

Bioimpedance-Driven Haptic Feedback for Human-Computer Interaction

Tianyang Yao*, Richard Bayford† and Andreas Demosthenous*

*Department of Electronic and Electrical Engineering, University College London, WC1E 7JE, United Kingdom

†Department of Natural Sciences, Middlesex University, NW4 4BT, United Kingdom

Email : {tianyang.yao.22, a.demosthenous}@ucl.ac.uk

Abstract—This work presents a novel method for establishing a feedback loop in future human-computer interactions by using bioimpedance measurements to enhance the sense of physical engagement. The proposed system consists of a bioimpedance measurement unit, a vibration motor, an inertial measurement unit (IMU) and a Bluetooth wireless communication module. By measuring the bioimpedance of flexor digitorum muscles, the system estimates the hand's grasping angle and applied force independently. To address the drift commonly observed in long-term bioimpedance measurements, the rate of change in bioimpedance is used instead of absolute values. The bioimpedance change rate-based method achieved a linear coefficient of determination (R^2) of 0.9845. Vibration motor rotational speed is then modulated in real time based on either the estimated hand grasping angle or force magnitude, depending on the application. The proposed haptic feedback bridges a key limitation of traditional vision-based interaction methods, which are unable to detect force, thereby enabling a more immersive interaction experience. The entire system is implemented as a wearable Bluetooth human interface device (HID), ensuring compatibility with a range of commercial consumer electronics.

Keywords—Bioimpedance measurement, haptic, human-computer interface, vibration feedback.

I. INTRODUCTION

Current human-computer interaction (HCI) methods for virtual reality primarily rely on vision-based tracking [1], [2], including depth sensing [3], and inertial measurement units (IMUs) [4], either individually or in fusion. Although these techniques effectively capture hand motion and position, they lack the capability to perceive the magnitude of force applied by the hand. Force perception, however, is essential for realistic interaction with elastic or deformable objects in virtual environments. In addition, providing haptic feedback near the hand is critical for enhancing the sense of immersion and realism during interaction.

Biosignal-based sensing approaches, such as surface electromyography (sEMG) [5], [6], electroencephalography (EEG) [7], [8], and electrical impedance tomography (EIT) [9], [10], have been widely investigated for HCI applications. Among these, EIT stands out as a non-invasive, radiation-free imaging method that offers a high signal-to-noise ratio (SNR) due to its unique operating principle. EIT functions by injecting a safe level alternating current (typically within the frequency range of 1 kHz to 1 MHz) into the body and sequentially measuring the resulting voltages across an array of electrodes. This modality is particularly well-suited for HCI, with the potential to measure the magnitude of muscle-generated force. However, EIT typically produces inner

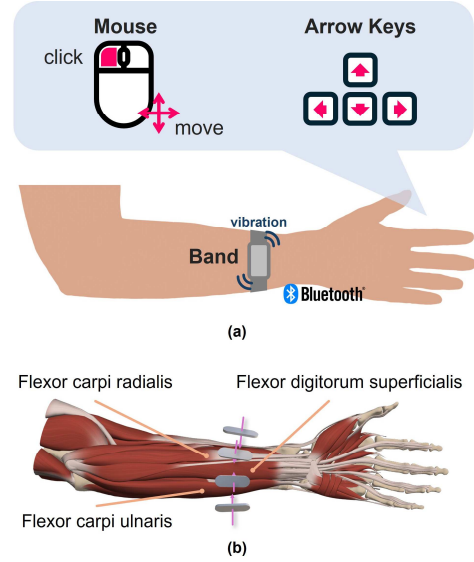


Fig. 1. (a) The function of the proposed wireless bioimpedance-based human-computer interaction system with haptic feedback. (b) The placement of four electrodes near the wrist. The anatomy diagrams sourced from Anatomy.TV [14].

impedance distribution images that require feature extraction through training. The trained models, however, are highly sensitive to electrode placement and contact quality [11].

