Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in
Biomedical Engineering

Non-invasive brain imaging to advance the understanding of human balance

Helen J. Huang[a,b,c,1] and Daniel P. Ferris[d,e,f]

Abstract

Humans depend on mobility for social interaction, cognitive development, and health maintenance. Successful mobility requires maintaining balance, which integrates sensory feedback, internal cognitive models of body dynamics, and musculoskeletal actions. There have been great strides in understanding these components of balance control in the last 20 years, but balance deficits persist in a large percentage of the population. We propose that combining non-invasive brain imaging using high-density electroencephalography (EEG) with behavioral and biomechanical measures could reveal unique insights about balance control. Source separation and localization of brain electrical activity during mobile tasks have improved with advancements in electrodes and motion artifact removal. This enables studying naturally occurring balance tasks with and without perturbations to identify the timing, magnitude, and quality of brain processing during balance. Along with efforts toward more inclusive EEG research and open resources, this approach could help diagnose and treat poor balance ability among more people.

Addresses

[a] Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, FL, USA
[b] Disability, Aging, and Technology Cluster, University of Central Florida, Orlando, FL, USA
[c] Biionix[TM] (Bionic Materials, Implants & Interfaces) Cluster, University of Central Florida, Orlando, FL, USA
[d] J. Crayton Pruitt Department of Biomedical Engineering, University of Florida, Gainesville, FL, USA
[e] Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL, USA
[f] Department of Neurology, University of Florida, Gainesville, FL, USA

Corresponding author: Huang, Helen J. (hjhuang@ucf.edu)
[1] Present/Permanent Address:University of Central Florida. Department of Mechanical and Aerospace Engineering. 12760 Pegasus Drive. Orlando, FL 32816

Current Opinion in Biomedical Engineering 2023, **28:**100505

This review comes from a themed issue on **Neural Motor Control of Robotics**

Edited By **He Huang** and **Gregory Sawicki**

For complete overview of the section, please refer the article collection - Neural Motor Control of Robotics

Received 6 February 2023, revised 13 September 2023, accepted 14 September 2023

https://doi.org/10.1016/j.cobme.2023.100505

Keywords

EEG, Perturbation, Balance control, Neural control, Inclusiveness.

Current state of fall prevention and interventions

From a baby's first steps, humans realize that a lack of balance control limits how far they can go. Successful mobility increases development of cognitive and social skills in early life [1] and helps to maintain cognitive and social skills later in life [2]. Fall-related injuries affect the quality of life, healthcare costs, and longevity of millions of individuals with limb loss, post-stroke hemiparesis, and aging-related sensorimotor and physical decline [3−5].

There are multiple fall prevention interventions that can reduce the incidence of falls among different populations, but current interventions provide incremental improvements in balance and require extensive training. Common balance interventions that have been tried include resistance exercise, endurance exercise, tai chi, yoga, and dancing. The magnitude of improvements with these interventions has been mixed at best [6]. One reason for a lack of reduction in real world falls is the high level of task specificity for balance training [7]. To improve balance and prevent falls, individuals need to train in situations and dynamics similar to what causes their falls and address individual deficiencies. For example, if an elderly individual's balance control deficiency is primarily sensory related, then stronger muscles are not likely to help them. Similarly, if an individual with prior traumatic brain injury has difficulty with the cognitive processing required to generate motor commands, then improved sensory augmentation technology may not prevent additional falls. These are just two examples, but they highlight the need to match the intervention with the patient specific deficits in balance control.

Some researchers have proposed more task specific training interventions based on repeated perturbations that cause a loss of balance [8]. The underlying premise is that forced practice of responding to physical perturbations will improve the ability to respond to real-world perturbations. Results so far have been relatively positive, with many clinical trials showing enhanced outcomes in fall prevention compared to more general strength/power/endurance/coordination training exercises. However, despite the improvements in balance performance with perturbation training, there is much we do not know about how individuals modify their balance control as a result of the training. What components of balance control are improved after repeated perturbation training? This is not yet known.

