Comparing Optimal and Commercially Available Bipolar and Tripolar Concentric Ring Electrode Configurations Using Finite Element Method Modeling Based on Their Finite Dimensions Models

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***Abstract*—While finite element method modeling has been used to compare bipolar and tripolar concentric ring electrode configurations in the past it was based on the simplistic negligible dimensions model of the electrode. This study uses realistic finite dimensions models including novel optimal bipolar and tripolar configurations and directly compares them to bipolar configurations of the same size with dimensions corresponding to the commercially available CoDe® electrodes manufactured by Spes Medica. Moreover, it also compares bipolar and tripolar configurations of different sizes. In particular, optimal tripolar concentric ring electrode configuration is compared to a bipolar configuration consisting out of its central disc and middle ring only. Obtained results include relative and normalized maximum errors of Laplacian estimation. Compared to the optimal tripolar concentric ring electrode configuration, commercially available bipolar electrode of the same size corresponds to a median increase in Laplacian estimation errors of 120-146 times while its counterpart one third of its size corresponds to an increase of 15-18 times. Compared to the optimal bipolar configuration, commercially available bipolar electrode of the same size corresponds to a median increase in Laplacian estimation errors of 1.2 times. These results are consistent with previously obtained results based on the negligible dimensions models.**

Keywords—electrophysiology, measurement, wearable sensors, noninvasive, concentric ring electrodes, Laplacian, estimation, optimization, finite element method, modeling.

I. INTRODUCTION

Finite element method (FEM) modeling has been used to compare bipolar and tripolar concentric ring electrode (CRE) configurations in the past [1]–[5] but it was based on the simplistic negligible dimensions model (NDM) of the electrode with a single point of negligible radius representing the central disc and circles of negligible width representing concentric rings. In [1], [2] they are simply referred to as a five-point method and a nine-point methods of surface Laplacian (second spatial derivative of the surface potential) estimation as opposed to bipolar (BCRE; single ring) and tripolar (TCRE; two concentric rings) CRE configurations of the same size. Their comparison that also included a quasi-bipolar method corresponding to a BCRE with shorted recording surfaces resulted in relative and maximum errors of Laplacian estimation that were the smallest for TCRE configuration with the difference being statistically significant. In [3]–[5] BCRE configuration was compared against CRE configurations with constant inter-ring distances (distances between the recording surfaces of a CRE) and higher numbers of concentric rings including TCRE, quadripolar (three rings), pentapolar (four rings), sextopolar (five rings), and septapolar (six rings) CREs [3] as well as against TCRE and quadripolar CRE configurations with different types of variable inter-ring distances including linearly increasing [4], [5], linearly decreasing [4], and quadratically increasing [5] ones respectively. In all the comparisons [3]–[5] the relative and maximum errors of Laplacian estimation for BCRE configuration were the largest which is consistent with [1], [2].

Realistic finite dimensions model (FDM) of a TCRE that includes the radius of the central disc and individual widths of concentric rings was first proposed as a proof of concept in [6]. Next this proof of concept has been developed into a comparison framework validated on human electrocardiogram data [7] before ultimately being used to solve a comprehensive FDM based TCRE optimization problem maximizing the accuracy of Laplacian estimation [8]. Resulting optimal TCRE configuration has been confirmed by FEM modeling adapted for the first time from NDM to FDM [8]. Moreover, FEM results suggested that optimal TCRE configuration may also offer improved sensitivity and spatial resolution [8].

This study uses FDMs including novel optimal BCRE (proposed in this study and based on the general principles defining optimal CRE configurations in terms of the accuracy of the surface Laplacian estimate from [8]) and TCRE

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configurations and directly compares them to BCRE configurations with dimensions corresponding to the commercially available CoDe® electrodes (Spes Medica, Genova, Italy). CoDe® electrodes have been widely used in studies ranging from ones related to sleep [9], [10] and awake [11] bruxism to evaluation of masticatory [12], swallowing [13], gastric [14] and respiratory [15] muscle activity. This comparison includes BCREs and TCREs of different sizes. In particular, optimal TCRE configuration is compared to a BCRE configuration consisting out of its central disc and middle ring only as well as to BCRE configurations of the same size. Obtained results include relative and normalized maximum errors of Laplacian estimation.

