessment at 8.8 [SD7.3] weeks post-stroke)	Impairments measured by no defined outcome measures - UL paresis - UL somatosensory deficit - Ideomotor apraxia (One time-point assessment at 8.8 [SD 7.3] weeks post-stroke)	- Pronounced alpha ERD at frontal, temporal and centroparietal regions in participants with hemiparesis
Kaiser et al., 2012	81%	EEG	Cross-sectional correlation study	Investigation of the relationship between the intensity of ERD and ERS patterns and severity of motor impairments after stroke	N = 29 G = 14 F; 15M Mean Age = 58 years ± 15 years Mean Time post-stroke = 4 ± 4 months Baseline UL motor impairment = Mean (SD) Muscle Strength Score: 57 (13) Stroke Type = 26I; 3H Stroke location = 8C; 11SC; 10CSC	Active Movement-related frequency analysis measured at 61 channels (One time-point assessment at 4 [SD 4] months post-stroke)	Impairments measured by: - MRC scale - Modified Ashworth Scale - European Stroke Scale (One time-point assessment at 4 [SD 4] months post-stroke)	- Significant negative correlation between muscle strength and LC for ERS of affected side (R = −0.51; p = 0.037)
Rossiter et al., 2014	69%	MEG	Cross-sectional study	Investigation of cortical oscillatory signals at rest and during movement of the affected hand in stroke	N = 23 G = 5 F; 18M Mean (SD) Age = 50 (13) years Mean Time post-stroke = 32 ± 5 months Baseline UL motor impairment = Mean (SD) Grip Strength Score:38 (22) lb Stroke Type = Not identified Stroke location = 14C; 8SC; 1CSC	Active Movement-related frequency analysis measured by whole-head 275 MEG system (One time-point assessment at 32[SD 50] months post-stroke)	Impairments measured by: - Nine-Hole Peg Test - Action Research Arm Test - Grip strength by dynamometer (One time-point assessment at 32 [SD 50] months post-stroke)	- Movement-related Beta Desynchronization in contralateral M1 correlated negatively with motor impairment [standardized regression coefficient (ß = -0.52, p = 0.008, r^2 = 0.26)
Anastasi et al., 2017	68%	EEG	Longitudinal study	Investigation of the role of quantitative EEG parameters, particularly BSI, in the assessment and prognostication of motor function in the sub-acute phase poststroke	N = 10 G = 0 F; 10M Mean (SD) Age = 59.4 (10.3) years Mean (SD) Time post-stroke at baseline = 25.7 (17.8) days Baseline UL motor impairment = Mean (SD) FMA Score:40.3 (25.6) Stroke Type = Not defined Stroke location = 4C; 6SC	Active Movement-related frequency analysis measured at 32 channels (Four time-point assessments: Session 1- Range 5-60 days post-stroke; Session 2- Range 31-91 days post-stroke, Session 3- Range 63-112 days post-stroke, Session 4- Range 92-146 days post-stroke)	Impairments measured by: - FMA - MRC scale - MI (Four time-point assessments: Session 1 - Range 5-60 days; Session 2 - Range 31-91 days ; Session 3 - Range 63-112 days; Session 4 - Range 92-146 days post-stroke)	- A significant difference in BSI between stroke and healthy (p = 0.023) - Significant differences in BSI in cortical stroke versus healthy subjects (p = 0.028). - The correlation between FMA and BSI at follow-up statistical significance (r = −0.543, p = 0.266) - No statistical significant differences in BSI over time (p = 0.077)
Chen et al., 2017	81%	EEG	Cross-sectional study	Study the linear and non-linear (cross-frequency) network connectivity patterns as favorable biomarkers for stratifying patients for upper limb rehabilitation	N = 37 G = 10 F; 27M Mean (SD) Age = 57.0 (12.6) Mean (SD) Time post-stroke = 6.5 (5.2) months Baseline UL motor impairment = Mean (SD) FMA Score: 30.9	Active Movement-related frequency analysis measured at 32 channels (One time point assessment at 6.5 [SD: 5.2] months post-stroke)	Impairment measured by: - FMA - WMFT - Upper extremity performance evaluation test for the elderly (One time point assessment at 6.5 [SD 5.2] months)	- Beta plus gamma or theta network features were identified as EEG-based motor network biomarkers yielding highest accuracies of 92% to the predictive model - Subcortical lesions, time post-stroke, and initial impairment scores

(*continued on next page*)

Table 3 (*continued*)

