3D-printable stimulation electrodes to improve precision, reproducibility, and reliability of transcranial electric current stimulation

Authors and Affiliations

Silke Kerstens[1], Luuk van Boekholdt[1], Jean-Jacques Orban de Xivry[2], Myles Mc Laughlin[1]

1. Department of Neurosciences, The Leuven Brain Institute, Faculty of Medicine, KU Leuven, Belgium
2. Movement Control & Neuroplasticity Research Group, The Leuven Brain Institute, Department of Movement Sciences, KU Leuven, Belgium

Corresponding Author

Silke Kerstens
silke.kerstens@kuleuven.be

Keywords

Transcranial direct current stimulation (tDCS)
Transcranial alternating current stimulation (tACS)
Transcranial electric stimulation (tES)
Conventional simulation electrodes
Reproducibility
Reliability
3D-printing

Highlights

- New electrodes were designed to improve reliability of noninvasive transcranial electric stimulation (tES)
- We provided 3D-printable stereolithography (STL) files for electrodes ranging in size in radii from 12–30mm
- By sharing these files we aimed to provide the tES field tools to address challenges related to reproducibility and reliability

Structured abstract

Objective

Transcranial electric stimulation (tES) refers to noninvasive neuromodulation techniques that apply a low-amplitude electric current through scalp electrodes to modulate brain activity. Conventional scalp electrodes are made of conductive rubber and are embedded in saline-soaked sponges, held in place using non-conductive rubber straps. Precisely positioning the electrodes at the desired location is challenging, and maintaining their position is equally difficult. In addition, as sponges are prone to drying out during prolonged use, they can compromise the electrode's conductivity and therefore cause fluctuations in connectivity.

Methods

To tackle these limitations of conventional tES electrodes, we designed new 3D-printable gel-filled tES electrodes.

Results

We developed electrodes in various sizes ranging in radius from 12mm to 30mm to allow a wide variety of options regarding stimulation parameters and electrode montages. By integrating the electrodes into a 10-20-cap, they can be positioned precisely according to the 10-20 coordinate system and the cap holds them in place, even during significant movements.

Conclusions

Sharing our 3D-printable electrode designs as open-source can improve precision, reproducibility, and reliability of tES.

Significance

In this way, we aim to tackle the reliability and reproducibility issues in the tES field as they provide an accessible and reliable tool to apply tES in humans.

Graphical abstract

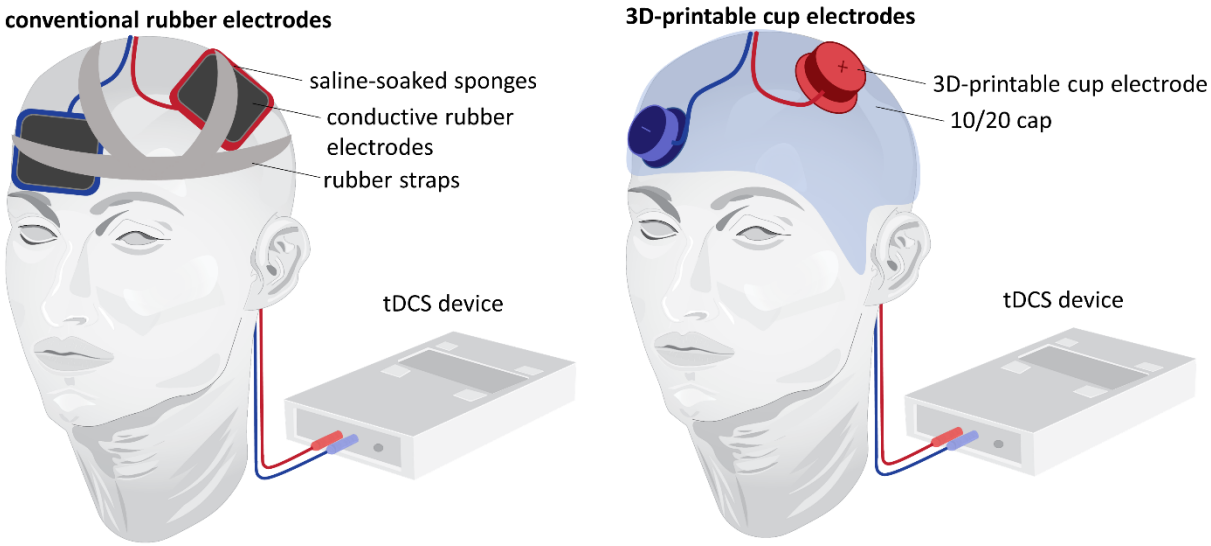

Figure Conventional rubber electrodes versus new 3D-printable cup electrodes.