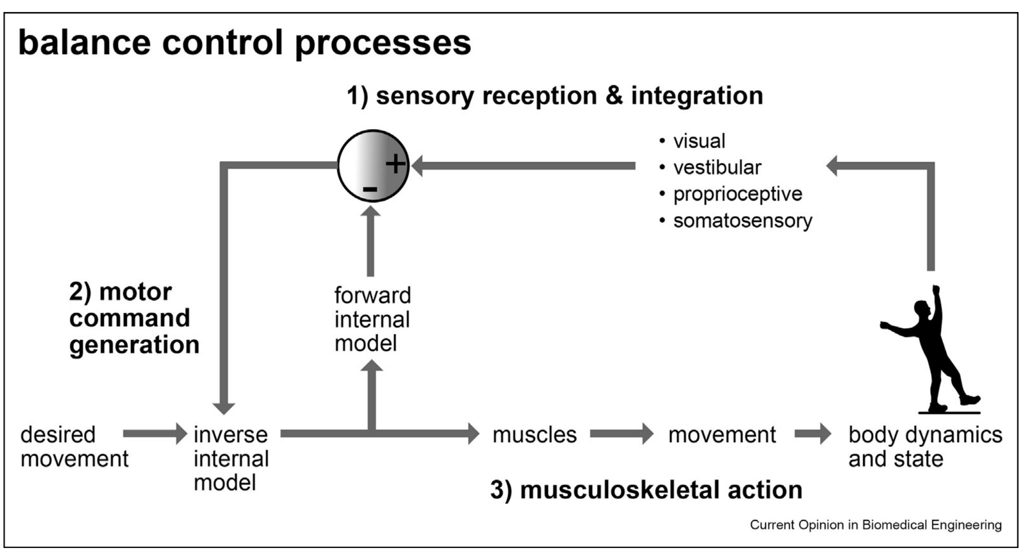
Cortical control of balance

Human balance control depends on sensory feedback, internal cognitive models of body dynamics, and musculoskeletal actions (Figure 1). Sensory feedback during standing and walking comes from vestibular, somatosensory, proprioceptive, and visual pathways [9], which helps the brain determine the current state of the body. These sensory inflows are integrated in areas throughout the brain, including the posterior parietal cortex and cerebellum. Considerable evidence supports the presence of feedforward and feedback internal models in the control of human movement in general [10], and in the control of balance in standing and walking specifically [11–13]. These internal models then use the sensory inflows to determine the appropriate motor commands to the musculoskeletal system to produce a desired response. Muscles then receive the motor commands, generating force to coordinate the body segments for maintaining balance. These separate processes in balance control can be hard to quantify when there are deficits in balance performance. Musculoskeletal actions can be studied with behavioral and biomechanical measures such as kinematic motion capture and electromyography (EMG), but processing of sensory feedback and updating internal models require high temporal resolution measurements of brain dynamics.

Current state of mobile brain imaging techniques

Electroencephalography (EEG) is currently the only non-invasive brain imaging technique that provides millisecond temporal resolution necessary to study rapid processes in dynamic balance control during real-world tasks. Portable magnetoencephalography (MEG) also has potential for future studies [14] but is not quite ready for experiments on humans during walking. The rise in mobile EEG for brain imaging studies have led to several recent reviews on EEG correlates of balance [15,16] and locomotion [16,17]. With more advanced quantitative analysis measures for EEG and combining mobile brain imaging with behavioral and biomechanical measures, it is possible to document the timing, magnitude, and quality of brain processes related to balance control. Other non-invasive brain imaging techniques are based on relatively slow blood oxygenation responses (functional near-infrared spectroscopy, fNIRS; functional magnetic resonance imaging, fMRI). These modalities can identify brain areas related to gait or gait-related motor imagery [18], but they have a time resolution of seconds at best. This temporal resolution cannot identify the changes in brain activity related to transient sensory signals or rapid motor responses to counteract an impending loss of balance. For example, a recent fMRI study found increased connectivity in the premotor, primary motor, and somatosensory cortices after six weeks of slackline training when at rest [19]. Imagine using EEG during slackline walking. EEG could

Figure 1



Schematic of human balance control: 1) sense body state and recognize loss of balance, 2) determine motor commands for the proper musculoskeletal response, and 3) execute the musculoskeletal response. The inverse internal model transforms sensory feedback and the desired movement into appropriate motor commands for the muscles. The forward internal model estimates the expected sensory feedback given the efference copy of the motor commands. Spinal and subcortical reflexes also activate muscles in losses of balance but are adjusted by cortical pathways based on environmental and task context, and included in the cognitive internal models.

identify changes in electrocortical activity occurring during loss of balance while behavioral and biomechanical measures could identify changes in body dynamics.

Combining EEG with behavioral and biomechanical measures to understand balance

In this perspective article, we make a case that combining EEG mobile brain imaging with behavioral and biomechanical measures provides the means for better understanding of deficits in balance control. The brain areas responsible for receiving and processing sensory information show clear electrocortical fluctuations related to sensory stimuli. The brain areas involved in sensorimotor transformations and motor planning show clear electrocortical fluctuations after sensory processing to determine appropriate motor responses. Lastly, behavioral and biomechanical measures provide indications of the timing, magnitude, and quality of the musculoskeletal responses. We also highlight new recommendations for inclusive EEG research and available open resources to help produce more generalizable EEG findings applicable to more of the overall population.

Recent advances in EEG technologies

EEG hardware has progressed significantly over the past 20 years, enabling EEG to be more readily used in mobile applications. Electrodes are smaller and lighter as new materials and form factors have been developed [20]. Wireless EEG systems have become abundant [21]. There are new hardware designs like dual-electrode setups with two physically coupled but electrically isolated EEG electrodes that can simultaneously record isolated motion artifact signals and traditional scalp EEG signals [22]. These dual-electrode setups can improve the removal of motion artifacts during highly dynamic tasks like table tennis [23].

EEG software has benefited from improved computational power, new algorithms, and testbeds for evaluating new artifact removal techniques. Blind source separation (BSS), adaptive filtering, machine learning, or a hybrid of techniques are able to remove muscle, eye, heart, and motion artifacts both in post hoc processing and even in real-time data collection [24]. There are new and more efficient methods and software to digitize accurately the electrode locations necessary for performing EEG source localization [25]. EEG phantoms, which are physical head and neck models with dipole generators embedded within a conductive medium that can project “ground truth” signals, provide a testbed for evaluating EEG signal processing techniques [26]. EEG phantoms combined with programmable moveable platforms can recreate the large motion artifacts often observed during gait, providing a valuable tool for developing and evaluating artifact removal techniques [27].

Examples of insights and uses

EEG combined with motion capture and EMG can provide insight into the timing and magnitude of the cortical resources involved in balance control. This knowledge could be used to help separately diagnose balance problems related to sensory perception, cognitive processes, or musculoskeletal deficits. For example, perturbations to standing and walking balance evoke changes in electrocortical event-related potentials (ERPs) [28,29] and EMG complexity [30] that scale with the magnitude of the perturbation and the balance capabilities of the individual measured with behavioral and biomechanical measures.

