Helmet-Integrated Flexible-Hybrid Electronics for Field Measurement of Head Kinematics in Military Training

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Key Message

Helmet-integrated sensing progressed from controlled validation to successful TOEE field data capture; the next step is optimizing helmet-to-head coupling so field measurements can be interpreted with confidence.

Introduction: Why Measure Head Kinematics?

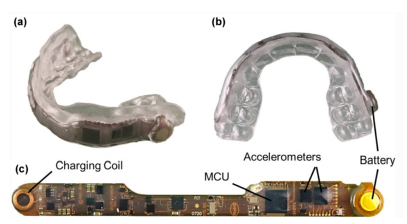
mTBI risk assessment needs motion histories, not only event labels.

Motivation

- **Military relevance:** Training and operational environments expose Service Members to blunt impact, vehicle motion, and blast-related loading.
- **mTBI challenge:** Symptoms may be subtle, delayed, or underreported, making objective exposure context valuable for medics.
- **Kinematic need:** Linear and rotational head acceleration histories support injury-risk metrics and event reconstruction.
- **Current gap:** Many wearable systems either interfere with communication/workflow or suffer from helmet-to-head and skin-coupling errors.
- **Design premise:** Put the sensor package into equipment already worn, then test whether the data remain usable outside the lab.

Previous work and limitation

- **Mouthguard:** Can be accurate but may interrupt communication in military training.
- **Skin-mounted patches:** Unobtrusive for operations, but data quality is often degraded by skin-slip artifacts.

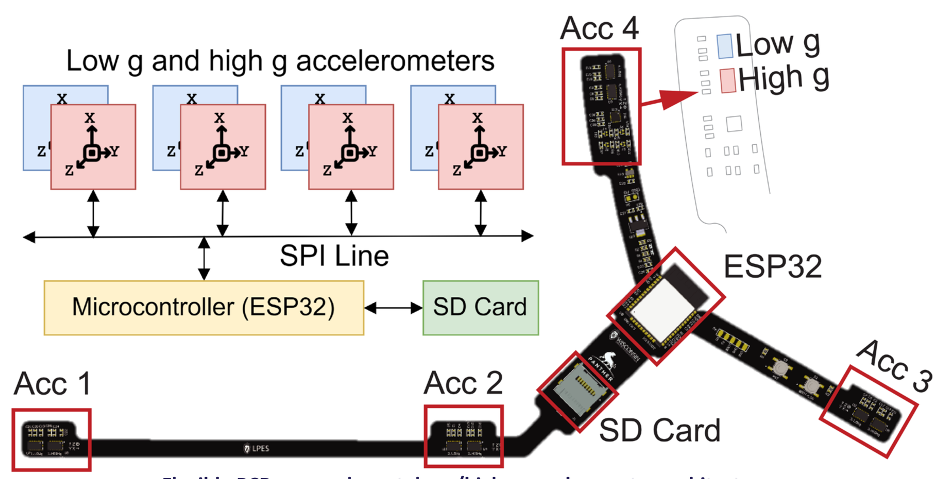


Mouthguard approaches

Skin -mounted xPatch

System Design

Flexible printed circuit board with multiple tri-axial linear accelerometers

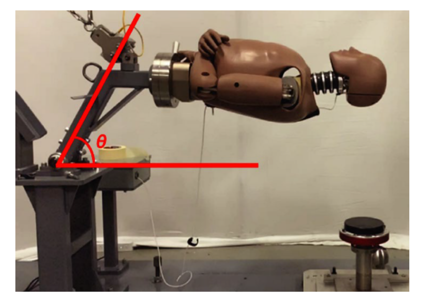


Flexible PCB, sensor layout, low-/high-g accelerometer architecture

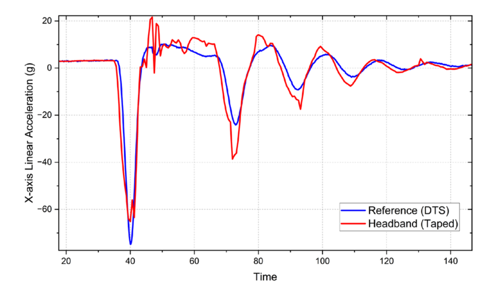
- **Sensor array:** 8 triaxial accelerometers arranged as 4 paired sensing locations.
- **Dynamic range:** ADXL345 low-g channels support routine motion below 16 g; ADXL375 high-g channels capture larger events approaching 200 g.
- **Sampling:** Firmware records high-rate data for impact waveform shape, not only peak values.
- **Computation:** The Acceleration-Only (AO) algorithm estimates head kinematics without gyroscopes.
- **Packaging:** Flexible-hybrid electronics support low-profile routing into a liner rather than a bulky add-on sensor.
- **Field output:** Raw and AO-processed traces can be reviewed for event timing, impact peaks, and motion signatures.