Objective

Transcranial electric stimulation (tES) is a widely used noninvasive neuromodulation technique to modulate brain activity in specific brain regions. By applying low-amplitude electric currents through stimulation electrodes strategically placed on the scalp, tES aims to modulate brain activity in these brain regions to achieve a specific behavioral outcome. Several types of tES can be distinguished based on the type of electric stimulation used, with direct current stimulation (tDCS) and transcranial alternating current stimulation (tACS) being the most commonly used. During tDCS, a small direct current of typically 1–2mA is applied across stimulation electrodes placed on the scalp. The direct current implies that one of the electrodes is positively charged, referred to as the anodal electrode, while the other electrode is negatively charged, referred to as the cathodal electrode. In the context of tDCS, anodal stimulation involves applying a positive charge to the targeted brain region by placing the anodal, or positively charged electrode, over the area of interest. Whereas, in cathodal stimulation, the cathodal, or negative charged electrode, is positioned over the targeted brain region(Adair et al. 2020). For tACS, on the other hand, the direction of the applied current alternates with a set frequency, resulting in an alternating electric field.

For these types of noninvasive brain stimulation, the most widely used stimulation electrodes are conductive rubber patches(Adair et al. 2020; Adelhöfer et al. 2019; Antal, Nitsche, and Paulus 2006; Ciechanski et al. 2018; DaSilva et al. 2011; Heimrath et al. 2020; Huang et al. 2017; Kunzelmann et al. 2018; Lang et al. 2005; Liebrand et al. 2020; Pollok, Schmitz-Justen, and Krause 2021; Utz et al. 2010; Williams, Hoffman, and Clark 2013). These rubber patches are usually not applied directly to the scalp, as this may impose risks of skin burns due to variations in conductivity with the skin. To increase conductivity on the interphase between the electrodes and the scalp, they are, therefore, usually inserted in saline-soaked sponges before being placed on the scalp. In this way, the sponge evenly distributes the applied current over the surface area of the stimulation electrodes, resulting in a more uniform current distribution. After positioning the electrodes, they are secured to the scalp and kept in place with nonconductive rubber straps. These conventional stimulation electrodes come in different shapes and sizes, offering a variety of electrode montages and stimulation protocols.

However, these conventional rubber electrodes entail major disadvantages, including a lack of precision, reproducibility, and reliability. Due to the properties of the electrodes, it is a challenge to accurately position them on the intended location, even though the intended location on the scalp was precisely and accurately determined using advanced tools(Nitsche et al. 2000). In addition, the straps used to secure the electrodes are uncomfortable and often result in inadequate electrode fixation. In addition to the precision and reproducibility issues regarding the positioning of the electrodes, the saline-soaked sponges also incline the risk of unreliable stimulation. If the sponges are too wet, the saline may leak and potentially cause short circuits between the stimulation electrodes. This leads to current shunting on the skin's surface, thereby reducing the applied current. If too little saline is used, the sponges become too dry and fail to establish proper contact with the skin. This might also occur during prolonged stimulation protocols, as the sponges naturally dry out over time due to evaporation. To resolve this issue, saline is often replaced by a conductive gel that resists drying out. However, it is important to note that the gel can lead to increased movement and sliding of the electrodes over the scalp. Given the inconsistency in electrode placement and applied current during tES, this could be a major source of variability and a key factor in the reproducibility and reliability issues in observed stimulation effects (Héroux et al. 2017a; Minarik et al. 2016). To tackle these limitations, several attempts have been made to improve conventional designs and application methods of tES electrodes (Solomons and Shanmugasundaram 2020a). However, to achieve precise, reproducible, and reliable stimulation during tDCS and tACs, we aimed to design new 3D-printable gel-filled cup electrodes that address these limitations.

Approach

3D-printable cup electrode design

The 3D-printable cup electrodes (Figure 1) were designed to be integrated into a 10-20 cap based on the standardized 10-20 system used for identifying scalp locations in electroencephalography (EEG) to ensure precise and reproducible electrode placement. The cup electrode design comprised four components (Figure 1): in addition to the cups (B1), three other components were incorporated into the design to integrate the cups into the 10-20 cap and ensure safety. The upper part of the B1 cups was designed to pass through a hole in the 10-20 cap, and then secured in place with the middle part (M1). A third component, the lid (T1), was designed to cover the top of the cup to prevent the gel in the cups from leaking. Finally, a fourth component, a safety grid (G1), was added to the design to prevent connecting cables from reaching the skin directly to avoid safety hazards during stimulation. A ledge was added to the inside of the upper part of the B1 cups to support the G1 grid. In this way, the gel within the B1 cups remains uninterrupted by the grid, while it effectively prevents connecting cables from reaching the bottom part of the B1 cups that is directly in contact with the skin.