Reference	Modified Downs and Black Score	Technique	Design of study	Aim of study	Stroke Participant Characteristics	Brain Activity Measure/s (time-point)	Clinical Outcome measure (time-point)	Results
					(13.9) Stroke Type = 20I; 17H Stroke location = 14C; 23SC			were the most significant clinical variables affecting the classification accuracy of the prediction model
Kawano et al., 2017	94%	EEG	Cross-sectional study	Investigation of the clinical relevance of hemispheric phase synchrony in stroke patients by calculating its correlation with clinical status	N = 19 G = 5 F; 14M Mean (SD) Age = 67.5(10.1) years Mean (SD)Time post-stroke = 52.5(38.3) days Baseline UL and LL motor impairment = Mean (SD) FMA Score = 63.5(26.0) Stroke Type = 19I Stroke location = 10C; 8SC; 1CSC	Frequency analysis at rest of 19 channels (One time-point assessment at 52.5 [SD: 38.3] days post-stroke)	Impairments measured by: - FMA (One time-point assessment at 52.5 [SD 38.3] days post-stroke)	- No significant correlations between Interhemispheric phase synchrony in alpha and beta bands with FMA scores (p = 0.49; 0.22) -
Parkkonen et al., 2017	68%	MEG	Longitudinal study	Study alterations in motor cortex excitability after stroke and its association with motor recovery	N = 23 G = 10 F; 13M Mean (SD) Age = 65 (2) years Time post-stroke = 1-7 days Baseline UL motor impairment = Mean (SD) Dynamometer score:16 (4) kg Stroke Type = Not defined Stroke location = 2C; 6SC; 15CSC	Passive index finger movement-related frequency analysis measured by 306-channel whole-scalp system (Three time-point assessments at 1-7 days, 1 month and 12 months post-stroke)	Impairments measured by/: - Jamar Hydraulic Hand Dynamometer to measure grip strength - Nine-Hole-Peg Board - Box and Block Test (Three time-point assessments at 1-7 days, 1 month and 12 months)	- Rebound amplitude of 20 Hz frequency was stronger with higher scores of the Box and Block test at all time-points and Nine-Hole Peg test at baseline and 12-month follow-up
Thibaut et al., 2017	69%	EEG	Cross-correlational study	Understand the neural mechanisms of motor function recovery after stroke using neurophysiological markers by means of brain oscillations	N = 55 G = 17 F; 38M Mean (SD) Age = 62 (14) years Time (SD) post-stroke = 32 (42) months Baseline UL motor impairment = Mean (SD) FMA score first center: 51.6(7.9); second centre:35.6 (22.9) Stroke Type = 49I; 6H Stroke location = Not defined	Frequency analysis at rest of 128 channels (One time-point assessment at 32 [SD 42] months post-stroke)	Impairments measured by: - FMA - WMFT (One time-point assessment at 32 [42] months post-stroke)	-High power spectrum (alpha, low and high beta) in ipsilesional and contralesional hemispheres associated with FMA
Pichiorri et al., 2018	81%	EEG	Cross-correlational study	Definition of an index of interhemispheric connectivity derived from EEG	N = 30 G = Not defined Mean (SD) Age = 63(10) years Time (SD) post-stroke = 1.9 (1) months Baseline UL motor impairment = Mean (SD) FMA score:50(10) Stroke Type = Not defined Stroke location = Mixed but numbers not defined	Frequency analysis at rest of 61 channels (One time-point assessment at 1.9 [SD 1] months post-stroke)	Impairments measured by: - FMA - ESS (One time-point assessment at 1.9 [SD 1] months post-stroke)	-Significant positive correlation identified between lower beta and FMA and ESS (FMA: Rs = 0.56, p = 0.002 and ESS: Rs = 0.45, p = 0.01)

* BSI = Brain symmetry index; C = Cortical; CSC = cortico-subcortical; ESS = European Stroke Scale; F = Female; FMA = Fugl-Meyer Assessment; G = Gender; H = Hemorrhagic; I = Ischemic; LC = Laterality Coefficient; LL = lower Limb; M = Male; MRC = Medical Research Council; MI = Motricity Index; N = Sample number; SC = Sub-cortical; UL = Upper Limb; WMFT = Wolf Motor Function Test.

Table 4
Summary of all included papers exploring functional connectivity.

Reference	Modified Downs and Black Score	Technique	Design of study	Aim of study	Stroke Participant Characteristics	Brain Activity Measure/s (time-point)	Clinical Outcome measure (time-point)	Results
Westlake et al., 2012	79%	MEG	Longitudinal study	Determination of the relationship between sensorimotor recovery and changes in resting-state functional connectivity in perilesional region	N = 14 G = 3 F; 11M Mean (SD) Age = 61 (11) years Mean (SD) TimePost-Stroke = 15(13) weeks Baseline UL motor impairment = Mean (SD) FMA Score: 27 (14) Stroke Type = 14I Stroke location = 4C; 2SC;8 CSC	Functional connectivity measured at rest using a whole-head 275-axial magnetometer system (Two time-point assessment at 8 and 12 weeks later post-stroke)	Impairments measured by: - FMA - Dynamometer (grip strength) Dynamometer (Two time-point assessments at 8 and 12 weeks later post-stroke)	-Reduction in underconnectivity from visit 1 to 2 was linked with better clinical recovery score ($pr^2 = 0.66$)
Wu et al., 2015	69%	EEG	Baseline Cross-sectional correlation data taken from an intervention study	Examination of resting-state EEG measure of functional connectivity, coherence with ipsilesional primary motor cortex in the beta band, as a biomarker of change in motor status	N = 12 G = 6 F; 6M Mean (SD) Age = 54.0(16.6) years Mean (SD) Time Post-stroke = 7.3 (4.0) months Baseline UL motor impairment = Mean (SD) FMA Score: 39 (12 Stroke Type = 12I Stroke location = 9C; 2SC;1 CSC	Functional connectivity measured at rest using 256 channels (One time-point assessment at 3 months post-stroke)	Impairments measured by: - FMA (upper limb) (One time-point assessment at 3 months post-stroke)	-Functional connectivity between ipsilesional and contralesional M1 was not significantly related to upper limb motor impairments (p = 0.87)
Guggisberg et al., 2017	74%	EEG	Longitudinal Study	Examination of the multivariate relationship between structural and functional correlates of proportional recovery patterns	N = 63 G = 27 F; 36M Mean Age = 64 years (range 28-85years) Time post-stroke = 2-4 weeks Baseline UL motor impairment = Mean(SD) FMA Score: 17.5 (17.9) Stroke Type = Not defined Stroke location = Not defined	Functional connectivity measured at rest using 128 channels (Two time-point assessment measured at 2-4 weeks and 3 months post-stroke)	Impairments measured by: -FMA (Two time-point assessment measured at 2-4 weeks and 3 months	- Participants with low scores on FMA at first time-point had disrupted beta-band weighted node degree at the affected hemisphere - Participants with higher FMA scores had high beta-band weighted node degree in the frontal brain region including ventral premotor cortex - No significant differences in longitudinal EEG changes were observed between the 2 groups ($p < .05$)

* C = Cortical; CSC = cortico-subcortical; F = Female; FMA = Fugl-Meyer Assessment; G = Gender; H = Hemorrhagic; I = Ischemic; M = Male; N = Sample number; SC = Sub-cortical; UL = Upper Limb; WMFT = Wolf Motor Function Test.

limb recovery but further work is warranted to collecting oscillatory measures of people with both sensory and motor impairments in the acute stage of stroke.