Bioimpedance measurement, a fundamental operation of EIT, has been validated as an effective approach for estimating multi-degree-of-freedom (DoF) motion of the upper limb [12]. By measuring bioimpedance variations in specific target muscles, corresponding motion angles can be predicted. For single-DoF motion prediction, simple remapping techniques can be employed, leveraging the intuitive relationship between muscle bioimpedance variation and motion. This approach eliminates the need for extensive data collection, regression model re-training, or reliance on high-performance hardware for real-time operation. However, the relationship between the magnitude of applied force and bioimpedance under constant joint angles has not yet been thoroughly explored.

A noticeable gradual drift in the measured impedance values can be observed during prolonged continuous bioimpedance measurements. Contributing factors include electrochemical polarization at the electrode-tissue interface caused by the applied current, variations in skin humidity and temperature, as well as mechanical deformation of the skin. A gradual change identification method is proposed in [13], which is carried out by tracking the relative change in mean of consecutive data windows. A Kalman filter is employed to suppress this gradual change in bioimpedance measurements. However, for wearable applications, a simpler and more

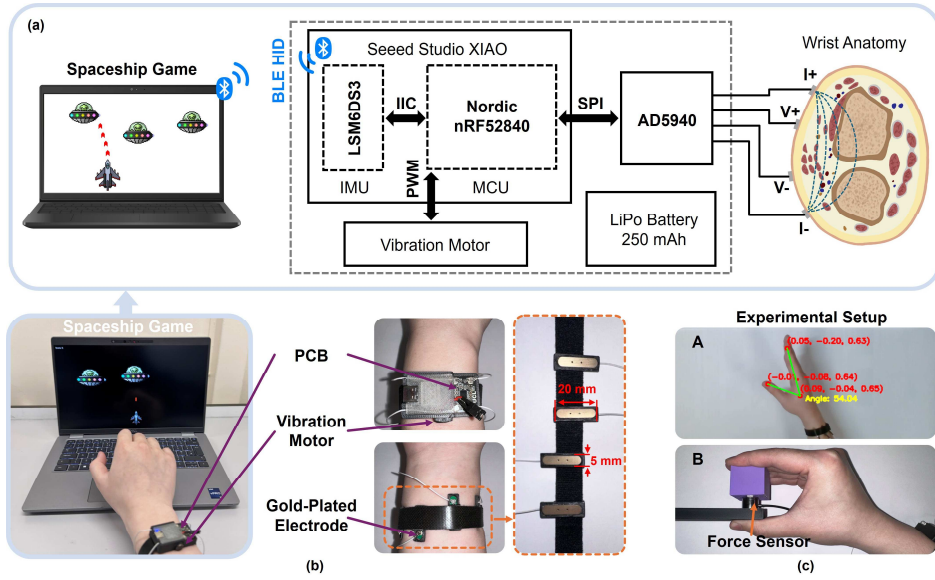


Fig. 2. (a) The system architecture showing the hardware components, including bioimpedance acquisition, inertial sensing, haptic feedback and wireless interaction with a spaceship game. (b) The photos of the designed wearable band, which consists of a PCB, a vibration motor and four gold-plated electrodes. (c) The experimental setups for measuring grasping angle using a depth camera and applied force under fixed posture using a pressure sensor.

efficient drift suppression method is required to enable deployment on low-power microcontrollers.

This paper presents the design and implementation of a wearable band for bioimpedance measurement, integrated with vibration feedback to enhance the realism of user interaction. As shown in Fig. 1(a), when the user wears the band, two distinct functions can be activated depending on different usage scenarios. The first function emulates mouse movement and left-click actions, while the second enables the control of keyboard arrow keys. This work makes the following three contributions: (i) It estimates the applied force or grasping angle by measuring the bioimpedance of target muscles, as shown in Fig. 1(b). (ii) It drives a vibration motor to provide intuitive haptic feedback. (iii) It effectively detects and suppresses drift by applying a moving average filter and imposing a threshold on the rate of bioimpedance change to window the bioimpedance data. The rest of the paper is organized as follows. Section II details the hardware system architecture and its applications in interactive gaming scenarios. Section III presents measured results and analyses the effectiveness of the drift suppression method. Conclusions are drawn in Section IV.

