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Abstract— **Ultrafast ultrasound imaging of muscle enables the assessment of mechanical and anatomical characteristics of contracting tissue with high temporal and spatial resolution, allowing for the identification of individual motor unit (MU) territories in 2D cross-sectional image sequences. Expanding this analysis to 3D imaging would allow a detailed characterization of MU fiber's characteristics and behavior. In this feasibility study, we compare sparse random aperture compounding (SRAC) against the standard transmit/aperture sequences (BLOCK) for ultrafast ultrasound imaging acquisition using a 2D matrix array in the reconstruction of the muscle volume encompassing fibers of single MUs. The Verasonics Vantage 256 programmable ultrasound research platform coupled with a 32x32 matrix array transducer was used to collect radiofrequency (RF) data for volume imaging of the abductor digiti minimi (ADM) muscle. A full transmission (TX) event coupled with two different multiplexing strategies, standard BLOCK and sparse random aperture compounding (SRAC), were employed and compared using a 500 Hz complete volume rate acquisition. The RF data, which was concurrently acquired with high density electromyography (HDEMG) signals during 5 second low-level isometric contractions, was reconstructed using delay-and-sum beamforming employing either 4 multiplexed receive events (4RX, all 1024 elements) or only 2 (2RX, 512 elements). The 3D tissue velocity sequence (3D-TVS) was estimated obtaining a sampled volume of ~20x10x10 mm^3. The firing instants of individual MUs identified from concurrent HDEMG signal acquisition and analysis were then used for spike-trigger averaging (±100 ms) the 3D-TVS. The final volume was reconstructed computing the mean correlation calculated from the triggered signals to highlight MU related motion in 3D. The obtained results are consistent with the fusiform muscle architecture of the ADM: circular territories of individual MUs are consistently localized across cross-sectional slices and elongate longitudinally along the direction of the fibers. The study demonstrates how using SRAC with a 2D matrix array enables ultrafast ultrasound imaging either using two or four RX events for analysis of single motor unit activation when coupled with HDEMG.**

Keywords—3D ultrafast ultrasound, SRAC, HDEMG, motor unit, fiber bundle.

I. INTRODUCTION

Ultrafast ultrasound imaging has recently emerged as a novel tool for assessing the characteristics of contracting skeletal muscle tissues [1]. The high temporal resolution of these devices complements the excellent spatial resolution typical of standard ultrasound systems, opening new possibilities for studying muscle tissue dynamics. This advancement allows for the investigation of mechanical tissue properties not only at a global muscle level [2], but also at the level of individual motor units (MUs) [3]. Indeed, the combination of high spatial and temporal resolution enables the detection of movements associated with groups of fibers innervated by a single motoneuron, providing the opportunity to study the firing characteristics of individual motoneurons and the anatomical/mechanical properties of the fibers they innervate. Over the past four years, methods have been developed for the characterization of single MUs from the two-dimensional (2D) cross-sectional image sequences [4]–[6]. All these methods rely on the computation of the tissue velocities from the beamformed signals of consecutive frames acquired at rates of a few hundreds up to thousands of frames per second (fps). Subsequently, the neural, anatomical, and mechanical characteristics of voluntarily activated MUs can be extracted from the sequence of tissue velocities [7]–[9].

The muscle tissue displacements associated with muscle contraction involve complex motion and interactions in various directions that are challenging to be fully captured by a traditional 2D field of view [10]. This limitation arises because the 2D imaging techniques can only detect movements within a single plane, leaving out-of-plane movements undetected. The computation of tissue velocities, which is crucial for understanding the mechanical properties and behavior of MU fibers, can be significantly enhanced by expanding from 2D to three dimensional (3D) imaging. High-frame-rate volume imaging has gained significant interest due to its potential for studying complex, high-velocity motion phenomena occurring in 3D [11]. This advanced imaging technique allows for the capture of movements across multiple planes, providing a more comprehensive understanding of tissue dynamics [12]. For example, the velocities of tissue particles can be tracked more accurately across all three spatial dimensions, improving the characterization of MU fibers' displacement. Detailed temporal and spatial data can facilitate the understanding of the biomechanical properties of muscle tissue, including how different fibers interact with each other, how they respond to various stimuli, and how their activation contributes to overall muscle contraction.