4.1. The relationship between somatosensory evoked potentials and upper limb motor recovery

Unilateral stimulation of the median nerve activates the contralateral primary somatosensory cortex representing the lowest level of cortical processing (Sutherland and Tang, 2006). Our results showed that presence or absence of median SSEPs in the acute and sub-acute stage of stroke could predict upper limb motor recovery. Additionally, certain components such as the negative peak latency and amplitude measured at 3 weeks post-stroke associated with motor ability measured clinically measured 10 weeks later (Keren et al., 1993). However, evidence provided for SSEPs comes from a majority of studies published over 10 years ago. Thus, due to lack of recent studies using this methodology, the conclusions drawn regarding the potential clinical utility should be considered with caution. Additionally, one must note that only two electrodes were used in the included studies and this does not depict a topographical image of the activity in the different areas of the brain. More channels were included for the measurement of somatosensory evoked fields by MEG which also provided information about upper limb motor recovery. The study of Oliviero et al. (2004) showed that such measurements had moderate to high association with motor function measures in acute stroke. MEG is dependent on the interaction between excitation and inhibition in cortical microcircuits which could be more responsive in the acute and sub-acute stages of stroke (Yamawaki et al., 2008). However, MEG is expensive and complex to employ (Boyd et al., 2017) and, therefore, using EEG with 32 or more electrodes when measuring SSEPs should be explored in future research.

4.2. Study of cortical oscillations in people with motor impairments after stroke

The role of intrahemispheric connectivity remains controversial in stroke. In animal studies, it has been reported that a reduction of alpha and beta waves in the ipsilesional hemisphere was identified (Moyanova and Dijkhuizen, 2014), while other studies reported an increase in rhythmic alpha waves in the contralesional hemisphere during the first seven days after total middle cerebral artery occlusion (Lu et al., 2001). In humans, the amount of activity in contralesional hemisphere and its influence on the ipsilesional hemisphere in relation to motor recovery is still unclear (Buetefisch, 2015; Dodd et al., 2017; Rehme et al., 2015). In this review, cortical oscillatory asymmetry between hemispheres were reported in four studies with moderate/good quality. Movement-related beta desynchronization was significantly smaller in the contralesional M1 during movement of the affected upper limb in people in the sub-acute and chronic stages and correlated negatively with motor impairment (Rossiter et al., 2014). On the contrary, high brain symmetry index and interhemispheric phase synchrony index of alpha and beta bands did not significantly correlate with upper limb motor impairments of participants with sub-acute stroke (Anastasi et al., 2017; Kawano et al., 2017). The different results could be due to measurements taken at different stages of stroke. Neural activity and network adaptions change over time and it has been suggested that the interhemispheric imbalance is more pronounced in the chronic stage (Koch and Hummel, 2017). The included studies in this review did not explore cortical oscillations in the acute stage. Predictive models of upper limb motor recovery include the initial TMS measurement within 72 h post-stroke to predict upper limb motor recovery at three months (Stinear et al., 2017). Due to the critical time window for recovery being in the first 30 days post-stroke (Murphy and Corbett, 2009) and the feasibility of using EEG in the acute stroke, future research should explore cortical oscillatory signals within 72 h post-stroke to three months post-stroke (Stinear, 2017). Additionally, an included study in this review reported that that a significant higher brain symmetry index was found in cortical stroke, and, therefore stroke location could also be one of the factors contributing to the interhemispheric imbalance and needs to be explored (Anastasi et al., 2017; Chen et al., 2017; Huynh et al., 2016).

4.3. Prediction of upper limb motor recovery

Different methodologies are able to investigate the wide field of underpinning motor recovery after stroke, such as TMS, fMRI and DTI. A recent systematic review identified that a combination of clinical and neurophysiological biomarkers measured by fMRI, DTI and TMS is more common and likely preferable than using neurophysiological biomarkers alone to accurately predicting motor recovery in stroke (Kim and Winstein, 2017). Currently, a useful and promising tool for predicting upper limb motor recovery at three months post-stroke is the PREP algorithm which combines clinical and neuroimaging markers or the PREP2 algorithm which combines clinical and TMS markers (Stinear et al., 2017; Byblow et al., 2015). However, the algorithm makes correct predictions for 75% of patients. Apart from exploring the integrity of the corticospinal tract, it has been suggested to also study the damage in multiple cortical and sub-cortical brain regions when predicting upper limb motor recovery (Boyd et al., 2017; Rondina et al., 2017). Functional connectivity in high beta band measured between the ipsilesional primary motor cortex and premotor regions by EEG which has a superior temporal resolution to MRI or TMS, demonstrated a specific marker for motor status. An increase in connectivity was a good predictor for motor improvement after 28 days of training (Wu et al., 2015). Additionally, our review showed that the addition of EEG measures such beta oscillatory activity at the ipsilesional and contralesional hemisphere and beta coherence also provided good prediction for upper limb motor recovery. This shows that adding EEG measures to predictive models could provide additional prognostic value for upper limb motor recovery. In this light, the benefit of measuring both corticospinal tract integrity and beta oscillatory activity in addition with clinical measures needs to be further explored.