Using high-density EEG with source separation and localization can provide greater insight into the timing of processes in various brain areas. As balance depends on multiple sensory modalities and sensory integration, do electrocortical fluctuations related to loss of balance occur first in visual, proprioceptive, or sensorimotor integration brain areas? This information could help identify which brain areas to target with brain stimulation interventions such as transcranial direct current stimulation or transcranial magnetic stimulation in individuals with balance deficits [31,32]. Studies that rely on ongoing perturbations, such as gait stabilization devices [33] and walking on uneven terrain [34], permit insight into the timing and magnitude of electrocortical activity changes related to reduced active balance control [33] and increased balance demands [34], respectively. An advantage of using high-density EEG with source separation is the potential for functional connectivity measures to determine causal relationships between brain areas [35]. This would reveal information about the timing required for sensory modality reception, sensory integration, and motor command generation. When combining EEG source signals with EMG, there is also the possibility to provide causal inferences about which brain areas have the most direct impact on muscle activation profiles [36].

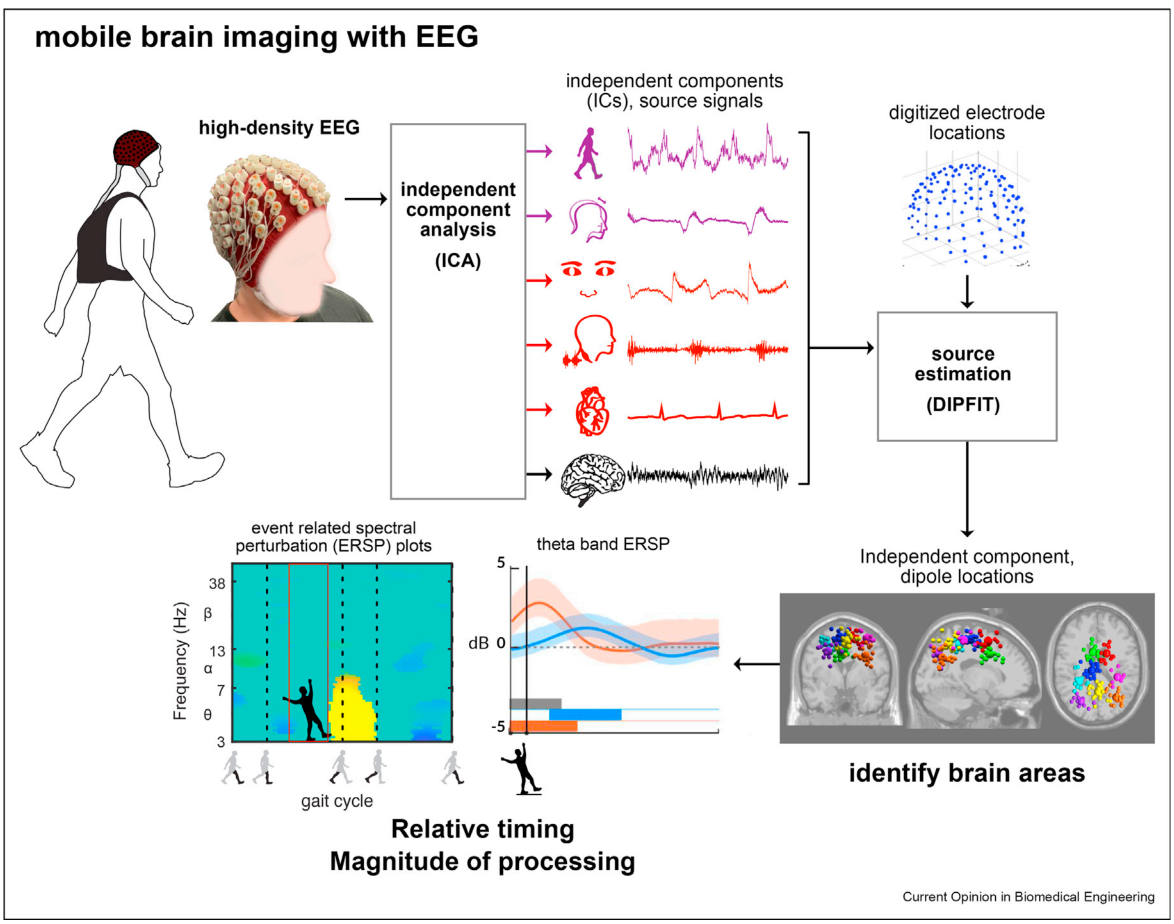
With patient populations, EEG mobile brain imaging, kinematic, and EMG measures would provide insight into which control processes demonstrate the greatest discrepancy with healthy, neurologically intact individuals. For example, an individual that is experiencing a decline in sensory acuity, mobile brain imaging with EEG should provide an indication of longer times involved before the brain recognizes the loss of balance. For an individual with reduced cognitive capabilities, there should be changes in cortical resources involved in the loss of balance response or a longer delay in motor centers involved in responding. With elderly individuals, the inclusion of EMG and biomechanical body data provides important context on the timing between cortical processes and the actual onset of the body response [37]. An individual with poor muscle strength and power may have typical electrocortical changes related to sensing the loss of balance and determining the proper response but is unable to achieve a restoration of balance because of biomechanical limitations.

Growing evidence that EEG can reveal components of balance control

More studies are demonstrating that EEG can identify brain areas and electrocortical changes related to a natural loss of balance, which occurs when there is no external perturbation. An improper decision of planned foot placement or poor execution of a proper foot placement can lead to a loss of balance without an external perturbation. For example, when standing on stable and unstable surfaces, event-related potentials (ERPs) and EEG channel-based connectivity analyses have revealed networks including frontal, central, and parietal cortices directly related to loss of balance [38]. A change in base of support from regular to a more balance challenging tandem (heel-to-toe) stance resulted in increased theta spectral power in the supplementary motor area [39]. High-density EEG, ICA, and source localization (schematically depicted in Figure 2) have identified substantial changes in theta, alpha, and beta spectral power within the anterior cingulate, anterior parietal, superior dorsolateral-prefrontal, medial sensorimotor, left sensorimotor, and right sensorimotor cortices during beam walking [40]. Importantly, the initial changes in electrocortical spectral power in multiple brain areas occurred more than a second before the step off the beam reached ground contact. This indicates that there is considerable time between sensing loss of balance and the actual motor response, which EEG was able to reveal.