The electrodes were designed in various B1 cup sizes, with radii ranging from 12 to 30 mm offering a wide range of options regarding electrode size and montage. Figure 1 represents a visual illustration of the design for the cup electrodes including a detailed description and dimensions for a B1 cup size of 19 mm in radius as a primary example. All 3D-designs were provided as STL files and made available in Supplementary Materials for download. STEP files are made available upon reader's request.

Materials

The B1 cups were printed in a rubber-like thermoplastic polyurethane (TPU) with a HP Multi Jet Fusion (MJF, iMaterialise, Haasrode, Belgium) to establish an optimal and seamless fit with the scalp. TPU has a high mechanical resistance and is considered heat resistant. However, it is important to keep in mind it is sensitive to higher temperatures approaching its melting point of 120-150°C. The MJF technology uses an inkjet array to precisely apply fusing and detailing agents onto a bed of nylon powder, which are then fused into a solid layer using heat. Powder is added after each layer, repeating the process until the cup is fully developed. After printing, the cup was dyed with an extra smooth finish using a chemical solvent that seals the surface by removing all porosities, resulting in an extra smooth surface. TPU is strong, but flexible, and inert for most chemicals, making the cups durable. It is also non-conductive, and watertight, making it the ideal material for the B1 cups.

All other components M1, T1, and G1 were printed in polyamide 12 (PA12) using the Laser Sintering technology (LS, iMaterialise, Haasrode, Belgium). PA12 is a non-conductive and more rigid material, strong but only mildly flexible, that can resist high degrees of impact and pressure to ensure the structure and durability of the stimulation electrodes. Additional material properties of TPU and PA12 are provided in the Supplementary Materials.

Application procedure

As soon as the desired electrode sizes and configuration are determined based on the intended outcome or research question, the individual components can be 3D-printed in the intended materials. To then integrate the electrodes into a 10-20 cap, the upper part of the B1 cups must be passed through the cap on the intended location based the 10-20 system coordinates system and secured in place using the M1 component (Figure 2). To ensure precision and reproducibility of electrode placement, it is important to note that the cap must always match the subject's head size and be properly aligned with anatomical features. While we recommend integrating the cups into multiple caps of varying sizes, the electrodes are designed for easy swapping between caps when needed. Once the electrodes are integrated and secured in the cap, it is ready for use.

To begin with stimulation, first ensure the cap is positioned precisely on the subject's head (Figure 2). Then, carefully fill the B1 cups with conductive gel, ensuring full contact with the scalp and complete coverage of each cup's bottom surface. To ensure optimal scalp coverage, consider aligning the subject's hair backwards before placing the cap so the gel can easily be applied between the hairs. Once the bottom part of each cup is filled, add the G1 safety grid on the ledge on the inside of the B1 cups. Next, place the connecting cable on top of the grid with the cable leaving through the front opening of the electrode (Figure 1). Afterwards, fill the cups to the brim and seal with the T1 lid. The safety grid prevents the connecting cable from making direct contact with the skin and the lid prevents the gel from leaking. After plugging the connecting cable into the stimulation device, the electrodes are ready for use in applying noninvasive tES in humans.

Compliance for human use

The electrodes were developed and designed in accordance with safety standards for tES applications, ensuring safety for use in humans. After development, their use for tES in human subjects was approved by the UZ/KU Leuven Research Ethics Committee (S63709).