4.4. Strengths and limitations of the review

This is the first review to explore the current evidence of EEG and MEG measures of upper limb sensorimotor recovery. In order to present sound quality of evidence, a detailed thorough methodology for selection of papers was employed. However, there are some limitations in this review. It was essential to include evidence from high-quality studies and therefore, only 17 from 47 full-text papers were included. This resulted in prohibiting subgroup analyses of different types, stages and locations of stroke, highlighting the need for additional high-quality studies to evaluate the potential clinical utility of EEG and MEG measures to inform stroke rehabilitation. Additionally, an unusual number of 25% of the sample were women included in this review compared to the expected 50% (Di Carlo et al., 2003). Therefore, gender bias could have influenced the results.

4.5. Future work

As soon as a substantial amount of high-quality spatio-temporal electrophysiological and hemodynamic data is available, a meta-analyses using odds ratio should be conducted to explore the value of the EEG and MEG in addition with fMRI, DTI, TMS and near-infrared spectroscopy measures in predicting upper limb sensorimotor recovery. From the meta-analyses, new scientific hypothesis could be generated. Also, brain computer interfacing also uses EEG to generate motor output and therefore future reviews should explore its important role in the recovery sensorimotor upper limb impairments after stroke (Frolov et al., 2017; Ang et al., 2015). This will provide valuable information

about the causal connection between brain signals and the rehabilitative intervention. The majority of the included studies in this review mainly explored motor upper limb impairments. To date, there are limited neuroimaging studies identifying biomarkers for somatosensory impairments in stroke (Goodin et al., 2018; Meyer et al., 2016b; Bannister et al.,2015, Schaechter et al., 2006). Therefore, a large sample of people after stroke with somatosensory in addition to motor upper limb impairments should be included when exploring including somatosensory evoked potentials and movement-related frequency measures in prediction models for upper limb recovery. Although acute stroke research has its challenges, future research should explore movement-related cortical oscillatory signals in the very early stage post-stroke and specifically identify the factors that contribute to mild, moderate and severe upper limb impairments. This could have the potential to accurately predict sensorimotor recovery at three and six months post-stroke and plan treatment programs accordingly.

5. Conclusion

This is the first review to explore different types of EEG and MEG measures in relation to sensorimotor upper limb impairments after stroke. Seventeen studies were included in the review. Presence of SSEPs are related to better outcome of upper limb motor impairment post stroke in the sub-acute and chronic stages. An imbalance of cortical oscillatory signals between the ipsilesional and contralesional hemispheres with movement of the affected upper limb was identified. An increase in beta activity in contralesional hemisphere correlated with poorer upper limb motor outcome in the chronic stage. Additionally, predictive models with beta oscillatory cortical signal factors with corticospinal integrity and motor clinical measures could predict upper limb motor recovery. Future research should explore EEG or MEG measurements in the acute stage of stroke with a larger sample of stroke participants with stratification for location of stroke and upper limb motor and somatosensory severity. This could provide accurate biomarkers of recovery leading to better stratification of patients for clinical trials and inform evidence-based practice.

Declarations of interest

None.

Acknowledgements

The research work disclosed in this publication is partially funded by the REACH HIGH Scholars Programme – Post-Doctoral Grants awarded to Lisa Tedesco Triccas. The project is part-financed by the European Union, Operational Programme II — Cohesion Policy 2014-2020 Investing in human capital to create more opportunities and promote the wellbeing of society -European Social Fund. We also would like to thank Promobilia foundation for funding this project (grant number: 17064). This work was also supported by the Wellcome Trust (grant number: 101253/A/13/Z).

References

Allison, T., McCarthy, G., Wood, C.C., Jones, S.J., 1991. Potentials evoked in human and monkey cerebral cortex by stimulation of the median nerve: a review of scalp and intracranial recordings. Brain 114 (6), 2465–2503.

Al-Rawi, M.A., Hamdan, F.B., Abdul-Muttalib, A.K., 2009. Somatosensory evoked potentials as a predictor for functional recovery of the upper limb in patients with stroke. J. Stroke Cerebrovasc. Dis. 18 (4), 262–268.

Altamura, C., Torquati, K., Zappasodi, F., Ferretti, A., Pizzella, V., Tibuzzi, F., et al., 2007. fMRI-vs-MEG evaluation of post-stroke interhemispheric asymmetries in primary sensorimotor hand areas. Exp. Neurol. 204 (2), 631–639.

Anastasi, A.Agius, Falzon, O., Camilleri, K., Vella, M., Muscat, R., 2017. Brain symmetry index in healthy and stroke patients for assessment and prognosis. Stroke Res. Treat. https://doi.org/10.1155/2017/8276136.

Ang, K.K., Chua, K.S.G., Phua, K.S., Wang, C., Chin, Z.Y., Kuah, C.W.K., et al., 2015. A randomized controlled trial of EEG-based motor imagery brain-computer interface robotic rehabilitation for stroke. Clin. EEG Neurosci. 46 (4), 310–320.

Bannister, L.C., Crewther, S.G., Gavrilescu, M., Carey, L.M., 2015. Improvement in touch sensation after stroke is associated with resting functional connectivity changes. Front. Neurol. 6, 165.

Berger, H., 1929. On the EEG in humans. Arch. Psychiatr. Nervenkr. 87, 527–570.

Bernhardt, J., Borschmann, K., Boyd, L., et al., 2016. Moving rehabilitation research forward: developing consensus statements for rehabilitation and recovery research. Int. J. Stroke 11, 454–458.

Bernhardt, J., Hayward, K.S., Kwakkel, G., Ward, N.S., Wolf, S.L., Borschmann, K., et al., 2017. Agreed definitions and a shared vision for new standards in stroke recovery research: the stroke recovery and rehabilitation roundtable taskforce. Int. J. Stroke 12 (5), 444–450.