Studies using external perturbations such as surface translations that often trigger a loss of balance tend to generate strong EEG responses. External balance

Figure 2



Schematic overview of an example of mobile brain imaging with EEG using high-density EEG, independent component analysis (ICA), and source estimation (DIPFIT). ICA separates high-density EEG into independent components (ICs) or source signals. DIPFIT, a source estimation method, uses the ICA and digitized electrode locations to model ICs as electric dipoles within the cortex (shown as colored dots in the brain scan image). Event-related spectral perturbation (ERSP) plots for a brain area show spectral fluctuations (changes in spectral power relative to a baseline frequency spectrum) with respect to the gait cycle and a loss of balance between the red solid lines. Theta band ERSP plots for a brain area could show significant differences in timing (horizontal bars) and magnitudes between conditions.

perturbations provide precise experimental control for targeting components of loss of balance and often evoke event-related potentials referred to as N1 responses (frontocentral negativities time-locked to the perturbation), which can help identify changes to the balance processes [41]. For example, translational surface perturbations during standing that generated compensatory steps resulted in large N1 responses, demonstrating a relationship between N1 and a subsequent compensatory balance response [42]. Increasing the size of backward translational surface perturbations resulted in larger N1 amplitudes and shorter latencies, indicating greater cortical engagement for more demanding balance conditions, whether it was due to a more difficult task or worse balance ability [28]. More recently, surface perturbations revealed a negative correlation between perturbation-evoked beta oscillatory activity with balance ability in young [29] and older adults [43].

Different features of balance perturbations could further identify brain areas and electrocortical changes specific to balance control. Virtual reality (VR) can be used to create predictable and unpredictable balance perturbations during standing without using a physical stimulus. During unpredictable perturbations where there is less time to process, frontocentral theta power (often associated with the anterior cingulate) increased, which could reflect the process of comparing sensory information with an internal model [44]. Another study compared physical and visual balance perturbations using waist-pulls and rotations of the subject's view captured with a webcam and then displayed in a VR headset, respectively [45]. They found a strong contrast in primary brain regions responding to visual perturbations (occipital and posterior parietal cortices) compared to physical perturbations (sensorimotor, supplementary motor, anterior cingulate, and anterior parietal cortices). Further, theta onset latencies among centro-frontal motor areas differed between perturbation types, demonstrating the potential to identify timing differences of more visual or proprioceptive sensory processing of balance control.

Perturbations during tasks that do not necessarily evoke corrective balance responses can also provide insight about balance control. For example, contrasting N1 responses involved with standing balance control of planned stepping and planned nonstepping responses revealed the potential role of N1 in the execution of compensatory steps in balance recovery [42]. Physical resistive perturbations during recumbent stepping, a locomotor task that does not involve balance, generated spatial motor errors and theta band synchronization in the anterior cingulate cortex and left and right supplementary motor areas [46]. The lack of the left or right sensorimotor cortices during perturbed recumbent stepping differs from beam walking [40] and perturbed beam walking [45], which had sensorimotor clusters. This implies that the sensorimotor cortices may be more involved for balance control in locomotor tasks than the anterior cingulate cortex and supplementary motor areas.

Next steps: emerging EEG technologies

Developing and validating new EEG technologies and analyses will help attain a more detailed understanding of balance control. EEG sensors and systems are getting smaller and more energy efficient every year. Some examples of the current state-of-the-art commercially available wireless systems are reviewed by Ref. [21]. A multitude of flexible electronic electrodes are in development [47]. Achieving higher spatial resolution with electrophysiological source imaging seems to be attainable when appropriate prior knowledge is used with sparse models or Bayesian methods [48]. There are also emerging EEG analyses available such as functional and effective connectivity [49].

Table 1

Selection of recommendations to improve inclusion in EEG research.

Category	Recommendation
Research team	• Increase racial diversity of research team [56,57] • Have the entire research team complete diversity (e.g. cultural competence, antiracist, inclusive practices) training [54,57]
Participant recruitment and retention	• Establish a presence in diverse communities and form community connections (e.g. go to the community to recruit, share research findings with the community) [57] • Have an open discussion about what is involved in EEG research (e.g. Will their hair get wet or have gel placed in it? How many electrodes? Can they use hair products? What about hair styles? etc.) [57] • Be flexible in scheduling and offer adequate compensation in consideration of hair care routines, wash cycles, or hair preparation/restoration costs [56,57]
Reporting	• Collect and report racial/ethnic data in publications and be transparent about exclusions [54,56,57]
Equipment and resources	• Develop, adopt, or leverage consumer power for more inclusive hardware (e.g. EEG electrodes that work in diverse hair types) [55–58] • Develop and use shared resources (networks, databases, guidelines, etc.) [57]

As new technologies emerge, their performance needs to be tested systematically, in mobile conditions, and with the desired EEG analyses [50]. Artifact subspace rejection (ASR) is a commonly used method for cleaning EEG [51] but was only recently systematically evaluated to identify guidelines for setting its numerous parameters [52]. A recent study surprisingly demonstrated that a passive EEG system could record comparable P3 event-related potential waveforms as an active EEG system during walking [53]. The authors noted, however, that their results using P3 analyses may not generalize to other EEG analyses where non-time-locked noise cannot be decreased through averaging [53].