II. Methods

A. Concentric Ring Electrode Configurations

All the CRE configurations included in this study are presented in Fig. 1. First step was determining an FDM for two commercially available models of CoDe® electrodes (Spes Medica, Genova, Italy): CODE401526 with 40 mm diameter and CODE501526 with 50 mm diameter (model numbers and dimensions taken from [16]). For CODE401526 with internal and external diameters of the outer ring equal to 20 mm and 30 mm respectively and the diameter of the central disc equal to 10 mm scaling its dimensions to the size of the optimal TCRE configuration from [8] with outer radius subdivided into 9 equal intervals (Fig. 1D) results in FDM from Fig. 1B while scaling it to a one third of its size results in FDM from Fig. 1A. The latter is also equivalent to just the central disc and middle ring only of the optimal TCRE from Fig. 1D and specifically allows assessment of the possible benefits of incorporating the outer ring. For CODE501526 with internal and external diameters of the outer ring equal to 30 mm and 42 mm respectively and the diameter of the central disc equal to 16 mm scaling its dimensions to the size of the optimal TCRE configuration from Fig.1D results in central disc radius equal to 3.429 and inner radius of the outer ring equal 6.429 which rounded to the nearest integer give us BCRE from Fig. 1B. Finally, the optimal BCRE configuration from Fig. 1C stems directly from the first general principle defining optimal CRE configurations in terms of the accuracy of the surface Laplacian estimate from [8]: "in the optimal configuration, central disc and concentric rings are kept at minimum distances with minimum radius/widths, except for the width of the outer ring".

B. Finite Element Method Modeling

NDM based FEM model from [1]–[5] has been adapted to FDM in [8] for the first time. This adaptation has been used in current study with the same parameters including an evenly spaced (0.278 mm) square mesh of 700 x 700 points corresponding to roughly 20 x 20 cm located in the first quadrant of the *X*-*Y* plane over a unit charge dipole projected to the center of the mesh and oriented towards the positive direction of the *Z* axis (Fig. 2). The medium was assumed to be homogeneous with a conductivity σ equal to 7.14 mS/cm to emulate biological tissue [17]. Electric potential v was generated and analytical Laplacian Δv calculated at each point of the mesh by taking the second spatial derivative of the electric potential for the dipole depth equal to 5 cm [18]:

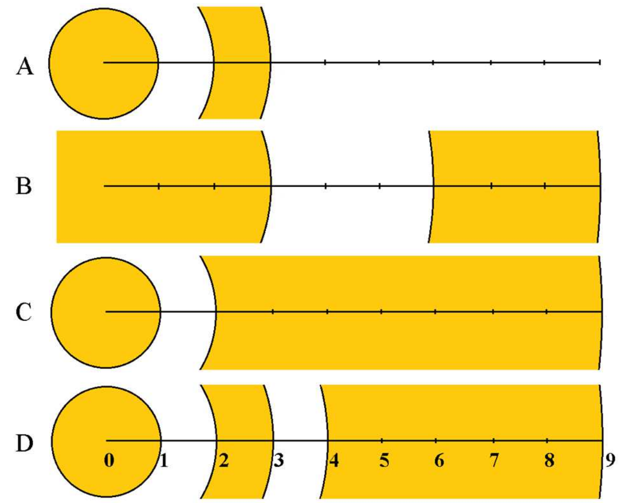

Fig. 1. Finite dimensions models of three bipolar and one tripolar concentric ring electrode configurations including: small (A), large (B), and optimal (C) bipolar configurations as well as optimal (D) tripolar configuration with respect to the accuracy of Laplacian estimation.