Bodmer, B., Beste, C., 2017. On the dependence of response inhibition processes on sensory modality. Hum. Brain Mapp. 38 (4), 1941–1951.

Bolton, D.A., Staines, W.R., 2014. Attention-based modulation of tactile stimuli: a comparison between prefrontal lesion patients and healthy age-matched controls. Neuropsychologia 57, 101–111.

Boyd, L.A., Hayward, K.S., Ward, N.S., Stinear, C.M., Rosso, C., Fisher, R.J., et al., 2017. Biomarkers of stroke recovery: consensus-based core recommendations from the stroke recovery and rehabilitation roundtable. Neurorehabil. Neural Repair 31 (10-11), 864–876.

Bressler, S.L., Ding, M., 2006. Event-Related Potentials. Wiley Encyclopedia of Biomedical Engineering. https://doi.org/10.1002/9780471740360.ebs0455.

Buetefisch, C.M., 2015. Role of the contralesional hemisphere in post-stroke recovery of upper extremity motor function. Front. Neurol. 6, 214.

Byblow, W.D., Stinear, C.M., Barber, P.A., Petoe, M.A., Ackerley, S.J., 2015. Proportional recovery after stroke depends on corticomotor integrity. Ann. Neurol. 78 (6), 848–859.

Campfens, S.F., Meskers, C.G., Schouten, A.C., van Putten, M.J., van der Kooij, H., 2015a. Stretch evoked potentials in healthy subjects and after stroke: a potential measure for proprioceptive sensorimotor function. IEEE Trans. Neural Syst. Rehabil. Eng. 23 (4), 643–654.

Campfens, S.F., Zandvliet, S.B., Meskers, C.G., Schouten, A.C., van Putten, M.J., van der Kooij, H., 2015b. Poor motor function is associated with reduced sensory processing after stroke. Exp. Brain Res. 233 (4), 1339–1349.

Chen, C.C., Chen, J.T., Wu, Z.A., Kao, K.P., Liao, K.K., 1998. Long latency responses in pure sensory stroke due to thalamic infarction. Acta Neurol. Scand. 98 (1), 41–48.

Chen, C.C., Lee, S.H., Wang, W.J., Lin, Y.C., Su, M.C., 2017. EEG-based motor network biomarkers for identifying target patients with stroke for upper limb rehabilitation and its construct validity. PLoS ONE 12 (6), e0178822.

Cohen, D., 1972. Magnetoencephalography: detection of the brain's electrical activity with a superconducting magnetometer. Science 175 (4022), 664–666.

Coupar, F., Pollock, A., Rowe, P., Weir, C., Langhorne, P., 2012. Predictors of upper limb recovery after stroke: a systematic review and meta-analysis. Clin. Rehabil. 26 (4), 291–313.

Cuspineda, E., Machado, C., Aubert, E., Galan, L., Liopis, F., Avila, Y., 2003. Predicting outcome in acute stroke: a comparison between QEEG and the Canadian Neurological Scale. Clin. Electroencephalogr. 34 (1), 1–4.

Di Carlo, A., Lamassa, M., Baldereschi, M., Pracucci, G., Basile, A.M., Wolfe, C.D., et al., 2003. Sex differences in the clinical presentation, resource use, and 3-month outcome of acute stroke in Europe: data from a multicenter multinational hospital-based registry. Stroke 34 (5), 1114–1119.

Dodd, K.C., Nair, V.A., Prabhakaran, V., 2017. Role of the Contralesional vs. Ipsilesional Hemisphere in stroke recovery. Front. Hum. Neurosci. 11, 469.

Downs, S.H., Black, N., 1998. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. J. Epidemiol. Community Health 52 (6), 377–384.

Eng, J., Teasell, R., Miller, W., Wolfe, D., Townson, A., Aubut, J.A., Konnyu, K., 2007. Spinal cord injury rehabilitation evidence: method of the SCIRE systematic review. Top. Spinal Cord Inj. Rehabil. 13 (1), 1–10.

Faria-Fortini, I., Michaelsen, S.M., Cassiano, J.G., Teixeira-Salmela, L.F., 2011. Upper extremity function in stroke subjects: relationships between the international classification of functioning, disability, and health domains. J. Hand Ther. 24 (3), 257–265.

Feys, H., De Weerdt, W., Nuyens, G., Van De Winckel, A., Selz, B., Kiekens, C., 2000. Predicting motor recovery of the upper limb after stroke rehabilitation: value of a clinical examination. Physiother. Res. Int. 5 (1), 1–18.

Forss, N., Hietanen, M., Salonen, O., Hari, R., 1999. Modified activation of somatosensory cortical network in patients with right hemisphere stroke. Brain 122 (10), 1889–1899.

Frolov, A.A., Mokienko, O., Lyukmanov, R., Biryukova, E., Kotov, S., Turbina, L., et al., 2017. Post-stroke rehabilitation training with a motor-imagery-based brain-computer interface (BCI)-controlled hand exoskeleton: a randomized controlled multicenter trial. Front. Neurosci. 11, 400.

Fugl-Meyer, A.R., Jääskö, L., Leyman, I., Olsson, S., Steglind, S., 1975. The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. Scand. J. Rehabil. Med. 7 (1), 13–31.

George, J.S., Aine, C.J., Mosher, J.C., Schmidt, D.M., Ranken, D.M., Schlitt, H.A., et al., 1995. Mapping function in the human brain with magnetoencephalography, anatomical magnetic resonance imaging, and functional magnetic resonance imaging. J. Clin. Neurophysiol. 12 (5), 406–431.

Giaquinto, S., Cobianchi, A., Macera, F., Nolfe, G., 1994. EEG recordings in the course of recovery from stroke. Stroke 25 (11), 2204–2209.