Next steps: attention to inclusion

Mobile brain imaging also needs to better address the systemic racial bias in EEG research that indicates that inequities and disparities persist [54–58] so that EEG findings related to human balance control are more inclusive and generalizable. Racial and ethnic communities with phenotypic characteristics such as hair type (curly, tightly coiled, textured, dense, etc.) that tend to have less reliable EEG data [55,58] are often excluded, whether that occurs at the recruitment, subject preparation, or data analysis stage. As such, evidence exists indicating a disproportionate exclusion of Black participants in EEG studies [55,56]. Some groups are working

Table 2

Selection of open resources for mobile brain imaging with EEG.

Open source resource	Description (website link)	Paper
EEGLAB	Software and programming environment for EEG processing, visualization, and analyses (https://eeglab.org/)	Delorme and Makeig 2004 [61]
MoBILAB	MATLAB toolbox for analyzing and visualizing mobile brain/body data (https://github.com/sccn/mobilab/wiki)	Ojeda et al., 2014 [64]
Open EEGLAB Portal Interface	Run EEGLAB scripts on a freely available high-performance computing resource via the Neuroscience Gateway Portal (https://github.com/sccn/nsgportal/wiki)	Martínez-Cancino et al., 2020 [62]
NeuroPycon	toolkit for analyzing multi-modal brain data focused on connectivity and graph analyses (https://github.com/neuropycon)	Meunier et al., 2020 [65]
PREP pipeline	early-stage EEG preprocessing pipeline (i.e. reject bad channels, robust average referencing) (http://vislab.github.io/EEG-Clean-Tools/)	Bigdely-Shamlo et al., 2015 [66]
BeMoBIL pipeline	MATLAB toolbox focused on importing, preprocessing, and visualizing mobile brain/body imaging EEG data https://github.com/BeMoBIL/bemobil-pipeline/wiki	Klug et al., 2022 [63]
ICLabel	collaborative project for identifying independent components of EEG (https://labeling.ucsd.edu/tutorial/overview)	Pion-Tonachini et al., 2019 [69]
ICMobi	collaborative project for identifying independent components specific to mobile brain imaging with EEG (https://www.icmobi.org/)	none
HED tags	Hierarchical Event Descriptors (HED) tags to annotate experiment events to know what happened at that moment in the time series data (https://www.hedtags.org/)	Bigdely-Shamlo et al., 2016a [67]
BigEEG	workflow for large-scale analysis (e.g. meta-study) of EEG (http://www.bigeeg.org/)	Bigdely-Shamlo et al., 2016b [68]
Lab Streaming Layer	ecosystem for streaming, synchronizing, and recording data from multiple systems (EEG, motion capture, forceplates, eye trackers, etc.) (https://labstreaminglayer.org/)	none
Open Source Phantom	Instructions for building an EEG phantom (https://osf.io/qrka2/)	Yu and Hairston 2019 [26]
EEG-BIDS	Extension of Brain Imaging Data Structure (BIDS) for EEG data (https://bids.neuroimaging.io/)	Pernet et al., 2019 [70]

on designing EEG electrodes specifically for coarse and curly hair [58] while other EEG groups have proposed recommendations to increase inclusion and diversity of participants [54,56,57] (Table 1).

Next steps: transparency and sharing of resources

As science overall and the EEG community works towards greater transparency, preregistration, expectations for detailed reporting of processing methods, and investing in open resources could help. Preregistration is time-stamped documentation of research protocols and analysis plans prior to starting a study [59]. Detailed reporting of EEG processing methods is necessary, as preprocessing methods can produce significant differences in low-frequency spectral features [60]. Several open resources are already available for EEG analyses, automatic preprocessing, standardizing event tagging, and classifying source signals (Table 2) [26,61–70]. Incorporating these practices will help promote transparency and reduce confirmation and hindsight biases in research to understand the components of balance control.

Conclusion

By combining EEG mobile brain imaging with kinematic and EMG measures, we can develop a better understanding of balance control processes, including the timing, magnitude, and quality of both brain and musculoskeletal dynamics. Recent studies have demonstrated that EEG has the potential to identify brain areas, relative timing of electrocortical activity, functional connectivity between brain areas and muscles, and processing delays related to balance control. This information will be highly valuable in better prescribing interventions and medications for individuals with reduced balance capabilities. We look forward to the decade ahead as EEG mobile brain and body imaging becomes more widespread.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the National Institutes of Health [R01 AG054621; U01 AG061389; R01 NS104772] and National Science Foundation [1942712; 1835317] awards.

References

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest
** of outstanding interest

1. Hadders-Algra M: **Challenges and limitations in early intervention**. *Dev Med Child Neurol* 2011, **53**(Suppl 4):52–55.

2. Rantakokko M, Mänty M, Rantanen T: **Mobility decline in old age**. *Exerc Sport Sci Rev* 2013, **41**:19–25.

3. Yang F, Lees J, Simpkins C, Butler A: **Interventions for preventing falls in people post-stroke: a meta-analysis of randomized controlled trials**. *Gait Posture* 2021, **84**: 377–388.

4. Vu K, Payne MWC, Hunter SW, Viana R: **Risk factors for falls in individuals with lower extremity amputations during the pre-prosthetic phase: a retrospective cohort study**. *Pharm Manag PM R* 2019, **11**:828–833.

5. Montero-Odasso M, van der Velde N, Martin FC, Petrovic M, Tan MP, Ryg J, Aguilar-Navarro S, Alexander NB, Becker C, Blain H, *et al.*: **World guidelines for falls prevention and management for older adults: a global initiative**. *Age Ageing* 2022:51.