$$v = \frac{1}{4\pi\sigma} \frac{(\overline{r}_p - \overline{r}) \cdot \overline{p}}{\left|\overline{r}_p - \overline{r}\right|^3} \tag{1}$$

$$\Delta v = \frac{3}{4\pi\sigma}\left[5(z_p - z)^2 \frac{(\overline{r}_p - \overline{r}) \cdot \overline{p}}{\left|\overline{r}_p - \overline{r}\right|^7} - \frac{(\overline{r}_p - \overline{r}) \cdot \overline{p} + 2(z_p - z)p_z}{\left|\overline{r}_p - \overline{r}\right|^5}\right] \tag{2}$$

where $\overline{r} = (x, y, z)$ is the location of the dipole, $\overline{p} = (p_x, p_y, p_z)$ is the moment of the dipole, and $\overline{r}_p = (x_p, y_p, z_p)$ is the observation point.

In order to obtain Laplacian estimate formulas for the three BCRE configurations from Fig. 1A-C FDM based analytic approach from [7] was used. First, potentials were calculated for all nine concentric circles as means of potentials at four points on each circle. Next, these circle potentials were used to calculate the potentials on the recording surfaces of each CRE configuration. For example, the potential on the central disc for three CRE configurations from Fig. 1A, C, and D is equal to the mean of the potential at the center of the central disc and potential on the smallest of the concentric circles. Another example would be potential on the outer ring of BCRE configuration from Fig. 1B being equal to mean of the potentials on the four largest concentric circles. Finally, for each BCRE configuration differences between the outer ring and central disc potentials were taken, scaled by a respective coefficient, and divided by the square of the distance between the concentric circles to produce the respective Laplacian estimate [7]. Resulting Laplacian estimate coefficients for BCREs from Fig. 1A-C were equal to 2/3, 2/27, and 4/35 respectively. Laplacian estimate formula for the optimal TCRE configuration from Fig. 1D was adopted from [8] and comprised of the two bipolar differences for each of the ring potentials minus the central disc potential that were linearly combined with coefficients (952/1227, –6/409) and divided by the square of the distance between the concentric circles. All four Laplacian estimates were computed at each point of the mesh where appropriate boundary conditions could be applied and compared with the

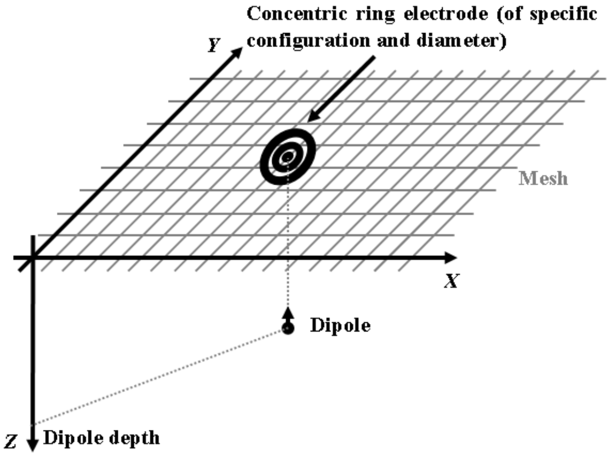

Fig. 2. Schematic of the finite element method model used to compare Laplacian estimates.

calculated analytical Laplacian using the following error measures adopted from [8]:

$$\text{Relative error}^i = \sqrt{\frac{\sum (\Delta v - \Delta^i v)^2}{\sum (\Delta v)^2}} \tag{3}$$

$$\text{Normalized maximum error}^i = \frac{\max \left| \Delta v - \Delta^i v \right|}{\max \left| \Delta v \right|} \tag{4}$$

where i represents CRE configuration, $\Delta^i v$ represents the corresponding Laplacian estimate, and Δv represents the analytical Laplacian at each point of the mesh. Relative errors has been adopted verbatim from [1]–[5], [8] while normalized maximum error has been modified in [8] to make visualization of the improvement in Laplacian estimation accuracy easier by representing the error as a percentage of the maximum absolute value of the analytical Laplacian.