II. PROPOSED SYSTEM ARCHITECTURE

A. Hardware Implementation

Fig. 2(a) presents the system architecture of the proposed wearable band, designed to enable HCI through integrated bioimpedance measurement, inertial sensing and vibration feedback. A Seed Studio XIAO development board with the Nordic nRF52840 microcontroller unit (MCU) is employed for signal processing and wireless communication via Bluetooth Low Energy (BLE) using the HID protocol. An onboard LSM6DS3 IMU interfaces with MCU to provide triaxial acceleration and gyroscope data. AD5940 is an analogue front-end used to perform bioimpedance measurements across the wrist using four gold-plated electrodes. After data processing, the final sample rate is standardised to 30 Hz. Two electrodes inject a 125 kHz ac current, while the other two measure the resulting voltage.

Additionally, the system includes a vibration motor driven by a pulse-width modulation (PWM) signal generated by the MCU for haptic feedback. The entire system is powered by a 250 mAh lithium polymer (LiPo) battery, enabling up to six hours of portable and continuous operation. The photos of the fully assembled wearable band are presented in Fig. 2(b).

The four electrodes are placed on the palmar side of the wrist, focusing on bioimpedance variations in target muscles including flexor carpi radialis, flexor digitorum superficialis and flexor carpi ulnaris, as shown in Fig. 1(b). The flexor carpi radialis and flexor carpi ulnaris are superficial wrist flexor muscles responsible for flexion of the wrist, contributing to radial and ulnar deviation, respectively. The flexor digitorum superficialis plays a key role in finger movement, facilitating flexion at the proximal interphalangeal joints of the second to fifth digits [14]. As a result, the measured bioimpedance can potentially reflect underlying muscle activity related to finger flexion and wrist rotation.

To facilitate comparison with traditional IMU-based HCI methods, a custom *Spaceship Game* was developed as an interactive demonstration. Through gameplay, users can directly experience the difference between conventional IMU-based HCI and a bioimpedance-driven HCI with vibration feedback. By capturing the muscle activity, bioimpedance measurement offers a complementary and potentially substitutive interaction that enhances the expressiveness and adaptability of wearable interfaces.

B. Experimental Setup

Two experimental setups, as shown in Fig. 2(c), were built to investigate the relationship between bioimpedance variations and hand grasping angle as well as applied force. Setup A follows the approach proposed in our previous work [12], where an Intel RealSense D435i depth camera is employed to measure the hand grasping angle while concurrently recording bioimpedance variations. Setup B utilises a rigid SIMBATOUCH SBT674 force sensor to measure the magnitude of normal force applied to the 3D-printed structure, with the hand posture held constant throughout the measurement.

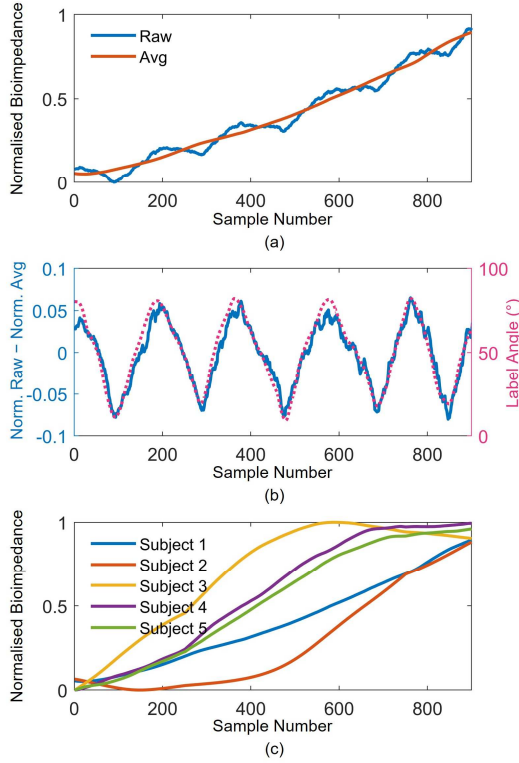


Fig. 3. (a) Raw data along with the corresponding moving average computed using a window size of 200 samples. (b) The drift-removed data together with the label angle captured by depth camera. (c) Extracted drift components from the raw data of five subjects.