6. Hamed A, Bohm S, Mersmann F, Arampatzis A: **Follow-up efficacy of physical exercise interventions on fall incidence and fall risk in healthy older adults: a systematic review and meta-analysis**. *Sports Med Open* 2018, **4**:56.

7. Kümmel J, Kramer A, Giboin L-S, Gruber M: **Specificity of balance training in healthy individuals: a systematic review and meta-analysis**. *Sports Med* 2016, **46**:1261–1271.

8. * McCrum C, Bhatt TS, Gerards MHG, Karamanidis K, Rogers MW, Lord SR, Okubo Y: **Perturbation-based balance training: principles, mechanisms and implementation in clinical practice**. *Front Sports Act Living* 2022, **4**, 1015394.
This is a review of current evidence of the mechanisms and efficacy of perturbation-based balance training for fall prevention.

9. Peterka RJ: **Chapter 2 - sensory integration for human balance control**. In *Handbook of clinical neurology*. Edited by Day BL, Lord SR, Elsevier; 2018:27–42.

10. Wolpert DM, Flanagan JR: **Motor prediction**. *Curr Biol* 2001, **11**: R729–R732.

11. van der Kooij H, Jacobs R, Koopman B, Grootenboer H: **A multisensory integration model of human stance control**. *Biol Cybern* 1999, **80**:299–308.

12. Hasson CJ, Goodman SE: **Learning to shape virtual patient locomotor patterns: internal representations adapt to exploit interactive dynamics**. *J Neurophysiol* 2019, **121**:321–335.

13. Lhomond O, Juan B, Fornerone T, Cossin M, Paleressompoulle D, Prince F, Mouchnino L: **Learned overweight internal model can Be activated to maintain equilibrium when tactile cues are uncertain: evidence from cortical and behavioral approaches**. *Front Hum Neurosci* 2021, **15**, 635611.

14. Seymour RA, Alexander N, Mellor S, O'Neill GC, Tierney TM, Barnes GR, Maguire EA: **Using OPMs to measure neural activity in standing, mobile participants**. *Neuroimage* 2021, **244**, 118604.

15. * Purohit R, Bhatt T: **Mobile brain imaging to examine task-related cortical correlates of reactive balance: a systematic review**. *Brain Sci* 2022:12.
This systematic review paper identified 31 EEG studies between 1980 and 2021 that examined cortical activity and behavioral and biomechanical measures of reactive balance perturbations. While there was evidence of cortical involvement during reactive balance responses, there were limited associations between cortical activity and behavioral measures.

16. Khajuria A, Sharma R, Joshi D: **EEG dynamics of locomotion and balancing: solution to neuro-rehabilitation**. *Clin EEG Neurosci* 2022. https://doi.org/10.1177/15500594221123690.

17. Song S, Nordin AD: **Mobile electroencephalography for studying neural control of human locomotion**. *Front Hum Neurosci* 2021:15.

18. Allali G, Blumen HM, Devanne H, Pirondini E, Delval A, Van De Ville D: **Brain imaging of locomotion in neurological conditions**. *Neurophysiol Clin* 2018, **48**:337–359.

19. Giboin L-S, Loewe K, Hassa T, Kramer A, Dettmers C, Spiteri S, Gruber M, Schoenfeld MA: **Cortical, subcortical and spinal neural correlates of slackline training-induced**

balance performance improvements. *Neuroimage* 2019, **202**, 116061.

20. Yuan H, Li Y, Yang J, Li H, Yang Q, Guo C, Zhu S, Shu X: **State of the art of non-invasive electrode materials for brain-computer interface**. *Micromachines (Basel)* 2021, **12**.

21. ** Niso G, Romero E, Moreau JT, Araujo A, Krol LR: **Wireless EEG: an survey of systems and studies**. *Neuroimage* 2022. https://doi.org/10.1016/j.neuroimage.2022.119774.
This paper presents a comprehensive comparison of 44 wireless EEG systems and compiled information on the EEG systems used in 110 high-impact publications.

22. Nordin AD, Hairston WD, Ferris DP: **Dual-electrode motion artifact cancellation for mobile electroencephalography**. *J Neural Eng* 2018, **15**, 056024.

23. Studnicki A, Downey RJ, Ferris DP: **Characterizing and removing artifacts using dual-layer EEG during table tennis**. *Sensors* 2022, **22**:5867.

24. ** Gorjan D, Gramann K, De Pauw K, Marusic U: **Removal of movement-induced EEG artifacts: current state of the art and guidelines**. *J Neural Eng* 2022:19.
This recent review focuses on EEG motion artifact removal methods. It discusses advantages and disadvantages for current methods, as well as provides recommendations for current methods.

25. Shirazi SY, Huang HJ: **More reliable EEG electrode digitizing methods can reduce source estimation uncertainty, but current methods already accurately identify brodmann areas**. *Front Neurosci* 2019, **13**:1159.

26. Yu A, David Hairston W: *Open EEG phantom*. 2019. https://doi.org/10.17605/OSF.IO/QRKA2.

27. Richer N, Downey RJ, Hairston WD, Ferris DP, Nordin AD: **Motion and muscle artifact removal validation using an electrical head phantom, robotic motion platform, and dual layer mobile EEG**. *IEEE Trans Neural Syst Rehabil Eng* 2020. https://doi.org/10.1109/TNSRE.2020.3000971.

28. Payne AM, Ting LH: **Worse balance is associated with larger perturbation-evoked cortical responses in healthy young adults**. *Gait Posture* 2020. https://doi.org/10.1016/j.gaitpost.2020.06.018.