Volume imaging can be performed using, for example, a 2D matrix array transducer of 1024 elements that can be controlled with different modalities of transmit events (TX) and receive apertures (RX). Sparse-random-aperture compounding (SRAC) was developed as a new approach which strategically uses a subset of available transducer elements in a random pattern to generate a composite image [13], when multiplexing is required. Moreover, by modifying the number of events (TX and RX), it is possible to optimize the data dimension for storage and computation purposes allowing for longer data acquisition time or increased volume rate with respect to standard transmit/aperture sequences (BLOCK) [14].

In this feasibility study, we compare two ultrafast ultrasound imaging acquisition modalities (BLOCK vs SRAC) using a 2D matrix array in the reconstruction of muscle tissue velocities within volumes encompassing the fibers of voluntary activated motor units. We also tested the impact the number of receive events has on single MU volume reconstruction. By moving from 2D to 3D imaging, we open the door to more detailed insights into the mechanical behavior of motor units. This study not only showcases the

potential of this cutting-edge technology but also sets the stage for future research that could improve our understanding of muscle dynamics.

II. Methods

The approach used to evaluate the performance of the two methods was based on the comparison of the muscle tissue velocities and the subsequent detection of the MU activation area (i.e., the area associated with the movement of fibers belonging to a single motor unit) in the various transverse and longitudinal sections of the muscle obtained through the 3D probe. The detection of the MU activation area was based on a method previously applied in 2D conditions. This method relies on the combined acquisition of ultrasound and high-density electromyography (HDEMG) [5], [15], [16]. Briefly, single MU activation instants are identified through HDEMG decomposition [17] and are used as trigger events to identify, in the muscle cross-section, the MU activation areas. In this study, we applied this method to 3D high-frame-rate scans of the abductor digiti minimi (ADM) muscle. The ADM muscle was chosen for this study due to its anatomical characteristics. This muscle, located in the hand, is superficial and has a relatively small size, which makes it suitable for comprehensive imaging using a 32x32 matrix (~1 cm^2) transducer. Moreover, its fusiform architecture, characterized by muscle fibers running parallel to the skin, facilitates the identification of individual MUs during imaging.

A. Experimental setting

One male subject (age: 30, height: 180 cm, weight: 70 kg) with no history of neurological or musculoskeletal impairments or disease was enrolled in the study. He was positioned comfortably with his hand stabilized to minimize wrist movement (Fig. 1). The little finger was secured to a load cell enabling the measurements of abduction force. Afterwards, the participant was asked to perform a maximum voluntary contraction (MVC) and the force was taken as reference for the following contractions. The RF data and HDEMG signals were collected simultaneously during controlled muscle contractions: two pairs of 30-seconds contractions at 5% MVC, with two minutes rest in between. The participant was provided with visual feedback showing the force trace in time and the target force. HDEMG signals were acquired during the entire contraction, while ultrasound RF data were detected for 5 seconds in the middle of the acquisition. A rectangular pulse provided by an external generator (StimTrig; LISiN, Politecnico di Torino, Italy) was used to start the RF acquisition, with this pulse being simultaneously recorded by the HDEMG system for signals' synchronization [18].

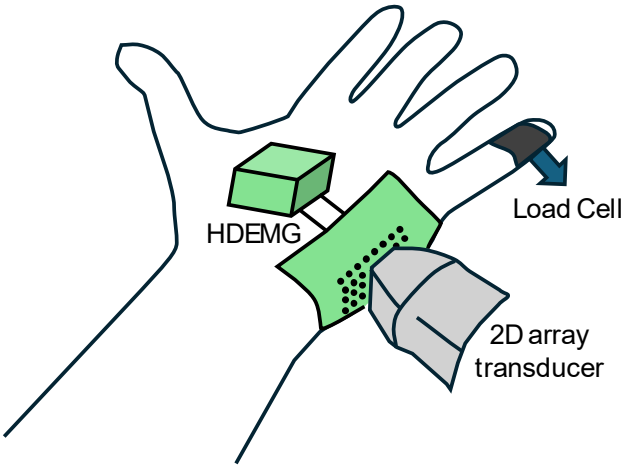

Fig. 1. Experimental setup. The HDEMG grid was positioned over the abductor digiti minimi, with the 4 rows along the longitudinal direction. The ultrasound probe was located over the grid in the central part of the muscle belly. The little finger was secured to a load cell to measure the abduction force.

