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Short Communication - A Comparative Physiological and Technical Evaluation of Skull Micro-Movement Detection Using Dual Mechanical Actuators and Flat Eddy-Current Sensor Systems: Toward a Standardized Framework for Cranial Micro-Oscillation Measurement in Humans

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Abstract: This short communication presents the first comparative analysis of two foundational skull micro-movement detection systems: dual mechanical actuators and flat eddy-current sensors. By synthesizing their technical performance, physiological findings, and limitations, the paper highlights how both systems consistently identify low-frequency cranial oscillations while offering complementary strengths in precision and artefact reduction. The communication proposes an integrated methodological framework that combines high-resolution displacement tracking with effective respiratory subtraction, offering a novel and standardized approach for future research on cranial micro-movements.

Keywords: Skull; Physiology; Cranial Sutures; Head Movements

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Objective detection of human cranial micro-movements has been historically difficult due to their extremely small amplitude, low frequency, and the challenge of separating true biological oscillations from breathing and artefactual head motion. Nonetheless, the existence of periodic skull micro-oscillations has been supported by two independent lines of experimental evidence. The first major system, described by Danish Fundamental Metrology, used two precisely calibrated mechanical actuators capable of detecting displacements at 1 µm resolution and a measurement range of 10,000 µm. These actuators, positioned bilaterally on either side of the skull, allowed measurement of both individual displacement signals and composite signals—specifically, the sum (expansion-like movement) and difference (shear or whole-head motion). Fast Fourier Transform (FFT) analysis revealed periodic micro-oscillations in resting subjects, with observed amplitudes up to 200 µm and dominant frequencies between ~6–12 cycles per minute. The system demonstrated excellent mechanical stability, minimal intrinsic noise, and high reliability during static object testing. Its dual-actuator configuration allowed physiological disambiguation between expansion and translation, offering a strong technical basis for precise cranial micro-movement detection [1].

The second system, developed earlier using flat eddy-current proximity sensors, provided a contact-free method to detect variation in sensor–target distance. The sensor functioned as an oscillator whose frequency shifted in proportion to changes in cranial distance. Importantly, a second identical sensor was placed near the clavicle to record respiratory movement, enabling spectral subtraction to isolate cranial signals. Testing on approximately 100 healthy subjects demonstrated rhythmic micro-movements with amplitudes of 20–50 μm and mean frequency of 9.7 cycles per minute. The system confirmed that these oscillations were distinct from breathing and suggested arteriolar vasomotion as a physiological contributor, based on similar oscillations detected in the hand [2].

Despite these advances, there remains no unified methodological framework that integrates the strengths of both systems. The mechanical actuator approach provides high spatial resolution and directional specificity, whereas the eddy-current approach provides practical non-contact measurement and strong respiratory artefact removal. No comparative analysis has systematically examined these complementary characteristics or developed a consolidated set of measurement principles for future cranial micro-movement research.

This article addresses this gap by synthesizing the technical and physiological insights from both systems and proposing a unified, standardized framework that can guide future clinical, physiologic, and neurobiomechanical research involving cranial micro-oscillations.

Methods

This article does not present new experimental data but provides a structured comparative evaluation of two existing measurement technologies. The evaluation is based on a comparative analytical methodology based exclusively on the technical descriptions, empirical observations, and methodological procedures outlined in the two reference systems for detecting cranial micro-movements. The first measurement approach, developed by Danish Fundamental Metrology, utilizes dual mechanical actuators capable of resolving linear displacements at a precision of 1 μm and recording movements within a range of 10,000 μm. The system provides bilateral measurements that enable calculation of both individual displacement values and composite outputs such as sum and difference signals, which allow differentiation between skull expansion and whole-head translational movements. Fast Fourier Transform (FFT) analysis is applied to 1024-point rolling data windows, corresponding to approximately 51 seconds of recorded measurements, thereby allowing extraction of dominant oscillatory frequencies. The second measurement approach, described in the IEEE study, employs flat eddy-current proximity sensors functioning as oscillators whose frequencies vary according to changes in sensor–target distance. A secondary sensor is used to capture respiratory motion, enabling digital subtraction of respiratory peaks from cranial data and improving spectral purity of the resulting cranial micro-movement signal.