29. Ghosn NJ, Palmer JA, Borich MR, Ting LH, Payne AM: **Cortical beta oscillatory activity evoked during reactive balance recovery scales with perturbation difficulty and individual balance ability**. *Brain Sci* 2020:10.

30. Allen JL, Carey HD, Ting LH, Sawers A: **Generalization of motor module recruitment across standing reactive balance and walking is associated with beam walking performance in young adults**. *Gait Posture* 2020, **82**:242–247.

31. Young DR, Parikh PJ, Layne CS: **The posterior parietal cortex is involved in gait adaptation: a bilateral transcranial direct current stimulation study**. *Front Hum Neurosci* 2020, **14**, 581026.

32. Young DR, Parikh PJ, Layne CS: **Non-invasive brain stimulation of the posterior parietal cortex alters postural adaptation**. *Front Hum Neurosci* 2020, **14**:248.

33. Bruijn SM, Van Dieen JH, Daffertshofer A: **Beta activity in the premotor cortex is increased during stabilized as compared to normal walking**. *Front Hum Neurosci* 2015, **9**: 593.

34. Jacobsen NSJ, Blum S, Scanlon JEM, Witt K, Debener S: **Mobile electroencephalography captures differences of walking over even and uneven terrain but not of single and dual-task gait**. *Front Sports Act Living* 2022, **4**, 945341.

35. * Chiarion G, Sparacino L, Antonacci Y, Faes L, Mesin L: **Connectivity analysis in EEG data: a tutorial review of the state of the art and emerging trends**. *Bioengineering (Basel)* 2023:10.
This review paper comprehensively covers technical aspects of data-driven functional connectivity analyses of EEG.

36. Peterson SM, Ferris DP: **Group-level cortical and muscular connectivity during perturbations to walking and standing balance**. *Neuroimage* 2019, **198**:93–103.

37. Rubega M, Di Marco R, Zampini M, Formaggio E, Menegatti E, Bonato P, Masiero S, Del Felice A: **Muscular and cortical activation during dynamic and static balance in the elderly: a scoping review**. *Aging Brain* 2021, **1**, 100013.

38. Mierau A, Pester B, Hulsdunker T, Schiecke K, Struder HK, Witte H: **Cortical correlates of human balance control**. *Brain Topogr* 2017. https://doi.org/10.1007/s10548-017-0567-x.

39. Malcolm BR, Foxe JJ, Joshi S, Verghese J, Mahoney JR, Molholm S, De Sanctis P: **Aging-related changes in cortical mechanisms supporting postural control during base of support and optic flow manipulations**. *Eur J Neurosci* 2020. https://doi.org/10.1111/ejn.15004.

40. Sipp AR, Gwin JT, Makeig S, Ferris DP: **Loss of balance during balance beam walking elicits a multifocal theta band electrocortical response**. *J Neurophysiol* 2013, **110**:2050–2060.

41. Payne AM, Ting LH, Hajcak G: **Do sensorimotor perturbations to standing balance elicit an error-related negativity?** *Psychophysiology* 2019, **56**, e13359.

42. * Payne AM, Ting LH: **Balance perturbation-evoked cortical N1 responses are larger when stepping and not influenced by motor planning**. *J Neurophysiol* 2020, **124**:1875–1884.
This EEG and translational surface balance perturbation study provided the first evidence that subsequent behavior was related to cortical N1

43. ** Palmer JA, Payne AM, Ting LH, Borich MR: **Cortical engagement metrics during reactive balance are associated with distinct aspects of balance behavior in older adults**. *Front Aging Neurosci* 2021, **13**, 684743.
This study combined EEG with behavioral balance assessments (miniBEST, Timed-Up-and-Go, and step threshold) during a support-surface perturbation protocol to investigate cortical processes and balance ability in older adults. More perturbation-evoked motor cortical beta power was evident in older adults with worse balance ability based on the behavioral balance measures.

44. Slobounov SM, Teel E, Newell KM: **Modulation of cortical activity in response to visually induced postural perturbation: combined VR and EEG study**. *Neurosci Lett* 2013, **547**:6–9.

45. * Peterson SM, Ferris DP: **Differentiation in theta and beta electrocortical activity between visual and physical perturbations to walking and standing balance**. *eNeuro* 2018, **5**.
This study used EEG and source localization with visual and physical perturbations during standing and walking to investigate electrocortical responses to balance perturbations. Visual and physical perturbation types involved substantively different brain areas but had similar electrocortical fluctuations. Perturbation types also produced distinctive theta band onset latencies among centro-frontal motor areas.

46. Shirazi SY, Huang HJ: **Differential theta-band signatures of the anterior cingulate and motor cortices during seated locomotor perturbations**. *IEEE Trans Neural Syst Rehabil Eng* 2021, **29**:468–477.

47. Ates HC, Nguyen PQ, Gonzalez-Macia L, Morales-Narváez E, Güder F, Collins JJ, Dincer C: **End-to-end design of wearable sensors**. *Nat Rev Mater* 2022, **7**:887–907.

48. Sohrabpour A, He B: **Exploring the extent of source imaging: recent advances in noninvasive electromagnetic brain imaging**. *Curr Opin Biomed Eng* 2021, **18**, 100277.

49. Cao J, Zhao Y, Shan X, Wei H-L, Guo Y, Chen L, Erkoyuncu JA, Sarrigiannis PG: **Brain functional and effective connectivity based on electroencephalography recordings: a review**. *Hum Brain Mapp* 2022, **43**:860–879.

50. Oliveira AS, Schlink BR, Hairston WD, Konig P, Ferris DP: **Proposing metrics for benchmarking novel EEG technologies towards real-world measurements**. *Front Hum Neurosci* 2016, **10**:188.