B. 3D ultrasound imaging

The Verasonics Vantage 256 programmable ultrasound research platform coupled with a 32x32 matrix array transducer (8 MHz center frequency) and the Verasonics UTA 1024-MUX Adapter was used to collect RF data for volume imaging. We acquired a 5-second sequence of volume data at a rate of 500 Hz using full transmission (TX) events involving all 1024 transducer elements. We compared two different modalities of receive apertures (RX). The first was the "standard" BLOCK acquisition, which uses a fixed pattern for receiving signals with blocks of 256 elements, as illustrated in Fig. 2. The second was the SRAC method, which selects 256 transducer elements in a random pattern to generate a composite image (Fig. 2). Four or two RX events (hereafter referred to as 4RX and 2RX) were employed to reconstruct one volume (Fig. 2). The RF data was reconstructed using delay-and-sum beamforming.

C. 3D tissue velocity sequence computation (3D-TVS)

The 3D tissue velocity sequence (3D-TVS) was reconstructed by computing the 2D-autocorrelation [19] with 1 mm maximal displacement in the depth direction and using

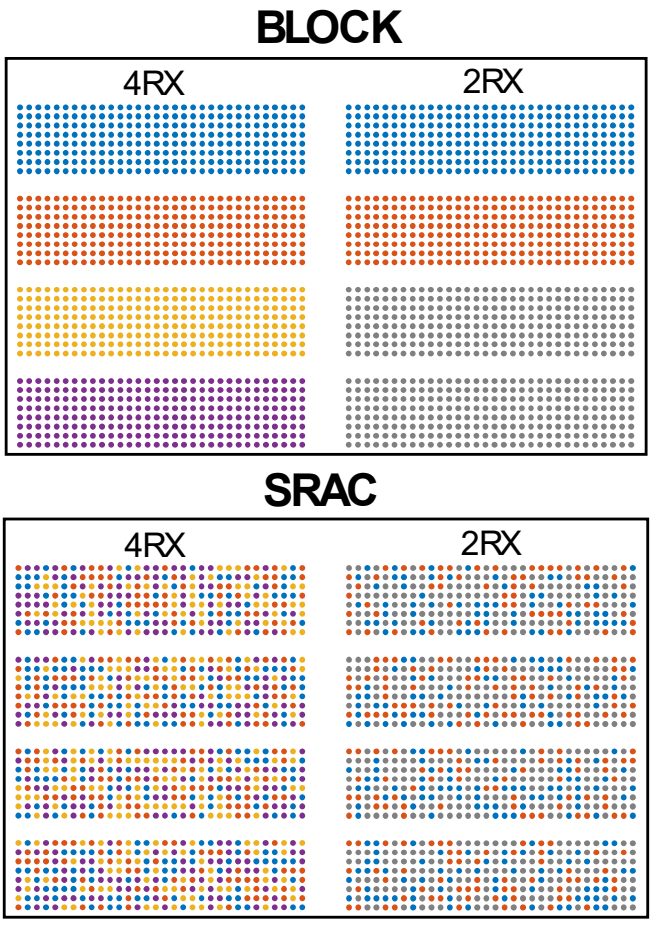

Fig. 2. Examples of receiving pattern of the 2D array elements using the BLOCK and SRAC acquisition modality, considerendi either 4 or 2 receive apertures. The colors represent complementary apertures.

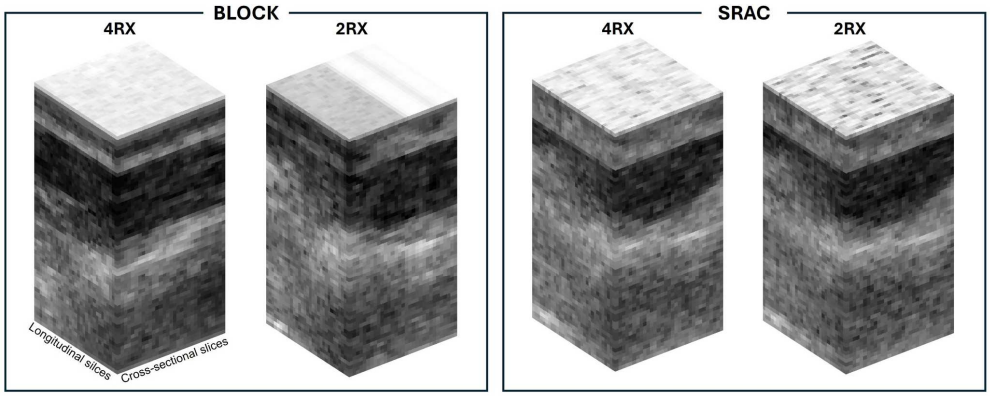

Fig. 3. Example of the B-mode volumes computed with 4 (4RX) or 2 (2RX) receive apertures using the BLOCK and SRAC modality.

two consecutive time samples of all the 32x32 beamformed RFs of all elements. The 3D-TVS sampled ~20 mm in the depth direction and 10 mm in the superficial directions giving a final volume of 64x32x32 voxels.