Ideal Testing: Skin-Coupled Validation

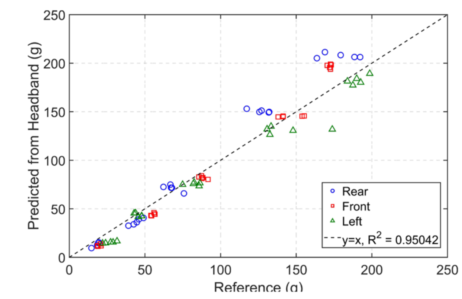
Sensor tested via directly coupled scenario using adhesives on an instrumented head form.



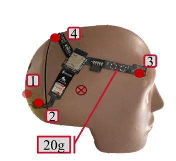
DREW impact rig



Waveform agreement



Peak summary across impact conditions



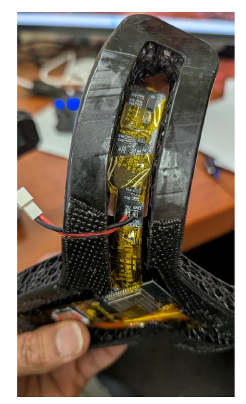
- **Setup:** Bare PCB adhered directly to HYBRID III skin.
- **Impacts:** Front, rear, and left directions across multiple magnitudes.
- **Range:** Low-g conditions below 16 g through events near the 200 g sensing range.
- **Metric:** CORrelation and Analysis (CORA) compared sensor waveforms with reference data.
- **Result:** Average CORA scores were rear 0.840, front 0.883, left 0.832; individual trials reached 0.98.

Test Conclusion: The electronics and AO workflow performed well under controlled coupling, justifying the harder helmet-integration step.

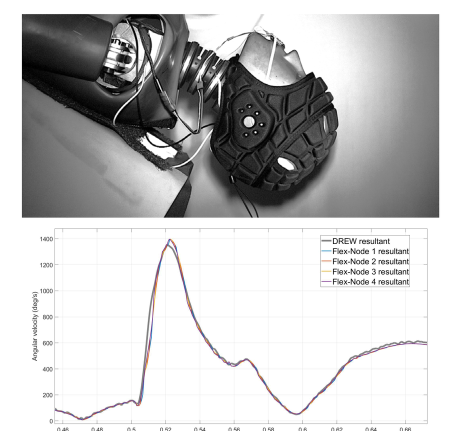
Helmet Integration: Preliminary Helmet Testing

A 3D-printed lattice liner supported helmet integration; preliminary DREW testing explored sensors on a skull-cap / flag-football-helmet setup.

3D-printed lattice liner



Embedded sensor routing



Preliminary DREW helmet test + response plot

- **Lattice integration:** Sensor pockets in the lattice pads preserve the AO sensor geometry.
- **Helmet transition:** Testing moves from skin-coupled PCB validation to helmet-worn sensing.
- **Whiplash test:** In the DREW flag football helmet setup over an instrumented skullcap, all four sensors followed the reference trend.
- **Operational fit:** Helmet integration avoids an extra wearable while staying close to real use.

Design takeaway: Move from liner integration toward a skull-cap sensor platform inside the helmet.

Field Testing: Technology Operational Experimentation Exercise (TOEE)

TOEE 25.1 and 25.2 tested vehicle motion, workflow, fit, and field data capture.

TOEE 25.1

- **Litter:** Instrumented helmet loaded onto a 7-ton vehicle.
- **Route:** Lap around TLZ Robin over bumpy field terrain.
- **Data:** Shows loading, ride vibration, and unloading peaks.