III. Results

Relative and normalized maximum errors computed via the FEM modeling using (3) and (4) are presented in Fig. 3 and Fig. 4 for CRE diameters ranging from 0.5 cm to 5 cm using linear and semi-log scales respectively. This CRE diameter range corresponds to large and optimal BCREs and optimal TCRE configurations from Fig. 1B-D. Sizes of small BCRE configuration from Fig.1A are one third of other CRE configurations considered.

Compared to the optimal TCRE configuration from Fig. 1D, commercially available BCRE of the same size from Fig. 1B corresponds to a median increase in Laplacian estimation error (ratios of respective errors obtained for 10 CRE sizes) of 146 (relative error) and 120 (normalized maximum error) times while its counterpart one third of its size from Fig. 1A corresponds to an increase of 18.45 (relative error) and 15.45 (normalized maximum error) times. Compared to the optimal BCRE configuration from Fig. 1C, commercially available BCRE of the same size from Fig. 1B corresponds to a median increase in Laplacian estimation errors of 1.2 times (both relative and normalized maximum errors). This pattern of

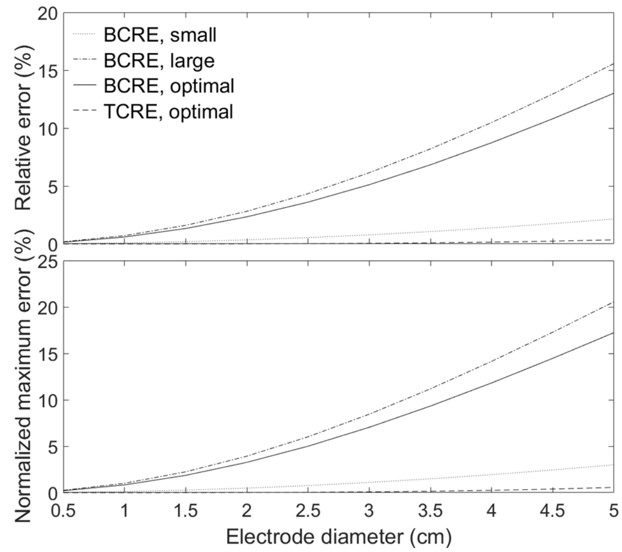

Fig. 3. Relative (top) and normalized maximum (bottom) errors of surface Laplacian estimation corresponding to four concentric ring electrode configurations presented on a linear scale.

relationship between BCRE and TCRE configurations is consistent with previously obtained NDM based FEM modeling results for constant inter-ring distances BCRE and TCRE configurations [1]–[3].

IV. Discussion

This study represents the first attempt to directly compare optimal BCRE and TCRE configurations from Fig. 1C-D to their commercially available counterparts in terms of the accuracy of the surface Laplacian estimation using FDM based FEM modeling. Such comparison is important since ability to estimate the surface Laplacian at each electrode constitutes the primary biomedical significance of CREs. Therefore, quantifying the difference between optimal and commercially available configurations could provide an insight to incorporate into the design of future CREs for real-life applications not limited to the ones that already rely on commercially available CREs [9]–[15]. While the median difference of 1.2 times in Laplacian estimation errors between the optimal BCRE configuration from Fig. 1C proposed in this study and BCRE configuration with dimensions corresponding to CoDe® electrodes (Spes Medica, Genova, Italy) of the same size from Fig. 1B is negligible for most practical applications that is not the case for comparison against the optimal TCRE configuration from Fig. 1D proposed in [8]. The importance of difference in Laplacian estimation errors of 120-146 times between the optimal TCRE configuration from Fig.1D and commercially available BCRE of the same size from Fig. 1B for practical real life applications is discussed in more detail below.