D. High density electromyography (HDEMG)

Muscle activity was recorded using a grid of 32 electrodes arranged in 8 rows and 4 columns with a 5 mm inter-electrode distance. Before placing the grid, the skin was appropriately prepared to ensure optimal electrode contact and signal quality, as recommended by established protocols [20]. The four rows of the electrode grid were aligned with the longitudinal axis of the ADM to capture the activity for all its accessible surface. Detected signals were amplified and transmitted to a personal computer through a wireless HDEMG amplifier (MEACS, Rec Bioengineering, Turin, Italy) [21]. Single MU activation instants were identified through HDEMG decomposition [17].

E. MU volume identification

By combining the two data sources (3D-TVS and MU activation timing), we were able to reconstruct the muscle volume involved in the displacement of the fibers belonging to single MUs. We analyzed the 3D-TVS in a small volume of interest (VOI of 4x4x4 voxels) spanning the whole volume with 50% overlap. For each VOI, we computed the spike triggered averaging of the average velocity signal of all voxels, obtaining a set of twitches. Computing the average zero-lag correlation between all the twitches, we reconstructed a volume (31x15x15 samples) that highlight regions of MU related motion in 3D (MU volume).

F. Data analysis

The MU volumes obtained from the two modalities of acquisition (BLOCK and SRAC) and the two cases of considered receive apertures for beamforming (4RX and 2RX) were visually inspected for consistency with the fusiform muscle architecture of the ADM. To determine if coherent MU volumes were found, we calculated the signal-to-noise ratio (SNR) considering the cross-sectional slices as follows: the areas showing higher correlation values (>50% of the maximum) were segmented and considered as 'true' signal while the rest of the image (i.e. background) was considered as noise.

III. Results and Discussion

Fig. 3 shows an example of the B-mode images of cross-sectional and longitudinal slices computed with 4 or 2 receives using the BLOCK and SRAC modality. As expected, the contrast is reduced between 4RX and 2RX with no particular differences between the BLOCK and SRAC modalities.

Fig. 4a shows an example of a reconstructed MU volume from the BLOCK acquisition using 4RX, which is consistent with the fusiform muscle architecture of the ADM. In cross-sectional slices, circular territories (black dashed lines) of individual MUs are consistently localized across slices. As expected, in longitudinal slices, MUs territories elongate along the direction of the fibers. The comparison of the central cross-sectional slices (i.e. #8) and the most representative