Goodin, P., Lamp, G., Vidyasagar, R., McArdle, D., Seitz, R.J., Carey, L.M., 2018. Altered functional connectivity differs in stroke survivors with impaired touch sensation following left and right hemisphere lesions. Neuroimage Clin. 18, 342–355.

Guggisberg, A.G., Nicolo, P., Cohen, L.G., Schnider, A., Buch, E.R., 2017. Longitudinal structural and functional differences between proportional and poor motor recovery after stroke. Neurorehabil. Neural Repair DOI: 1545968317740634.
Hankey, G.J., 2013. The global and regional burden of stroke. Lancet Glob. Health 1, e239–e240.
Hari, R., 2011. Magnetoencephalography: methods and applications. In: Schomer, D.L., Lopes da Silva, F.H. (Eds.), Niedermeyer's Electroencephalography: Basic Principles, Clinical Applications and Related Fields, 6th edition. Lippincott Williams & Wilkins, Philadelphia (2011), pp. 865-900.
Haupt, W.F., Chopan, G., Sobesky, J., Liu, W.C., Dohmen, C., 2015. Prognostic value of somatosensory evoked potentials, neuron-specific enolase, and S100 for short-term outcome in ischemic stroke. J. Neurophysiol. 115 (3), 1273–1278.
Hendricks, H.T., Pasman, J.W., Mulder, T., Notermans, S.L., Schoonderwaldt, H.C., 1994. Value of somatosensory evoked potentials for the prediction of motor recovery of the upper extremity after cerebral infarction. Int. J. Health Rehabil. Sci. 7 3-3.
Houwink, A., Nijland, R.H., Geurts, A.C., Kwakkel, G., 2013. Functional recovery of the paretic upper limb after stroke: who regains hand capacity? Arch. Phys. Med. Rehabil. 94 (5), 839–844.
Hunter, J.V., 2002. Magnetic resonance imaging in pediatric stroke. Top. Magn. Reson. Imaging 13 (1), 23–38.
Huynh, W., Vucic, S., Krishnan, A.V., Lin, C.S., Kiernan, M.C., 2016. Exploring the evolution of cortical excitability following acute stroke. Neurorehabil. Neural Repair 30 (3), 244–257.
Kaiser, V., Daly, I., Pichiorri, F., Mattia, D., Müller-Putz, G.R., Neuper, C., 2012. Relationship between electrical brain responses to motor imagery and motor impairment in stroke. Stroke 43 (10), 2735–2740.
Kawano, T., Hattori, N., Uno, Y., Kitajo, K., Hatakenaka, M., Yagura, H., Miyai, I., 2017. Large-scale phase synchrony reflects clinical status after stroke: an EEG study. Neurorehabil. Neural Repair 31 (6), 561–570.
Keren, O., Ring, H., Solzi, P., Pratt, H., Groswasser, Z., 1993. Upper limb somatosensory evoked potentials as a predictor of rehabilitation progress in dominant hemisphere stroke patients. Stroke 24 (12), 1789–1793.
Keren, O., Ring, H., Pratt, H., Growasser, Z., 1995. Dynamic changes in upper limb short latency somatosensory-evoked potentials following stroke in the dominant hemisphere. Clin. Rehabil. 9 (1), 52–60.
Kim, B., Winstein, C., 2017. Can neurological biomarkers of brain impairment be used to predict poststroke motor recovery? A systematic review. Neurorehabil. Neural Repair 31 (1), 3–24.
Koch, P.J., Hummel, F.C., 2017. Toward precision medicine: tailoring interventional strategies based on noninvasive brain stimulation for motor recovery after stroke. Curr. Opin. Neurol. 30 (4), 388–397.
Kusoffsky, A., Wadell, I., Nilsson, B.Y., 1982. The relationship between sensory impairment and motor recovery in patients with hemiplegia. Scand. J. Rehabil. Med. 14 (1), 27–32.
Kwakkel, G., Kollen, B.J., van der Grond, J., Prevo, A.J.H., 2003. Probability of regaining dexterity in the flaccid upper limb impact of severity of paresis and time since onset in acute stroke. Stroke. 34 (9), 2181–2186.
La, W.J., Reddy, N.M., Melvin, J.L., 1982. Somatosensory evoked potentials: their predictive value in right hemiplegia. Arch. Phys. Med. Rehabil. 63 (5), 223–226.
Laaksonen, K., Helle, L., Parkkonen, L., Kirveskari, E., Mäkelä, J.P., Mustanoja, S., et al., 2013. Alterations in spontaneous brain oscillations during stroke recovery. PLoS ONE 8 (4), e61146.
Labar, D., Petty, G., Emerson, R., Pedley, T., Mohr, J.P., 1991. Median nerve somatosensory evoked potentials in patients with lacunar and other small subcortical strokes. J. Neurol. Sci. 101 (2), 221–226.
Larsen, L.H., Zibrandtsen, I.C., Wienecke, T., Kjaer, T.W., Langberg, H., Nielsen, J.B., et al., 2018. Modulation of task-related cortical connectivity in the acute and subacute phase after stroke. Eur. J. Neurosci. 47 (8), 1024–1032.
Lopes da Silva, F.L., 2013. EEG and MEG: relevance to neuroscience. Neuron 80 (5), 1112–1128.
Lu, X., Williams, A.J., Tortella, F.C., 2001. Quantitative electroencephalography spectral analysis and topographic mapping in a rat model of middle cerebral artery occlusion. Neuropathol. Appl. Neurobiol. 27 (6), 481–495.
Magnuson, M.E., Thompson, G.J., Schwarb, H., Pan, W.J., McKinley, A., Schumacher, E.H., et al., 2015. Errors on interrupter tasks presented during spatial and verbal working memory performance are linearly linked to large-scale functional network connectivity in high temporal resolution resting state fMRI. Brain Imaging Behav. 9 (4), 854–867.
Meyer, S., Karttunen, A.H., Thijs, V., Feys, H., Verheyden, G., 2014. How do somatosensory deficits in the arm and hand relate to upper limb impairment, activity, and participation problems after stroke? A systematic review. Phys. Ther. 94 (9), 1220–1231.
Meyer, S., De Bruyn, N., Krumlinde-Sundholm, L., Peeters, A., Feys, H., Thijs, V., et al., 2016a. Associations between sensorimotor impairments in the upper limb at 1 week and 6 months after stroke. J. Neurol. Phys. Ther. 40 (3), 186–195.
Meyer, S., Kessner, S.S., Cheng, B., Bönstrup, M., Schulz, R., Hummel, F.C., et al., 2016b. Voxel-based lesion-symptom mapping of stroke lesions underlying somatosensory deficits. Neuroimage Clin. 10, 257–266.
Moyanova, S.G., Dijkhuizen, R.M., 2014. Present status and future challenges of electroencephalography-and magnetic resonance imaging-based monitoring in preclinical models of focal cerebral ischemia. Brain Res. Bull. 102, 22–36.
Murakami, S., Okada, Y., 2006. Contributions of principal neocortical neurons to magnetoencephalography and electroencephalography signals. J. Physiol. 575 (3), 925–936.
Murphy, T.H., Corbett, D., 2009. Plasticity during stroke recovery: from synapse to behaviour. Nat. Rev. Neurosci. 10 (12), 861.
Nicolo, P., Rizk, S., Magnin, C., Pietro, M.D., Schnider, A., Guggisberg, A.G., 2015. Coherent neural oscillations predict future motor and language improvement after stroke. Brain 138 (10), 3048–3060.