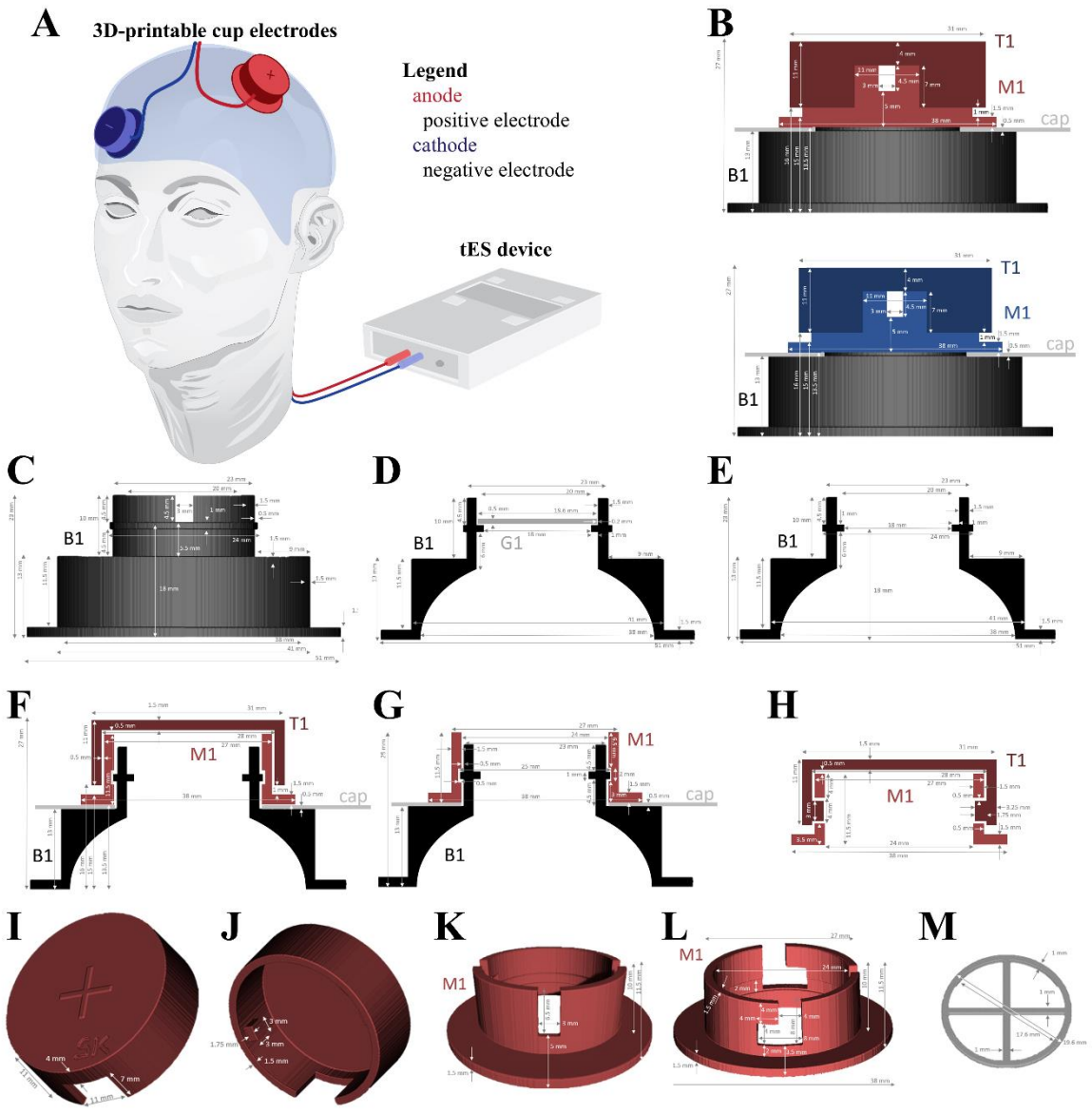

Figure 1 3D-printable cup electrode design.
(A) The stimulation electrodes were designed to increase precision and reproducibility during tES in humans. **(B)** The electrodes comprised four components: the cup (B1), a middle part (M1), a safety grid (G1), and a lid (T1). **(C-E)** The B1 cup was printed in a non-conductive and flexible TPU material, **(F-L)** while the other components were printed in a more rigid PA12 material. **(A)** The electrodes were designed to be integrated in a 10-20 cap by passing the upper part of the B1 cups through a hole in a 10-20 cap and securing them in place **(F-G)** using the M1 middle component. To achieve a secure fit, an indentation on the inner side of the M1 component aligns precisely with a ridge on the outer surface of the top part of the B1 cup. In addition to the ridge on the outside of the cup, a ledge was provided on the inside of the upper part of the B1 cup **(D-E)** for the G1 safety grid **(D-M)**, designed to prevent the connecting cable from reaching the skin. Finally, a lid **(I-J)** was designed to seal the cups **(F)** to prevent leaking. On the front of the electrodes, **(B)** an opening is added to the design to allow for the connecting cable to exit the electrodes. **(A)** For the purpose of tDCS, anodal (positive, red) and cathodal (negative, blue) stimulation electrodes were provided, indicated by both colors and with a + or – symbol on the lid respectively.