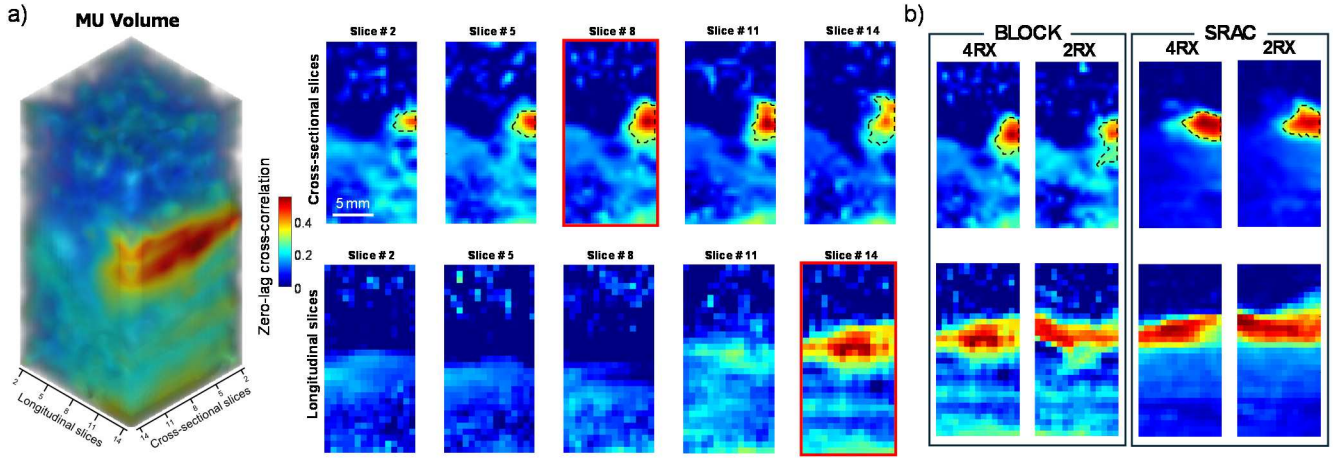

Fig. 4 a) Example of the B-mode images of cross-sectional and a longitudinal slices computed with 4 or 2 receives using the BLOCK modality. b) Comparison of a single slice of the same MU of panel a) (highlighted in red) in one cross-sectional slice (#8) and one longitudinal slice (#14) in all the conditions (BLOCK and SRAC using 4RX and 2RX).

longitudinal slices (i.e. #14) between the two acquisitions and reconstructed both considering 4RX or 2RX is shown in Fig. 4b. Indeed, we were able to identify the similar volume of the same MU between the two contractions used for the BLOCK and SRAC acquisition. In the representative MU of Fig. 2b, we can qualitatively observe that the SRAC volume is less noisy when compared to BLOCK, especially for the 2RX. This fact was corroborated by the average SNR across all cross-sectional slices which was 3.93 and 4.09 for 4RX and 2RX of the BLOCK acquisition, and 6.50 and 6.72 for 4RX and 2RX of the SRAC acquisition.

IV. Conclusion

This study first demonstrates the use of a 2D matrix array with ultrafast ultrasound imaging for single MU volume identification when coupled with HDEMG. No difference between 4 or 2 receives was highlighted, particularly when considering the SRAC aperture; this is important due to the fact that with 2 receives we can reduce the data dimension, optimizing storage and processing capabilities and hence allowing for longer acquisition times or higher frame rates. Although the acquisitions in the BLOCK and SRAC modality consisted of two separate trails, we were able to identify similar volumes related to the same MU as detected by the HDEMG. Future research will focus on assessing the repeatability of MU localizations across different contractions, ensuring consistent results of MU volume identification. This work showcases the potential of this innovative technology and paves the way for future advancements in understanding muscle dynamics.

References

[1] T. Deffieux, J. L. Gennisson, M. Tanter, and M. Fink, "Assessment of the mechanical properties of the musculoskeletal system using 2-D and 3-D very high frame rate ultrasound," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 55, no. 10, pp. 2177–2190, 2008, doi: 10.1109/TUFFC.917.

[2] E. Martinez-Valdes *et al.*, "Modulations in motor unit discharge are related to changes in fascicle length during isometric contractions," *J. Appl. Physiol.*, vol. 133, no. 5, pp. 1136–1148, 2022, doi: 10.1152/japplphysiol.00758.2021.

[3] R. Rohlen, E. Stalberg, K. H. Stoverud, J. Yu, and C. Gronlund, "A Method for Identification of Mechanical Response of Motor Units in Skeletal Muscle Voluntary Contractions Using Ultrafast Ultrasound Imaging - Simulations and Experimental Tests," *IEEE Access*, vol. 8, pp. 50299–50311, 2020, doi: 10.1109/ACCESS.2020.2980053.

[4] R. Rohlén, E. Stålberg, and C. Grönlund, "Identification of single motor units in skeletal muscle under low force isometric voluntary contractions using ultrafast ultrasound," *Sci. Rep.*, vol. 10, no. 1, pp. 1–11, 2020, doi: 10.1038/s41598-020-79863-1.

[5] M. Carbonaro, K. M. Meiburger, S. Seoni, E. F. Hodson-Tole, T. Vieira, and Alberto Botter, "Physical and electrophysiological motor unit characteristics are revealed with simultaneous high-density electromyography and ultrafast ultrasound imaging," *Sci. Rep.*, vol. 12, no. 1, p. 8855, 2022, doi: https://doi.org/10.1038/s41598-022-12999-4.

[6] E. Lubel, B. Grandi Sgambato, D. Y. Barsakcioglu, J. Ibáñez, M. X. Tang, and D. Farina, "Kinematics of individual muscle units in natural contractions measured in vivo using ultrafast ultrasound," *J. Neural Eng.*, vol. 19, no. 5, 2022, doi: 10.1088/1741-2552/ac8c6c.

