HiveGuard: Honeycomb-Structured Helmet with Embedded EEG System

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***Abstract*—We present HiveGuard, a wearable helmet that integrates a honeycomb structure for impact absorption with a multi-channel EEG system for real-time monitoring. EEGConvTrans, a lightweight CNN–Transformer hybrid model, runs directly on-device to reduce latency and provide immediate feedback. By integrating structural protection with edge intelligence, HiveGuard demonstrates how wearable systems can deliver both safety and cognitive assessment in a single deployable solution.**

***Index Terms*—EEG, wearable, deep learning, honeycomb**

I. Introduction

Concussions, a mild form of traumatic brain injury (TBI), frequently affect adolescent athletes in contact sports. They result from a direct blow to the head or sudden motion of the brain and may induce headaches, dizziness, and in some cases loss of consciousness [4, 5]. Recent studies[7] show that adolescents aged 10–19 represent the highest proportion admitted to emergency departments for sports-related head injuries, highlighting the need for improved helmet design and real-time concussion monitoring. Traditional helmets use expanded polystyrene foam liners that are effective in reducing linear impacts but less effective at rotational or oblique forces [6, 8]. Graded honeycomb layers improve dissipation but often transmit larger residual forces, raising safety concerns [2]. In parallel, wearable EEG technology enables real-time brain activity tracking during movement [3, 10]. Recent advances in deep learning have further enhanced EEG analysis in tasks such as sleep staging and emotion recognition [9, 11].

Building on these developments, we propose HiveGuard, a helmet that integrates a honeycomb structure for impact dispersion, a multi-channel EEG system for brain monitoring, and an on-device inference pipeline for real-time assessment. By processing EEG signals at the edge, HiveGuard reduces latency and provides immediate feedback, combining impact protection with proactive monitoring in one deployable system.

II. HiveGuard Design

HiveGuard consists of three main features: honeycomb structure, EEG system, and real-time inference.

A. Helmet Structure

As shown in Fig.1, a honeycomb structure is incorporated to improve impact absorption and minimize weight. The surface of the helmet is covered by hexagonal cells, with tighter patterns in high-risk areas (crown/lateral) to achieve optimum energy absorption and airflow. A protective compartment accommodates the EEG electronics, shielding the circuit boards, allowing for effective wire routing, while ensuring a secure and accessible mount, as shown in Fig.2.

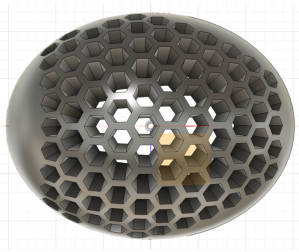


Fig. 1: Honeycomb pattern.

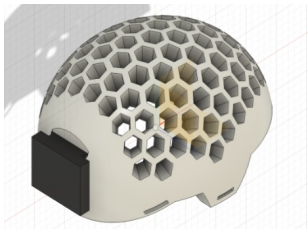


Fig. 2: Optimized design.

B. EEG System

The EEG signal chain consists of electrode leads with electrostatic discharge (ESD)/electromagnetic interference (EMI) protection, analog pre-conditioning, a multi-channel Δ–Σ ADC, and an embedded controller. Low-capacitance ESD arrays and passive low-pass filters stabilize inputs, while the LH00199 analog front end provides eight simultaneous 24-bit channels with sufficient resolution for non-invasive EEG. An ESP32-S3 microcontroller handles synchronization, buffering, and wireless telemetry. Power is supplied by a Li-ion cell, with separate analog and digital rails from low-noise regulators. Optimized for motion environments, the system balances safety, fidelity, and portability, enabling continuous multi-channel monitoring and real-time inference at the edge.

C. Real-time Inference System

We developed EEGConvTrans, a compact hybrid model optimized for edge deployment in the helmet, which provides immediate feedback without cloud reliance while maintaining low latency.

TABLE I: Task taxonomy with labels.

Task	Labels
Attention/Emotion	Focused, Difficulty, Unable
Speech Fluency	Fluent, Disfluent, Blocked
Finger Tapping	Normal, Medium, Abnormal
Breathing	Normal, Medium, Abnormal

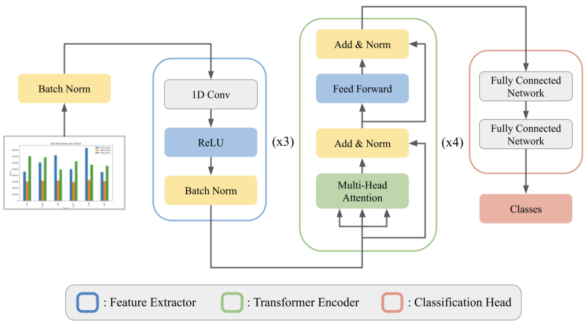


Fig. 3: EEGConvTrans architecture overview.