Okada, Y.C., Wu, J., Kyuhou, S., 1997. Genesis of MEG signals in a mammalian CNS structure. Electroencephalogr. Clin. Neurophysiol. 103, 474–485.
Oliviero, A., Tecchio, F., Zappasodi, F., Pasqualetti, P., Salustri, C., Lupoi, D., et al., 2004. Brain sensorimotor hand area functionality in acute stroke: insights from magnetoencephalography. Neuroimage 23 (2), 542–550.
Parkkonen, E., Laaksonen, K., Piitulainen, H., Pekkola, J., Parkkonen, L., Tatlisumak, T., et al., 2017. Strength of ~20-Hz rebound and motor recovery after stroke. Neurorehabil. Neural Repair 31 (5), 475–486.
Persson, H.C., Parziali, M., Danielsson, A., Sunnerhagen, K.S., 2012. Outcome and upper extremity function within 72 hours after first occasion of stroke in an unselected population at a stroke unit. A part of the SALGOT study. BMC Neurol. 12 (1), 162.
Peurala, S.H., Pitkänen, K., Sivenius, J., Tarkka, I.M., 2002. Cutaneous electrical stimulation may enhance sensorimotor recovery in chronic stroke. Clin. Rehabil. 16 (7), 709–716.
Pichiorri, F., Petti, M., Caschera, S., Astolfi, L., Cincotti, F., Mattia, D., 2018. An EEG index of sensorimotor interhemispheric coupling after unilateral stroke: clinical and neurophysiological study. Eur. J. Neurosci. 47 (2), 158–163.
Platz, T., Kim, I.H., Pintschovius, H., Winter, T., Kieselbach, A., Villringer, K.H., et al., 2000. Multimodal EEG analysis in man suggests impairment-specific changes in movement-related electric brain activity after stroke. Brain 123 (12), 2475–2490.
Rehme, A.K., Volz, L.J., Feis, D.L., Eickhoff, S.B., Fink, G.R., Grefkes, C., 2015. Individual prediction of chronic motor outcome in the acute post-stroke stage: behavioral parameters versus functional imaging. Hum. Brain Mapp. 36 (11), 4553–4565.
Rondina, J.M., Park, C.H., Ward, N.S., 2017. Brain regions important for recovery after severe post-stroke upper limb paresis. J. Neurol. Neurosurg. Psychiatry. https://doi.org/10.1136/jnnp-2016-315030.
Rossini, P.M., Tecchio, F., Pizzella, V., Lupoi, D., Cassetta, E., Pasqualetti, P., et al., 1998. On the reorganization of sensory hand areas after mono-hemispheric lesion: a functional (MEG)/anatomical (MRI) integrative study. Brain Res. 782 (1-2), 153–166.
Rossini, P.M., Pauri, F., Cicinelli, P., Pasqualetti, P., Traversa, R., Tecchio, F., 1999. Neuromagnetic recordings and magnetic brain stimulation in the evaluation of sensorimotor hand area interhemispheric differences: normative, experimental and patients' data. Electroencephalogr. Clin. Neurophysiol. Suppl. 50, 210–220.
Rossini, P.M., Tecchio, F., Pizzella, V., Lupoi, D., Cassetta, E., Paqualetti, P., 2001. Interhemispheric differences of sensory hand areas after monohemispheric stroke: MEG/MRI integrative study. Neuroimage 14 (2), 474–485.
Rossiter, H.E., Davis, E.M., Clark, E.V., Boudrias, M.H., Ward, N.S., 2014. Beta oscillations reflect changes in motor cortex inhibition in healthy ageing. Neuroimage 91, 360–365.
Schaechter, J.D., Stokes, C., Connell, B.D., Perdue, K., Bonmassar, G., 2006. Finger motion sensors for fMRI motor studies. Neuroimage 31 (4), 1549–1559.
Schulz, R., Park, E., Lee, J., Chang, W.H., Lee, A., Kim, Y.H., et al., 2017. Interactions between the corticospinal tract and premotor–Motor pathways for residual motor output after stroke. Stroke 48 (10), 2805–2811.
Shiner, C.T., Tang, H., Johnson, B.W., McNulty, P.A., 2015. Cortical beta oscillations and motor thresholds differ across the spectrum of post-stroke motor impairment, a preliminary MEG and TMS study. Brain Res. 1629, 26–37.
Squire, L., Berg, D., Bloom, F.E., Du Lac, S., Ghosh, A., Spitzer, N.C., 2012. Fundamental Neuroscience. Academic Press, Oxford.
Stępień, M., Conradi, J., Waterstraat, G., Hohlefeld, F.U., Curio, G., Nikulin, V.V., 2011. Event-related desynchronization of sensorimotor EEG rhythms in hemiparetic patients with acute stroke. Neurosci. Lett. 488 (1), 17–21.
Stinear, C.M., 2017. Prediction of motor recovery after stroke: advances in biomarkers. Lancet Neurol. 16 (10), 826–836.
Stinear, C.M., Byblow, W.D., Ackerley, S.J., Smith, M.C., Borges, V.M., Barber, P.A., 2017. PREP2: a biomarker-based algorithm for predicting upper limb function after stroke. Ann. Clin. Transl. Neurol. 4 (11), 811–820.
Sunderland, A., Tinson, D., Bradley, L., Hewer, R.L., 1989. Arm function after stroke. An evaluation of grip strength as a measure of recovery and a prognostic indicator. J. Neurol. Neurosurg. Psychiatry 52 (11), 1267–1272.
Sutherland, M.T., Tang, A.C., 2006. Reliable detection of bilateral activation in human primary somatosensory cortex by unilateral median nerve stimulation. Neuroimage 33 (4), 1042–1054.
Tecchio, F., Pasqualetti, P., Zappasodi, F., Tombini, M., Lupoi, D., Vernieri, F., et al., 2007a. Outcome prediction in acute monohemispheric stroke via magnetoencephalography. J. Neurol. 254 (3), 296–305.
Tecchio, F., Zappasodi, F., Tombini, M., Caulo, M., Vernieri, F., Rossini, P.M., 2007b. Interhemispheric asymmetry of primary hand representation and recovery after stroke: a MEG study. Neuroimage 36 (4), 1057–1064.
Thibaut, A., Simis, M., Battistella, L.R., Fanciullacci, C., Bertolucci, F., Huerta-Gutierrez, R., et al., 2017. Using brain oscillations and corticospinal excitability to understand and predict post-stroke motor function. Front. Neurol. 8, 187.
Timmerhuis, T.P., Hageman, G., Oosterloo, S.J., Rozeboom, A.R., 1996. The prognostic value of cortical magnetic stimulation in acute middle cerebral artery infarction compared to other parameters. Clin. Neurol. Neurosurg. 98 (3), 231–236.
Tzvetanov, P., Rousseff, R.T., 2003. Median SSEP changes in hemiplegic stroke: long-term predictive values regarding ADL recovery. NeuroRehabil 18 (4), 317–324.
Tzvetanov, P., Rousseff, R.T., 2005. Predictive value of median-SSEP in early phase of stroke: a comparison in supratentorial infarction and hemorrhage. Clin. Neurol. Neurosurg. 107 (6), 475–481.
Tzvetanov, P., Rousseff, R.T., Atanassova, P., 2005. Prognostic value of median and tibial somatosensory evoked potentials in acute stroke. Neurosci. Lett. 380 (1-2), 99–104.
Vlaar, M.P., Solis-Escalante, T., Dewald, J.P., Van Wegen, E.E., Schouten, A.C., Kwakkel,