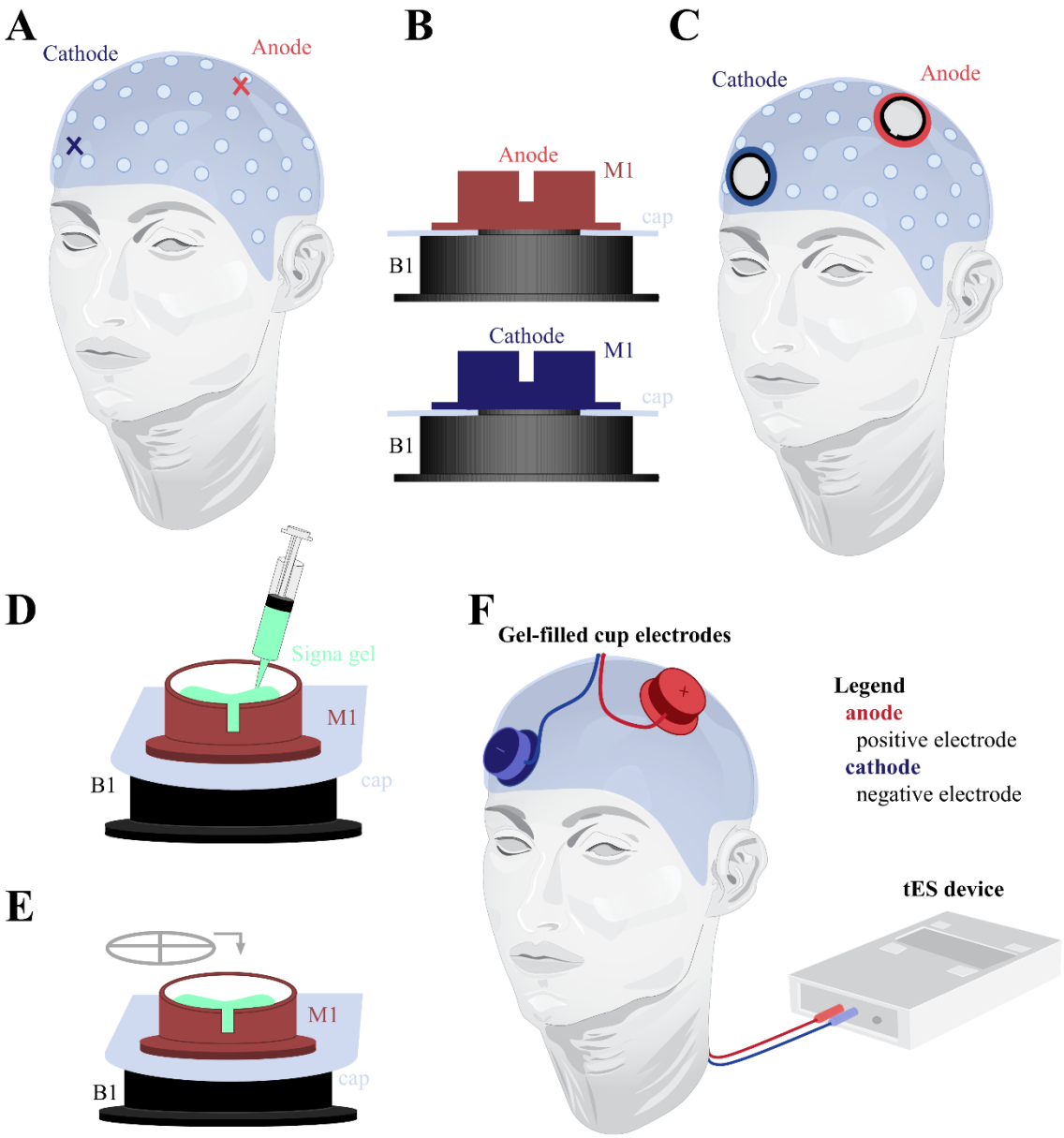

Figure 2 3D-printable cup electrodes application procedure.
(A) Prior to integrating the cups in the 10-20 cap, determine the desired location of the electrodes in the cap based on the 10-20-system. **(B)** Then, integrate the B1 cups into the 10-20-cap and secure them using the M1 components. **(C)** Next, precisely place the cap including the electrodes on the human subject's head, making sure to match the cap size with the subject's head size and to align the cap with the anatomical features. **(D)** After applying the cap, fill the B1 cups with a conductive gel from the top. **(E)** After filling the bottom part of the cups**,** place the safety grid on the ledge on the inside of the cups. Next, add the connecting cable on top of the grid, and continue to fill the cups to the rim. **(F)** Once the cups are filled with a conductive gel, seal them with the T1 lid. Finally, after plugging the connecting cables into a stimulation device, the setup is ready for use, and stimulation can be started.