The comparative method used in this paper synthesizes the technical properties, operational procedures, and physiological observations of both systems. Attention is given to measurement resolution, noise behavior, calibration demands, and sensitivity to artefact such as breathing, posture, and sensor alignment. The analysis also integrates the physiological frequency bands reported by each system, particularly the low-frequency skull oscillations in the approximate range of 6–12 cycles per minute. Limitations inherent to both approaches such as the actuator system's need for physical contact and alignment precision, and the eddy-current system's sensitivity to drift in target distance are critically examined to establish methodological complementation. These combined insights are used to construct a unified framework, drawing on the actuator system's directional measurement logic and FFT structure, and the eddy-current system's respiratory subtraction technique, to propose an integrated set of principles for standardized cranial micro-movement measurement in future research.

Results

The comparative analysis of the two measurement systems revealed that both technologies independently demonstrated the presence of rhythmic cranial micro-movements in humans, typically occurring within a low-frequency physiological range of approximately 6–12 cycles per minute. The dual mechanical actuator system exhibited high spatial resolution, detecting linear skull displacements with a precision of 1 μm across a measurement span of 10,000 μm. Human testing showed that this system recorded micro-movement amplitudes as large as 200 μm, with the bilateral arrangement allowing clear separation between cranial expansion-like oscillations and lateral head movements through the use of sum and difference signals. Across static object testing and mechanical simulation using a rotation table, the actuator system demonstrated excellent stability and minimal noise, validating its capacity to detect very small amplitude changes. Application of Fast Fourier Transform (FFT) analysis further confirmed distinct frequency peaks corresponding to skull micro-oscillations, breathing, and cardiac-related components, providing high spectral clarity.

In contrast, the flat eddy-current sensor system produced a non-contact means of measuring cranial micro-movements and demonstrated sensitivity to displacement amplitudes within the range of 20–50 μm. When applied to approximately 100 healthy individuals, this system consistently detected a mean oscillation frequency of 9.7 cycles per minute at the cranial surface. The incorporation of a secondary sensor placed near the clavicle allowed effective identification and subtraction of respiratory artefacts, which typically occurred around 20–30 cycles per minute. Through this spectral subtraction technique, the system was able to isolate the cranial frequency peak with considerable clarity, confirming that the observed oscillations were independent of respiration. The system also revealed the presence of similar oscillatory frequencies in the hand, supporting the interpretation that the movements could be influenced by arteriolar vasomotion.

Taken together, these results demonstrate that the mechanical actuator system offers superior spatial resolution and directional specificity, whereas the flat eddy-current system provides practical non-contact measurement with effective physiological artefact suppression. Both systems converge in detecting consistent low-frequency cranial oscillations, yet they differ in amplitude detection, susceptibility to noise, and methodological constraints. Their complementary strengths suggest that an integrated approach combining precision displacement tracking, bilateral differentiation, and respiratory subtraction could provide a more comprehensive and standardized method for future research on cranial micro-oscillations.

Discussion

The findings of this comparative analysis demonstrate that both mechanical actuator and flat eddy-current sensor systems provide credible, mutually reinforcing evidence for the presence of rhythmic cranial micro-movements in humans. Despite relying on different physical measurement principles, the two systems converge on a similar physiological frequency range, suggesting that the detected oscillations represent a genuine biological phenomenon rather than artefactual noise. The mechanical actuator system offers high-precision displacement measurement and the unique ability to distinguish cranial expansion from whole-head translation through bilateral signal interpretation. In contrast, the eddy-current sensor system, while less precise in amplitude detection, offers a practical non-contact method with effective respiratory artefact suppression through spectral subtraction. Together, these complementary strengths highlight the potential value of integrating the methodological features of both systems to establish a more robust, standardized protocol for future investigations. Such an approach could enhance measurement reliability, reduce artefacts, and provide a unified framework for clinical and physiological research exploring subtle cranial dynamics.

Conclusion

Mechanical actuator and flat eddy-current sensor systems each independently verify that the human skull exhibits small, rhythmic micro-movements. Their methodological integration combining precision displacement tracking, bilateral differentiation, non-contact feasibility, and respiratory spectral subtraction provides a robust foundation for future standardized measurement approaches. This combined framework can accelerate physiologic research and clinical applications where subtle cranial dynamics may hold diagnostic or mechanistic relevance.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Reference

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