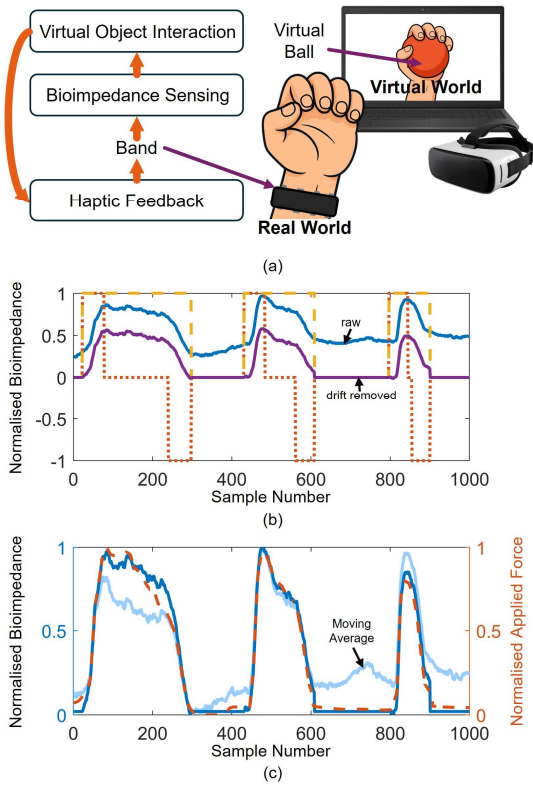


Fig. 4. (a) Bioimpedance-driven interactive loop between real-world user and virtual object with haptic feedback. (b) Bioimpedance windowing and drift removal based on the rate of bioimpedance change. (c) Comparison between the bioimpedance rate-based method and the moving average method, together with the applied force magnitude.

C. Bioimpedance Drift Suppression

The drift in bioimpedance measurement typically occurs at a slow rate. This low-frequency component can be extracted using methods such as low-pass filtering or moving average. Additionally, applying a threshold to the rate of bioimpedance change then windowing the bioimpedance and removing the bias can suppress slow drift. The detailed performance of drift extraction and suppression is presented in the following section.

III. MEASURED RESULTS

Five subjects were invited to attend these experiments to measure the bioimpedance variation on target muscles. Approval for all ethical and experimental procedures and protocols was granted by the University College London Humanities, Arts and Sciences (HAS) Research Ethics Committee on September 9, 2024 (Project ID: 26247/001).

The first experiment investigates the variation of bioimpedance with different grasping angle using setup A. As shown in Fig. 3(a), the raw data of bioimpedance from one subject exhibits a noticeable drift over time. By applying a moving average with a window size of 400, the drift trend can be effectively extracted. After removing the extracted drift, the bioimpedance data aligns closely with the grasping angle measured by the depth camera, yielding a linear coefficient of determination (R^2) of 0.9173, as shown in Fig. 3(b). Fig. 3(c) illustrates the drift extracted bioimpedance raw data across all subjects.

The second experiment, conducted with setup B, explores the response of bioimpedance to applied force under fixed grasping angle. It establishes an interactive loop to generate haptic feedback to interact with virtual objects, as shown in Fig. 4(a). Since the force needs to be continuously applied over a long period during interaction, the moving average method does not work. Therefore, a threshold $0.5 \Omega/s$ is applied to the absolute value of the bioimpedance change rate to detect transitions, as indicated by the orange dotted line in Fig. 4(b). Based on the detected transitions, valid segments of bioimpedance variation are subsequently identified, as marked by yellow dashed line. As shown in Fig. 4(c), the bioimpedance rate-based method provides a closer fit to the measured force compared to the moving average method. Quantitatively, it achieves a linear R^2 of 0.9845 with respect to applied force labels across five subjects, significantly outperforming the moving average method, which yields a linear R^2 of 0.8203.