G., et al., 2017. Quantification of task-dependent cortical activation evoked by robotic continuous wrist joint manipulation in chronic hemiparetic stroke. J. Neuroeng. Rehabil. (1), 30.
Wade, D.T., Langton-Hewer, R., Wood, V.A., Skilbeck, C.E., Ismail, H.M., 1983. The hemiplegic arm after stroke: measurement and recovery. J Neurol Neurosurg Psychiatry 46 (6), 521–524.
Ward, N.S., 2017. Restoring brain function after stroke [mdash] bridging the gap between animals and humans. Nat. Rev. Neurol. 13 (4), 244–255.
Westlake, K.P., Hinkley, L.B., Bucci, M., Guggisberg, A.G., Findlay, A.M., Henry, R.G., et al., 2012. Resting state alpha-band functional connectivity and recovery after stroke. Exp. Neurol. 237 (1), 160–169.
Winters, C., van Wegen, E.E., Daffertshofer, A., Kwakkel, G., 2015. Generalizability of the proportional recovery model for the upper extremity after an ischemic stroke. Neurorehabil. Neural Repair 29 (7), 614–622.
Wu, J., Quinlan, E.B., Dodakian, L., McKenzie, A., Kathuria, N., Zhou, R.J., Cramer, S.C., 2015. Connectivity measures are robust biomarkers of cortical function and plasticity after stroke. Brain 138 (8), 2359–2369.
Yamawaki, N., Stanford, I.M., Hall, S.D., Woodhall, G.L., 2008. Pharmacologically induced and stimulus evoked rhythmic neuronal oscillatory activity in the primary motor cortex in vitro. Neuroscience 151 (2), 386–395.
Yao, J., Chen, A., Carmona, C., Dewald, J.P., 2009. Cortical overlap of joint representations to the loss of independent joint control. Neuroimage 45 (2), 490–499.
Yoshida, H., Kondo, T., Nakasato, N., 2008. Neuromagnetic investigation of somatosensory cortical reorganization in hemiplegic patients after thalamic hemorrhage. J. Phys. Ther. Sci. 20 (2), 123–127.