Discussion

We developed 3D-printable gel-filled cup electrodes for noninvasive tES stimulation such as tDCS and tACS to allow for more precise and reproducible stimulation compared to conventional rubber patch electrodes. By integrating the electrodes in a 10-20 cap, the electrodes can be positioned precisely on the scalp based on the 10-20 system provided that the cap matches the human subject's head size. In addition to the increased precision in the initial placement of the electrodes, the cap also prevents the electrodes from moving or sliding over the scalp, even in case of significant body or head movements.

The cups were designed to be 3D-printed in a flexible rubber-like material to allow them to conform closely to the surface of the scalp, thereby eliminating the risk of gel leakage from underneath the electrodes, as is often the case when using conventional saline-soaked or gel-based electrodes. As a result, the targeted stimulation area remains highly consistent throughout stimulation and there is no risk of unintended electrical bridging between nearby electrodes. Additionally, caps were added to the design to seal the gel within the cups, preventing drying during prolonged use, addressing another common problem of conventional saline-soaked or gel-based electrodes. Furthermore, a safety grid was incorporated in the design to form a physical barrier between the connecting cables and the scalp. This eliminates the risk of skin burns, one of the major safety hazards associated with noninvasive electrical brain stimulation, without compromising the electrical connectivity within the gel in the cups. Although we were able to tackle almost all limitations associated with conventional electrodes, achieving optimal scalp coverage for thicker or denser hair types remains challenging, similar to conventional electrodes.

We recommend using Signa gel in our electrodes for its proven reliable conductivity and stability. We have previously demonstrated in vitro that 2 mA electrical stimulation through Signa Gel remains stable at low conductivity levels with a resistivity of $\rho = 0.3\ \Omega m$ (Kerstens, Orban de Xivry, and Mc Laughlin 2022) for at least 30 minutes. In addition, other researchers assessed Signa gel's stability at the gel-scalp interface in a wide variety of electrode types and configurations (Minhas et al. 2010) and found that Signa gel performs reliably across various electrode types and configurations (Minhas et al. 2010). Although the stability at the gel-scalp interface has not been validated in our electrodes specifically yet, there is no indication that it would be compromised in our designs.

We believe that our electrodes are an important improvement of the conventional electrodes due to their design characteristics specifically intended to address common issues of these electrodes and encourage researchers in the field to use our electrodes in their own experimental protocols. To facilitate broad application, we provided a wide range of electrode sizes ranging from 12 mm to 30 mm in radius. This offers a wide variety of electrode sizes and montages, which are critical factors in the resulting stimulation characteristics, such as current density, focality (Edwards et al. 2013; Kuo et al. 2013), and spatial resolution (Solomons and Shanmugasundaram 2020b). We also ensured that our electrodes are compatible with all commercially available electrical stimulation devices and that they do not rely on proprietary components or interfaces.

By designing 3D-printable electrodes, we aimed to provide researchers in the tES field with a versatile tool of multifunctional stimulation electrodes that can be used for conventional tDCS and tACS, as well as for high-definition tDCS applications (HD-tDCS) (Datta et al. 2009; Kuo et al. 2013) and beyond. Our electrodes ensure optimal precision and reproducibility, which is crucial for achieving consistent stimulation parameters across studies. At this point, our electrodes have not been directly compared to other electrode types, yet additional studies could provide valuable insights into their usability, tolerability, and comfort compared to others, from both the subject's and the experimenter's perspectives. By sharing the 3D-printable STL files, we aim to enhance accessibility for other researchers in the fields, thereby ameliorating the challenges of replicability and reproducibility that have long affected tES research (Héroux et al. 2017b).

Conclusion

Our newly developed 3D-printable cup electrodes were specifically designed to enhance precision and reproducibility of noninvasive transcranial brain stimulation in humans, addressing limitations associated with conventional rubber patch electrodes. By improving precision of tDCS and tACS, these electrodes provide a more reliable method and have the potential to improve replicability in human studies. By sharing the 3D-printable files, we aim to contribute to our toolbox to tackle the reproducibility crisis in the tDCS and tACS field.

Acknowledgements

We would like to thank iMaterialise (Haasrode, Belgium) for the 3D-printing service, and Thomas Pilkington and Simone Marcigaglia for offering valuable guidance and support in CAD design.

Author statement

Silke Kerstens: Conceptualization, Methodology, Validation, Analysis, Investigation, Writing – Original Draft, Review and Editing, Visualization, Funding acquisition. Luuk van Boekholdt: Validation, Investigation, Writing – Review and Editing. Jean-Jacques Orban de Xivry: Methodology, Writing – Review and Editing, Myles Mc Laughlin: Resources, Funding acquisition.