Task Taxonomy. On-device cognitive assessment is evaluated through four categories (Table I) associated with concussion risk: attention/emotion, speech fluency, finger tapping, and breathing. Each category contains three levels (normal, impaired, abnormal).

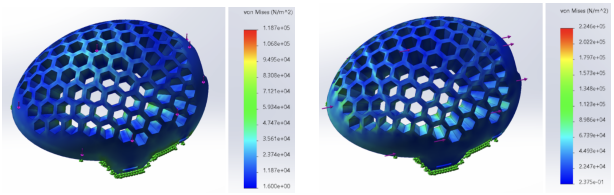
EEGConvTrans Architecture. The EEGConvTrans (Fig. 3) takes a normalized EEG window and applies a lightweight 1D-CNN feature extractor (three conv–ReLU–BN blocks) to map channels into a latent dimension. A transformer encoder then processes the resulting sequence by capturing long-range dependencies. Global average pooling is applied over time to produce a fixed-length representation that is passed through a two-layer classification head with ReLU and dropout, projecting to multiple classes. Optimized for edge computing, the design constrains parameters to support real-time inference on the device.

III. Demonstration Highlights

We evaluate *HiveGuard* across (i) structural safety and impact reduction, and (ii) multi-task classification with the proposed *EEGConvTrans*. In the live demonstration, we will exhibit the physical prototype of the HiveGuard and showcase its embedded EEG-based on-device inference across four task families.

A. Helmet Impact and Structural Evaluation

We compared 3D-printed samples (solid, circular, honeycomb) using a controlled drop test with a 303 g steel ball and thin-film pressure sensing. The results showed that the honeycomb sample absorbed the most force horizontally and vertically ($\sim$ 190 N), outperforming circular ($\sim$ 210 N) and solid ($\sim$ 215 N) samples. In addition, we performed finite-element analysis (FEA) for two load cases (top-down and front-to-back) with



(a) Top-down force. (b) Front-to-back force.

Fig. 4: Von Mises stress distributions tests.

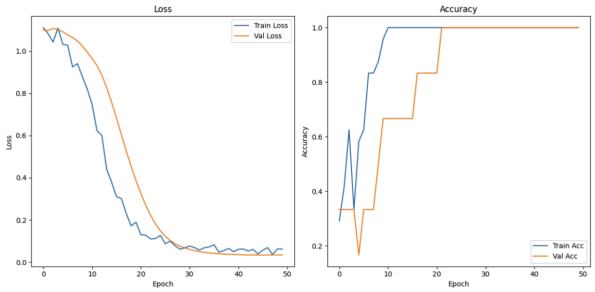


Fig. 5: Attention/emotion task: loss and accuracy.

a 500 N applied force, and studied the distributions of von Mises stress. The simulations showed uniform stress distributions in top-down (Fig. 4a) impacts but localized concentrations of high stress at the honeycomb edges with front-to-back force (Fig. 4b). These results confirm the honeycomb structure's energy-dissipating advantage.

B. Classification Results with EEGConvTrans

To demonstrate on-device utility, we trained EEGConvTrans separately across four task families (Table I). The lightweight edge model achieved fast convergence and high accuracy on attention/emotion and speech, both stabilizing above 90–95% with minimal overfitting, as shown in Fig. 5. Finger tapping showed higher variance across sessions, and breathing remained the most challenging, plateauing near 80% accuracy (detailed results are in [1]). These results highlight the trade-offs of real-time edge inference, showing strong performance on cognitive and language tasks but greater variability for subtle motor and physiological states. Overall, the results confirm that EEGConvTrans can deliver reliable multi-class classification directly inside the helmet, balancing accuracy and efficiency for immediate feedback.

IV. Conclusion

HiveGuard demonstrates the potential of edge computing by delivering low-latency feedback without cloud reliance, integrating a honeycomb structure for impact absorption, a motion-optimized EEG system, and the EEGConvTrans model for on-device inference. The results show strong accuracy in cognitive and speech-related tasks, while highlighting challenges in motor and respiratory states.

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