[7] E. Lubel *et al.*, "Accurate Identification of Motoneuron Discharges From Ultrasound Images Across the Full Muscle Cross-Section," *IEEE Trans. Biomed. Eng.*, vol. 71, no. 5, pp. 1466–1477, 2024, doi: 0.1109/TBME.2023.3340019.

[8] R. Rohlén, M. Carbonaro, G. L. Cerone, K. M. Meiburger, A. Botter, and C. Gronlund, "Spatially repeatable components from ultrafast ultrasound are associated with motor unit activity in human isometric contractions," *J. Neural Eng.*, vol. 20, no. 046016, 2023, doi: https://doi.org/10.1101/2023.04.17.537211.

[9] R. Rohlén, R. Raikova, E. Stålberg, and C. Grönlund, "Estimation of contractile parameters of successive twitches in unfused tetanic contractions of single motor units – A proof-of-concept study using ultrafast ultrasound imaging in vivo," *J. Electromyogr. Kinesiol.*, vol. 67, Dec. 2022, doi: 10.1016/j.jelekin.2022.102705.

[10] J. M. Wakeling *et al.*, "The Energy of Muscle Contraction. I. Tissue Force and Deformation During Fixed-End Contractions," *Front. Physiol.*, vol. 11, 2020, doi: 10.3389/fphys.2020.00813.

[11] A. Fenster, "Three-dimensional ultrasound imaging," Phys. Med. Biol. vol 46, pp R67–R99, 2001, doi: 0031-9155/01/050067+33$30.00.

[12] J. Provost *et al.*, "3D ultrafast ultrasound imaging in vivo," *Phys. Med. Biol.*, vol. 59, no. 19, pp. L1–L13, 2014, doi: 10.1088/0031-9155/59/19/L1.

[13] M. Bernal, B. Cunitz, D. Rohrbach, and R. Daigle, "High-frame-rate volume imaging using sparse-random-aperture compounding," *Phys. Med. Biol.*, vol. 65, no. 17, 2020, doi: 10.1088/1361-6560/ab9372.

[14] J. Yu, H. Yoon, Y. M. Khalifa, and S. Y. Emelianov, "Design of a Volumetric Imaging Sequence Using a Vantage-256 Ultrasound Research Platform Multiplexed with a 1024-Element Fully Sampled Matrix Array," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 67, no. 2, pp. 248–257, 2020, doi: 10.1109/TUFFC.2019.2942557.

[15] M. Carbonaro *et al.*, "Combining high-density electromyography and ultrafast ultrasound to assess individual motor unit properties in vivo," Convegno Nazionale di Bioingegneria, 2023.

[16] M. Carbonaro, S. Zaccardi, S. Seoni, K. M. Meiburger, and A. Botter, "Detecting anatomical characteristics of single motor units by combining high density electromyography and ultrafast ultrasound: a simulation study," *Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. IEEE Eng. Med. Biol. Soc. Annu. Int. Conf.*, vol. 2022, pp. 748–751, 2022, doi: 10.1109/EMBC48229.2022.9871578.

[17] A. Holobar and D. Zazula, "Multichannel blind source separation using convolution Kernel compensation," *IEEE Trans. Signal Process.*, vol. 55, no. 9, pp. 4487–4496, 2007, doi: 10.1109/TSP.2007.896108.

[18] G. L. Cerone, A. Giangrande, M. Ghislieri, M. Gazzoni, H. Piitulainen, and A. Botter, "Design and validation of a wireless Body Sensor Network for integrated EEG and HD-sEMG acquisitions," *IEEE Trans. Neural Syst. Rehabil. Eng.*, 2022, doi: 10.1109/TNSRE.2022.3140220.

[19] T. Loupas, R. W. Gill, and J. T. Powers, "An Axial Velocity Estimator for Ultrasound Blood Flow Imaging, Based on a Full Evaluation of the Doppler Equation by Means of a Two-Dimensional Autocorrelation Approach," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 42, no. 4, pp. 672–688, 1995, doi: 10.1109/58.393110.

[20] R. Merletti and G. L. Cerone, "Tutorial. Surface EMG detection, conditioning and pre-processing: Best practices," *J. Electromyogr. Kinesiol.*, vol. 54, 2020, doi: 10.1016/j.jelekin.2020.102440.

[21] G. L. Cerone, A. Botter, and M. Gazzoni, "A Modular, Smart, and Wearable System for High Density sEMG Detection," *IEEE Trans. Biomed. Eng.*, 2019, doi: 10.1109/tbme.2019.2904398.