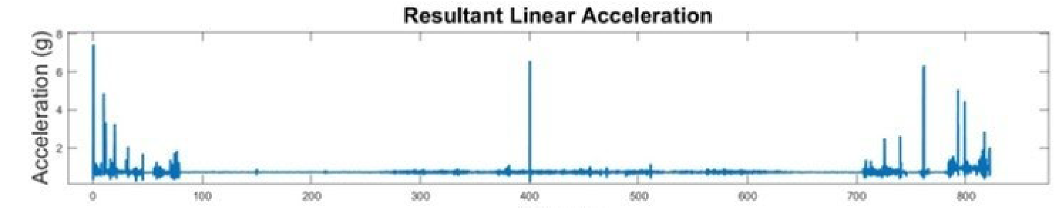
TOEE 25.2

- **Human-worn:** Helmet worn by a passenger in a military vehicle.
- **Condition:** Bumpy-field vehicle motion tested real fit.
- **Outcome:** System successfully recorded usable head kinematics indused from vehicle-motion data.

TOEE 25.1: dummy/litter on 7-ton truck

TOEE 25.2: human-worn helmet in vehicle

Resultant Linear Acceleration



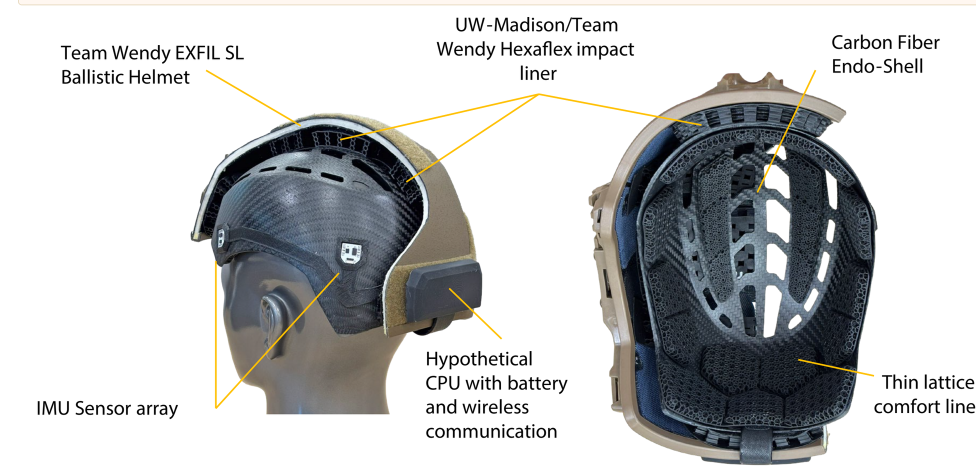
AO-processed acceleration trace: loading, ride motion, unloading

Marine and medic feedback

- **Integrated + comfortable:** Helmet-based sensing was preferred over another wearable.
- **Ease of use:** On-helmet manual trigger, clear status, and battery life matter.
- **Operational value:** Objective data can help medics when symptoms are absent or underreported.

Next Steps: Skull-Cap Integration and Coupling-Aware Correction

Continue progression on the skull-cap concept with helmet integration and slip measurement.



Next Concept

Helmet slip sensing / coupling correction

- **ENDO-SHELL platform:** Mount sensors to an inner carbon-fiber skull cap rather than the external ballistic shell.
- **Reduced decoupling:** Keep the sensing reference closer to the wearer to improve kinematic interpretation.
- **Lattice interface:** Integrate a 3D-printed comfort/impact liner between shell and skull cap.
- **Sensor geometry:** Preserve rigid sensor-to-sensor spacing for AO reconstruction.
- **Coupling correction:** Use slip sensing or confidence flags when helmet and head motion diverge.
- **Usability:** Keep the package unobtrusive, vented, and practical for helmet wear.

Next aim: Integrate the skull-cap sensor platform inside the helmet and quantify coupling before field interpretation.

Conclusion: Achievements and Key Challenges

The system has moved from controlled validation to helmet-based preliminary testing and field data capture.

Achievements so far

- **Validated sensing:** Ideal HYBRID III testing showed strong waveform agreement and CORA scores up to 0.98.
- **Helmet translation:** Electronics were integrated into a 3D-printed lattice liner while preserving sensor geometry.
- **Field recording:** TOEE 25.1/25.2 captured usable helmet-mounted acceleration data during dummy/litter and human-worn vehicle testing.
- **User relevance:** Marine and medic feedback supported integrated sensors and objective exposure data.

Key challenges before interpretation

- **Coupling:** Quantify helmet-to-head slip during real motion.
- **Workflow:** Simplify trigger, status, charging, and data retrieval.
- **Validation:** Repeat controlled and field tests with synchronized event notes.
- **Translation:** Convert recorded kinematics into trustworthy exposure context for medics and researchers.

Bottom line: The platform records in realistic testing; the next work is skull-cap integration plus coupling-aware interpretation.

Acknowledgment

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