51. Kothe CAE, Jung T-P: **Artifact removal techniques with signal reconstruction**. *Patent* 2014.

52. Chang C-Y, Hsu S-H, Pion-Tonachini L, Jung T-P: **Evaluation of artifact subspace reconstruction for automatic artifact components removal in multi-channel EEG recordings**. *IEEE Trans Biomed Eng* 2020, **67**:1114–1121.

53. Scanlon JEM, Jacobsen NSJ, Maack MC, Debener S: **Does the electrode amplification style matter? A comparison of active and passive EEG system configurations during standing and walking**. *Eur J Neurosci* 2020. https://doi.org/10.1111/ejn.15037.

54. Webb EK, Etter JA, Kwasa JA: **Addressing racial and phenotypic bias in human neuroscience methods**. *Nat Neurosci* 2022, **25**:410–414.

55. ** Choy T, Baker E, Stavropoulos K: **Systemic racism in EEG research: considerations and potential solutions**. *Affective Science* 2021. https://doi.org/10.1007/s42761-021-00050-0.
This position paper was among the first to focus on the inadvertent exclusion of communities, primarily the Black community, from EEG research due to hair type and hairstyles.

56. Bradford DE, DeFalco A, Perkins ER, Carbajal I, Kwasa J, Goodman FR, Jackson F, Richardson LNS, Woodley N, Neuberger L, *et al.*: **Whose signals are being amplified? Toward a more equitable clinical psychophysiology**. *Clin Psychol Sci* 2022. https://doi.org/10.1177/21677026221112117.

57. Penner F, Wall KM, Guan KW, Huang HJ, Richardson L, Dunbar AS, Groh AM, Rutherford HJV: **Racial disparities in EEG research and their implications for our understanding of the maternal brain**. *Cognit Affect Behav Neurosci* 2022. https://doi.org/10.3758/s13415-022-01040-w.

58. Etienne A, Laroia T, Weigle H, Afelin A, Kelly SK, Krishnan A, Grover P: **Novel electrodes for reliable EEG recordings on coarse and curly hair**. In *2020 42nd annual international conference of the IEEE engineering in medicine biology society (EMBC)*; 2020:6151–6154.

59. Paul M, Govaart GH, Schettino A: **Making ERP research more transparent: guidelines for preregistration**. *Int J Psychophysiol* 2021, **164**:52–63.

60. * Robbins KA, Touryan J, Mullen T, Kothe C, Bigdely-Shamlo N: **How sensitive are EEG results to preprocessing methods: a benchmarking study**. *IEEE Trans Neural Syst Rehabil Eng* 2020, **28**:1081–1090.
This study systematically compared how changes in EEG preprocessing methods could alter EEG measures and results across 17 studies. Their analyses suggest that significant differences can emerge in EEG measures with small changes in artifact removal methods.

61. Delorme A, Makeig S: **EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis**. *J Neurosci Methods* 2004, **134**:9–21.

62. Martínez-Cancino R, Delorme A, Truong D, Artoni F, Kreutz-Delgado K, Sivagnanam S, Yoshimoto K, Majumdar A, Makeig S: **The open EEGLAB portal interface:high-performance computing with EEGLAB**. *Neuroimage* 2020. https://doi.org/10.1016/j.neuroimage.2020.116778.

63. ** Klug M, Jeung S, Wunderlich A, Gehrke L, Protzak J, Djebbara Z, Argubi-Wollesen A, Wollesen B, Gramann K: **The BeMoBIL Pipeline for automated analyses of multimodal mobile brain and body imaging data**. *bioRxiv* 2022. https://doi.org/10.1101/2022.09.29.510051.
This paper presents an open-source pipeline focused on processing multimodal data for mobile brain/body imaging studies. One of the goals of the pipeline is to facilitate the use of EEG in mobile tasks. Further, by making the pipeline an open-source project, the EEG community can help update and improve the pipeline as mobile brain imaging studies evolve.

64. Ojeda A, Bigdely-Shamlo N, Makeig S: **MoBILAB: an open source toolbox for analysis and visualization of mobile brain/body imaging data**. *Front Hum Neurosci* 2014, **8**:121.

65. Meunier D, Pascarella A, Altukhov D, Jas M, Combrisson E, Lajnef T, Bertrand-Dubois D, Hadid V, Alamian G, Alves J, *et al.*: **NeuroPycon: an open-source python toolbox for fast multimodal and reproducible brain connectivity pipelines**. *Neuroimage* 2020, **219**, 117020.

66. Bigdely-Shamlo N, Mullen T, Kothe C, Su KM, Robbins KA: **The PREP pipeline: standardized preprocessing for large-scale EEG analysis**. *Front Neuroinf* 2015, **9**:16.

67. Bigdely-Shamlo N, Cockfield J, Makeig S, Rognon T, La Valle C, Miyakoshi M, Robbins KA: **Hierarchical event descriptors (HED): semi-structured tagging for real-world events in large-scale EEG**. *Front Neuroinf* 2016, **10**:42.

68. Bigdely-Shamlo N, Makeig S, Robbins KA: **Preparing laboratory and real-world EEG data for large-scale analysis: a containerized approach**. *Front Neuroinf* 2016, **10**:7.

69. Pion-Tonachini L, Kreutz-Delgado K, Makeig S: **ICLabel: An automated electroencephalographic independent component classifier, dataset, and website**. *Neuroimage* 2019, **198**:181–197.

70. Pernet CR, Appelhoff S, Gorgolewski KJ, Flandin G, Phillips C, Delorme A, Oostenveld R: **EEG-BIDS, an extension to the brain imaging data structure for electroencephalography**. *Sci Data* 2019, **6**:103.