IV. CONCLUSION

This paper proposed a wearable system that use bioimpedance measurement to enable HCI with integrated haptic feedback. By estimating hand grasping angle or applied force from bioimpedance variations of target muscles, the system establishes a real-time feedback loop through vibration actuation. To mitigate bioimpedance drift inherent in long-term measurements, a bioimpedance rate-based and a moving average method were investigated to improve the reliability of the interaction. Additionally, the Bluetooth HID implementation supports a wide range of consumer devices, enabling potential development of future immersive interactive applications.

REFERENCES

- [1] 'Apple Vision Pro - Apple (UK)'. Accessed: Jun. 08, 2025. [Online]. Available: <https://www.apple.com/uk/apple-vision-pro/>
- [2] 'Meta Quest 3: Mixed reality VR headset – Shop now'. Accessed: Jun. 08, 2025. [Online]. Available: <https://www.meta.com/gb/quest/quest-3/>
- [3] J. Liu, G. Wang, P. Hu, L.-Y. Duan, and A. C. Kot, 'Global context-aware attention LSTM networks for 3D action recognition', in *2017 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, Jul. 2017, pp. 3671–3680.
- [4] H. P. Gupta, H. S. Chudgar, S. Mukherjee, T. Dutta, and K. Sharma, 'A continuous hand gestures recognition technique for human-machine interaction using accelerometer and gyroscope sensors', *IEEE Sens. J.*, vol. 16, no. 16, pp. 6425–6432, Aug. 2016.
- [5] A. Furui *et al.*, 'A myoelectric prosthetic hand with muscle synergy-based motion determination and impedance model-based biomimetic control', *Sci. Robot.*, vol. 4, no. 31, p. eaaw6339, Jun. 2019.
- [6] J. M. Hahne, M. A. Schweisfurth, M. Koppe, and D. Farina, 'Simultaneous control of multiple functions of bionic hand prostheses: performance and robustness in end users', *Sci. Robot.*, vol. 3, no. 19, p. eaat3630, Jun. 2018.
- [7] M. S. Fifer *et al.*, 'Simultaneous neural control of simple reaching and grasping with the modular prosthetic limb using intracranial EEG', *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 22, no. 3, pp. 695–705, May 2014.
- [8] M. R. Carneiro, A. T. de Almeida, and M. Tavakoli, 'Wearable and comfortable e-textile headband for long-term acquisition of forehead EEG signals', *IEEE Sens. J.*, vol. 20, no. 24, pp. 15107–15116, Dec. 2020.
- [9] E. Zheng, Y. Li, Z. Zhao, Q. Wang, and H. Qiao, 'An electrical impedance tomography based interface for human-robot collaboration', *IEEEASME Trans. Mechatron.*, vol. 26, no. 5, pp. 2373–2384, Oct. 2021.
- [10] Y. Wu, D. Jiang, X. Liu, R. Bayford, and A. Demosthenous, 'A human-machine interface using electrical impedance tomography for hand prosthesis control', *IEEE Trans. Biomed. Circuits Syst.*, vol. 12, no. 6, pp. 1322–1333, Dec. 2018.
- [11] S. Yoshimoto, Y. Toyoda, and A. Yamamoto, 'Influence of electrode positions on performance of hand motion capture using EIT', *IEEE Trans. Med. Robot. Bionics*, vol. 4, no. 1, pp. 285–288, Feb. 2022.
- [12] T. Yao, Y. Wu, D. Jiang, R. Bayford, and A. Demosthenous, 'Forearm motion and hand grasp prediction based on target muscle bioimpedance for human-machine interaction', *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 33, pp. 760–769, 2025.
- [13] K. Dheman, P. Mayer, M. Eggimann, M. Magno, and S. Schuerle, 'Towards artefact-free bio-impedance measurements: evaluation, identification and suppression of artefacts at multiple frequencies', *IEEE Sens. J.*, vol. 22, no. 1, pp. 589–600, Jan. 2022.
- [14] 'Anatomy.tv home'. Accessed: Jun. 08, 2025. [Online]. Available: <https://www.anatomy.tv/titles>