Conflict of Interest Statement

There are no conflicts of interest. This work was supported by the following grants: FWO SB fellowship 1S32421N, FWO-Project G0B4520N, and NIH 1R01MH123508-01.

References

Adair, Devin, Dennis Truong, Zeinab Esmaeilpour, Nigel Gebodh, Helen Borges, Libby Ho, J. Douglas Bremner, Bashar W. Badran, Vitaly Napadow, Vincent P. Clark, and Marom Bikson. 2020. 'Electrical Stimulation of Cranial Nerves in Cognition and Disease'. *Brain Stimulation* 13(3):717–50. doi:10.1016/j.brs.2020.02.019.

Adelhöfer, Nico, Moritz Mückschel, Benjamin Teufert, Tjalf Ziemssen, and Christian Beste. 2019. 'Anodal TDCS Affects Neuromodulatory Effects of the Norepinephrine System on Superior Frontal Theta Activity during Response Inhibition'. *Brain Structure and Function* 224(3):1291–1300. doi:10.1007/s00429-019-01839-3.

Antal, Andrea, Michael A. Nitsche, and Walter Paulus. 2006. 'Transcranial Direct Current Stimulation and the Visual Cortex.' *Brain Research Bulletin* 68(6):459–63. doi:10.1016/j.brainresbull.2005.10.006.

Ciechanski, Patrick, Helen L. Carlson, Sabrina S. Yu, and Adam Kirton. 2018. 'Modeling Transcranial Direct-Current Stimulation-Induced Electric Fields in Children and Adults'. *Frontiers in Human Neuroscience* 12(July):1–14. doi:10.3389/fnhum.2018.00268.

DaSilva, Alexandre F., Magdalena Sarah Volz, Marom Bikson, and Felipe Fregni. 2011. 'Electrode Positioning and Montage in Transcranial Direct Current Stimulation'. *Journal of Visualized Experiments* (51). doi:10.3791/2744.

Datta, Abhishek, Varun Bansal, Julian Diaz, Jinal Patel, Davide Reato, and Marom Bikson. 2009. 'Gyri-Precise Head Model of Transcranial Direct Current Stimulation: Improved Spatial Focality Using a Ring Electrode versus Conventional Rectangular Pad'. *Brain Stimulation* 2(4). doi:10.1016/j.brs.2009.03.005.

Edwards, Dylan, Mar Cortes, Abhishek Datta, Preet Minhas, Eric M. Wassermann, and Marom Bikson. 2013. 'Physiological and Modeling Evidence for Focal Transcranial Electrical Brain Stimulation in Humans: A Basis for High-Definition TDCS'. *NeuroImage* 74:266–75. doi:10.1016/j.neuroimage.2013.01.042.

Heimrath, K., A. Brechmann, R. Blobel-Lüer, J. Stadler, E. Budinger, and Tino Zaehle. 2020. 'Transcranial Direct Current Stimulation (TDCS) over the Auditory Cortex Modulates GABA and Glutamate: A 7 T MR-Spectroscopy Study'. *Scientific Reports* 10(1):1–8. doi:10.1038/s41598-020-77111-0.

Héroux, Martin E., Colleen K. Loo, Janet L. Taylor, and Simon C. Gandevia. 2017a. 'Questionable Science and Reproducibility in Electrical Brain Stimulation Research' edited by J. M. Wicherts. *PLOS ONE* 12(4):e0175635. doi:10.1371/journal.pone.0175635.

Héroux, Martin E., Colleen K. Loo, Janet L. Taylor, and Simon C. Gandevia. 2017b. 'Questionable Science and Reproducibility in Electrical Brain Stimulation Research'. *PLoS ONE* 12(4):1–11. doi:10.1371/journal.pone.0175635.

Huang, Yu, Anli A. Liu, Belen Lafon, Daniel Friedman, Michael Dayan, Xiuyuan Wang, Marom Bikson, Werner K. Doyle, Orrin Devinsky, and Lucas C. Parra. 2017. 'Measurements and Models of Electric Fields in the in Vivo Human Brain during Transcranial Electric Stimulation'. *ELife* 6:1–26. doi:10.7554/eLife.18834.

Kerstens, Silke, Jean-Jacques Orban de Xivry, and Myles Mc Laughlin. 2022. 'A Novel TDCS Control Condition Using Optimized Anesthetic Gel to Block Peripheral Nerve Input'. *Frontiers in Neurology* 13. doi:10.3389/fneur.2022.1049409.