With the external diameter of the outer ring of the CODE401526 model being equal to 30 mm and external diameter of the outer ring of the CODE501526 model being equal to 42 mm, the two most relevant CRE sizes out of the 10 sizes total included in this study are CRE diameters of 3 cm (identical to CODE401526) and 4 cm (closest to CODE501526). As can be seen from Fig. 3 for these two sizes the error of Laplacian estimation corresponding to the BCRE from Fig. 1B

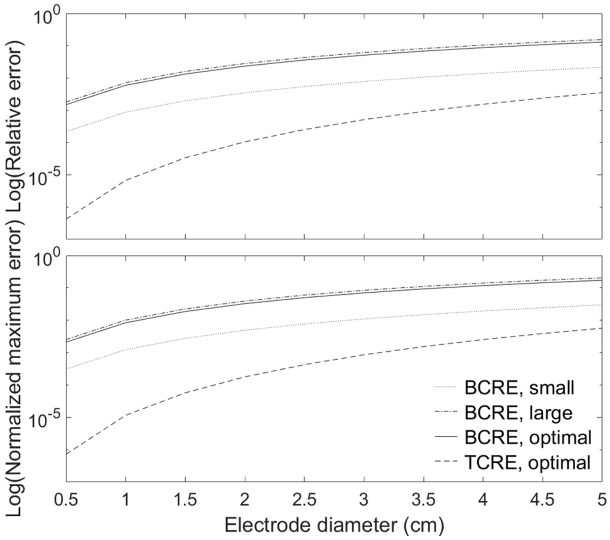

Fig. 4. Relative (top) and normalized maximum (bottom) errors of surface Laplacian estimation corresponding to four concentric ring electrode configurations presented on a semi-log scale.

is substantial for vast majority of real life applications. For the 3 cm diameter BCRE from Fig. 1B corresponds to the Laplacian estimation errors of 6.15% (relative error) and 8.45% (normalized maximum error) while optimal TCRE from Fig. 1D of the same size allows decreasing these errors to 0.05% and 0.09% respectively. For the 4 cm diameter BCRE from Fig. 1B corresponds to the Laplacian estimation errors of 10.49% (relative error) and 14.15% (normalized maximum error) while optimal TCRE from Fig. 1D of the same size allows decreasing these errors to 0.15% and 0.25% respectively.

Moreover, as can be seen from Fig. 4 this difference in Laplacian estimation errors between the BCRE configurations from Fig. 1A-C and the optimal TCRE from Fig. 1D of the same size increases with the decrease in the electrode diameter which is consistent with previously obtained NDM based FEM modeling results for constant inter-ring distances BCRE and TCRE configurations [1]–[3]. This is important since, for example, commercially available t-Lead TCREs (CREmedical, Kingston, RI, USA) have an external diameter of the outer ring equal to 1 cm for which the difference in Laplacian estimation error between commercially available BCRE from Fig. 1B and optimal TCRE configuration from Fig. 1D reaches 1065.83 (relative error) and 878.58 (normalized maximum error) times.

Finally, BCRE configuration from Fig. 1A one third of the size of BCRE and TCRE configurations from Fig. 1B-D that is equivalent to just the central disc and middle ring of the optimal TCRE configuration from Fig. 1D has been included into this study to assess the possible benefits of incorporating the outer ring. Obtained results of the median difference of 15-18 times in Laplacian estimation error between these two configurations constitute an important benefit. For example, as can be seen from Fig. 4 going from an optimal TCRE from Fig. 1D with a diameter of 1 cm equivalent to the size of commercially available t-Lead TCREs (CREmedical, Kingston, RI, USA) to a BCRE from Fig. 1A that is equivalent to removing the outer ring of the TCRE would result in an increase of 129.94 (relative) and 107.4 (normalized maximum) times in Laplacian estimation errors. This result is consistent with previous NDM and FDM based studies that have shown (in [3] for NDM and in [6] for FDM respectively) the highest order of the truncation term that can be cancelled out during derivation of the Laplacian estimate to be equal to twice the number of concentric rings in the electrode. In case of BCRE and TCRE configurations this translates to the fourth order truncation term being cancelled out in TCRE Laplacian estimates but not in BCRE ones. This difference is meaningful for the truncation error of Laplacian estimation since "higher-order terms usually contribute negligibly to the final sum and can be justifiably discarded" from the Taylor series [19].

While different interpretations of improvement in Laplacian estimation accuracy due to optimal BCRE and TCRE configurations are possible, one oversimplified interpretation may be that potential recorded by the outer ring of a CRE is less representative of the sources under the central disc compared to the potential recorded by the central disc. Because of that in case of, for example, BCRE configuration it is subtracted from the potential recorded by the central disc to emphasize the local sources. Optimal BCRE configuration from Fig. 1C has smaller central disc, so its recorded potential is more representative of the sources under it than potential recorded by the central disc of the BCRE from Fig. 1B. At the same time, the median line of the outer ring from Fig. 1C is closer to the central disc than that from Fig. 1B which could be interpreted as a smaller equivalent electrode in NDM terms. As seen from the comparison of BCRE configuration from Fig. 1A with the BCRE configurations from Fig. 1B-C such smaller outer diameter of the electrode has significant impact on the Laplacian estimation errors. Another potential oversimplified interpretation could be related to the optimal BCRE configuration from Fig. 1C corresponding to a larger portion of the electrode surface area being used to record potentials in comparison to BCRE configuration of the same size from Fig. 1B. However, since BCRE configurations from Fig. 1B and Fig. 1C correspond to an increase in surface area utilized for recording surfaces of almost 30% (from 66.67% to 96.3% respectively) which results in a median difference of just 1.2 times in Laplacian estimation errors this particular interpretation appears to be unlikely based on the results obtained in this study.

One limitation of this study is that at this point of time only BCREs with dimensions corresponding to the CoDe® electrodes (Spes Medica, Genova, Italy) are included in the comparison. Next step would be to add TCRE with dimensions corresponding to t-Lead electrodes (CREmedical, Kingston, RI, USA). Measures quantifying sensitivity and spatial resolution as in [8] will also be added for all the CRE configurations included. Future work also involves moving from a single-layer FEM model used in this study to a more comprehensive one that could provide more realistic estimations of the amplitude of the bioelectric potential from each pair of poles of CRE and thus to study the influence of configurations and dimensions of the CRE on this important parameter in real life applications.

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REFERENCES

[1] W. G. Besio, K. Koka, R. Aakula, and W. Dai, "Tri-polar concentric ring electrode development for Laplacian electroencephalography," *IEEE Transactions on Biomedical Engineering*, vol. 53, no. 5, pp. 926–933, May 2006.

[2] W. G. Besio, R. Aakula, K. Koka, and W. Dai, "Development of a Tri-polar Concentric Ring Electrode for Acquiring Accurate Laplacian Body Surface Potentials," *Ann Biomed Eng*, vol. 34, no. 3, pp. 426–435, Feb. 2006, doi: 10.1007/s10439-005-9054-8.

[3] O. Makeyev, Q. Ding, and W. G. Besio, "Improving the accuracy of Laplacian estimation with novel multipolar concentric ring electrodes," *Measurement*, vol. 80, pp. 44–52, Feb. 2016, doi: 10.1016/j.measurement.2015.11.017.

[4] O. Makeyev and W. G. Besio, "Improving the Accuracy of Laplacian Estimation with Novel Variable Inter-Ring Distances Concentric Ring Electrodes," *Sensors*, vol. 16, no. 6, p. 858, Jun. 2016, doi: 10.3390/s16060858.

[5] O. Makeyev, "Solving the general inter-ring distances optimization problem for concentric ring electrodes to improve Laplacian estimation," *BioMedical Engineering OnLine*, vol. 17, no. 1, p. 117, Aug. 2018, doi: 10.1186/s12938-018-0549-6.

[6] O. Makeyev, C. Lee, and W. G. Besio, "Proof of concept Laplacian estimate derived for noninvasive tripolar concentric ring electrode with incorporated radius of the central disc and the widths of the concentric rings," *Conf Proc IEEE Eng Med Biol Soc*, vol. 2017, pp. 841–844, Jul. 2017, doi: 10.1109/EMBC.2017.8036955.