Kunzelmann, Katharina, Lea Meier, Matthias Grieder, Yosuke Morishima, and Thomas Dierks. 2018. 'No Effect of Transcranial Direct Current Stimulation of the Auditory Cortex on Auditory-Evoked Potentials'. *Frontiers in Neuroscience* 12(NOV):1–10. doi:10.3389/fnins.2018.00880.

Kuo, Hsiao I., Marom Bikson, Abhishek Datta, Preet Minhas, Walter Paulus, Min Fang Kuo, and Michael A. Nitsche. 2013. 'Comparing Cortical Plasticity Induced by Conventional and High-Definition 4 × 1 Ring TDCS: A Neurophysiological Study'. *Brain Stimulation* 6(4):644–48. doi:10.1016/j.brs.2012.09.010.

Lang, Nicolas, Hartwig R. Siebner, Nick S. Ward, Lucy Lee, Michael A. Nitsche, Walter Paulus, John C. Rothwell, Roger N. Lemon, and Richard S. Frackowiak. 2005. 'How Does Transcranial DC Stimulation of the Primary Motor Cortex Alter Regional Neuronal Activity in the Human Brain?' *European Journal of Neuroscience* 22(2):495–504. doi:10.1111/j.1460-9568.2005.04233.x.

Liebrand, Matthias, Anke Karabanov, Daria Antonenko, Agnes Flöel, Hartwig R. Siebner, Joseph Classen, Ulrike M. Krämer, and Elinor Tzvi. 2020. 'Beneficial Effects of Cerebellar TDCS on Motor Learning Are Associated with Altered Putamen-Cerebellar Connectivity: A Simultaneous TDCS-FMRI Study'. *NeuroImage* 223(April):117363. doi:10.1016/j.neuroimage.2020.117363.

Minarik, Tamas, Barbara Berger, Laura Althaus, Veronika Bader, Bianca Biebl, Franziska Brotzeller, Theodor Fusban, Jessica Hegemann, Lea Jesteadt, Lukas Kalweit, Miriam Leitner, Francesca Linke, Natalia Nabielska, Thomas Reiter, Daniela Schmitt, Alexander Spraetz, and Paul Sauseng. 2016. 'The Importance of Sample Size for Reproducibility of TDCS Effects.' *Frontiers in Human Neuroscience* 10:453. doi:10.3389/fnhum.2016.00453.

Minhas, Preet, Varun Bansal, Jinal Patel, Johnson S. Ho, Julian Diaz, Abhishek Datta, and Marom Bikson. 2010. 'Electrodes for High-Definition Transcutaneous DC Stimulation for Applications in Drug Delivery and Electrotherapy, Including TDCS'. *Journal of Neuroscience Methods* 190(2):188–97. doi:10.1016/j.jneumeth.2010.05.007.

Nitsche, M. a, M. a Nitsche, W. Paulus, and W. Paulus. 2000. 'Excitability Changes Induced in the Human Motor Cortex by Weak Transcranial Direct Current Stimulation.' *The Journal of Physiology* 527 Pt 3:633–39. doi:PHY_1055 [pii].

Pollok, Bettina, Claire Schmitz-Justen, and Vanessa Krause. 2021. 'Cathodal Transcranial Direct Current Stimulation (Tdcs) Applied to the Left Premotor Cortex Interferes with Explicit Reproduction of a Motor Sequence'. *Brain Sciences* 11(2):1–18. doi:10.3390/brainsci11020207.

Solomons, Cassandra D., and Vivekanandan Shanmugasundaram. 2020a. 'Transcranial Direct Current Stimulation: A Review of Electrode Characteristics and Materials'. *Medical Engineering and Physics* 85:63–74.

Solomons, Cassandra D., and Vivekanandan Shanmugasundaram. 2020b. 'Transcranial Direct Current Stimulation: A Review of Electrode Characteristics and Materials'. *Medical Engineering and Physics* 85:63–74.

Utz, Kathrin S., Violeta Dimova, Karin Oppenländer, and Georg Kerkhoff. 2010. 'Electrified Minds: Transcranial Direct Current Stimulation (TDCS) and Galvanic Vestibular Stimulation (GVS) as Methods of Non-Invasive Brain Stimulation in Neuropsychology-A Review of Current Data and Future Implications'. *Neuropsychologia* 48(10):2789–2810. doi:10.1016/j.neuropsychologia.2010.06.002.

Williams, Petra S., Richard L. Hoffman, and Brian C. Clark. 2013. 'Preliminary Evidence That Anodal Transcranial Direct Current Stimulation Enhances Time to Task Failure of a Sustained Submaximal Contraction'. *PLoS ONE* 8(12). doi:10.1371/journal.pone.0081418.