[7] O. Makeyev, M. Musngi, L. Moore, Y. Ye-Lin, G. Prats-Boluda, and J. Garcia-Casado, "Validating the Comparison Framework for the Finite Dimensions Model of Concentric Ring Electrodes Using Human Electrocardiogram Data," *Applied Sciences*, vol. 9, no. 20, p. 4279, Jan. 2019, doi: 10.3390/app9204279.

[8] O. Makeyev, Y. Ye-Lin, G. Prats-Boluda, and J. Garcia-Casado, "Comprehensive Optimization of the Tripolar Concentric Ring Electrode Based on Its Finite Dimensions Model and Confirmed by Finite Element Method Modeling," *Sensors (Basel)*, vol. 21, no. 17, p. 5881, Aug. 2021, doi: 10.3390/s21175881.

[9] T. Castroflorio, L. Mesin, G. M. Tartaglia, C. Sforza, and D. Farina, "Use of electromyographic and electrocardiographic signals to detect sleep bruxism episodes in a natural environment," *IEEE journal of biomedical and health informatics*, vol. 17, no. 6, pp. 994–1001, 2013.

[10] A. Deregibus, T. Castroflorio, A. Bargellini, and C. Debernardi, "Reliability of a portable device for the detection of sleep bruxism," *Clinical oral investigations*, vol. 18, no. 8, pp. 2037–2043, 2014.

[11] I. Cioffi, D. Landino, V. Donnarumma, T. Castroflorio, F. Lobbezoo, and A. Michelotti, "Frequency of daytime tooth clenching episodes in individuals affected by masticatory muscle pain and pain-free controls during standardized ability tasks," *Clinical oral investigations*, vol. 21, no. 4, pp. 1139–1148, 2017.

[12] T. Lou, J. Tran, T. Castroflorio, A. Tassi, and I. Cioffi, "Evaluation of masticatory muscle response to clear aligner therapy using ambulatory electromyographic recording," *American Journal of Orthodontics and Dentofacial Orthopedics*, vol. 159, no. 1, pp. e25–e33, 2021.

[13] J. Garcia-Casado, G. Prats-Boluda, Y. Ye-Lin, S. Restrepo-Agudelo, E. Perez-Giraldo, and A. Orozco-Duque, "Evaluation of Swallowing Related Muscle Activity by Means of Concentric Ring Electrodes," *Sensors*, vol. 20, no. 18, p. 5267, 2020, doi: 10.3390/s20185267.

[14] Y. Ye-Lin, J. L. Martinez-De-Juan, A. Jareño-Silvestre, and G. Prats-Boluda, "Concentric ring electrodes for non-invasive recording of gastric myoelectric activity," *Measurement*, p. 110607, 2021.

[15] L. Estrada-Petrocelli *et al.*, "Evaluation of Respiratory Muscle Activity by Means of Concentric Ring Electrodes," *IEEE Transactions on Biomedical Engineering*, vol. 68, no. 3, pp. 1005–1014, Mar. 2021, doi: 10.1109/TBME.2020.3012385.

[16] GVB-geliMED, "Electrodo adhesivo bipolar (IOM)," *GVB-SPES ES*. https://www.gvb-spes.es/accesorios-de-iom/iom-electrodos-de-neurocirugia/329/electrodo-adhesivo-bipolar-iom (accessed Jan. 18, 2022).

[17] W. G. Besio and M. Fasiuddin, "Quantizing the depth of bioelectrical sources for non-invasive 3D imaging," *J Bioelectromagn*, vol. 7, pp. 90–3, 2005.

[18] B. He and D. Wu, "Laplacian electrocardiography.," *Crit Rev Biomed Eng*, vol. 27, no. 3–5, pp. 285–338, Dec. 1998.

[19] M. R. King and N. A. Mody, *Numerical and statistical methods for bioengineering: applications in MATLAB*. Cambridge University Press, 2010.