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Towards Data Driven Soldier Readiness Assessment and Injury Prevention using Longitudinal Activity and Musculoskeletal Injury Monitoring

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DISCLOSURE
Omer T. Inan, Co-Principal Investigator on this research, is a co-founder, board member, and chief scientific advisor for Arthroba, Inc.

Introduction

Musculoskeletal injury from high training loads is a frequent challenge in military populations and athletes. In 2025, the Georgia Tech Research Institute (GTRI) performed a longitudinal field study of NCAA Division I distance runners to identify objective markers of training load and physiological measures linked to self-reported injury. Subjects were assessed across **Spring (N=19)** and **Fall (N=11)** 2025 training seasons using multiple sensing modalities: cardiovascular, inertial, and location data (Garmin watches, HIPS (Heat Injury Prevention System) chest sensors) during outdoor sessions. Bi-weekly in-lab joint bioimpedance, knee acoustic emissions were measured with custom sensors, and countermovement jumps (CMJ) using Sparta force plates (Spring only). Participants self-reported weekly mileage, exertion, pain, and injury.

These measurements were utilized to address **4 overarching research questions:**

R1 — **Is it possible to predict and model athletic fitness progression by leveraging wearable sensors measurements taken longitudinally across training seasons?**

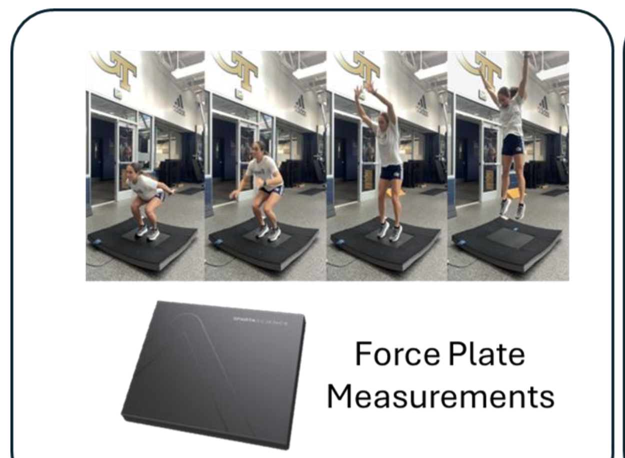
R2 — **Is it possible to predict real work metabolic efficiency based on a laboratory baseline and real-time physiological measurements?**

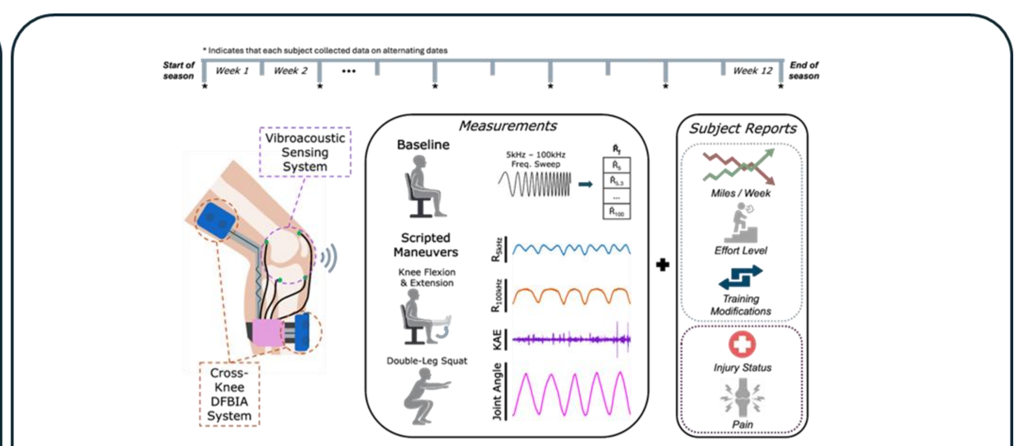
R3 — **Is it possible to evaluate and predict lower limb musculoskeletal injuries using joint data collected during controlled movement exercises?**

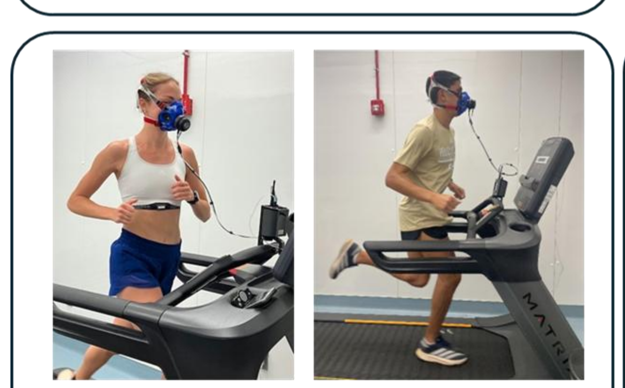
R4 — **Is it possible to evaluate the impact of lower limb musculoskeletal injuries on training performance?**

The data from each sensing modality in this study were analyzed in isolation by means of statistical analyses relative to reported injury state, as well as collectively using multi-modal fusion models for injury likelihood prediction.

Sensing Modalities


Force Plate Measurements


Joint Bioimpedance and Knee Acoustic Emissions


Laboratory Performance Evaluations

HIPS Chest Sensor and Fitness Watches e.g. Garmin

Methods

Cohort Summary

- Health state of the subjects were tracked across the seasons using session labels defined based on self-reporting as 'control', 'injury-exposed', and 'injured'.
- Injury locations span ankle, hip, and leg.
- Some injuries were chronic, while others occurred over the training season.

25 Subjects	7 Season-Long Injuries
19 Spring	3 Left Injuries
11 Fall	4 Right Injuries
5 Overlapped	

Data Collection

Longitudinal data collection of training activity, joint health signals, and self-reported contextual information

Countermovement Jump (CMJ) Analysis	Joint Bioimpedance Analysis	Joint Acoustic Emission (JAE) Analysis	Training Load Analysis
"Investigate relationships between training load and CMJ force production"	*"Investigate relationships between bioimpedance measurements and injury state"*	*"Investigate relationships between JAE measurements and injury state"*	*"Investigate relationships between training load and cardiac and metabolic parameters"*
SUBTASKS: • CMJ feature extraction from force plate signals • Statistical Analysis	SUBTASKS: • Bioimpedance feature extraction • Signal Quality Assessment • Statistical Analysis	SUBTASKS: • JAE feature extraction • Signal Quality Assessment • Statistical Analysis	SUBTASKS: • Sensor parity evaluation • Metabolic Rate Estimation • Statistical Analysis

Measurement Protocol

Countermovement Jump:

- CMJ metrics were compared between high and low load training weeks.
- Subjects were requested to jump on Sparta force plate in 2-week intervals.
- Only subjects who were healthy through the full Spring 2025 training season were included in analysis.

Bioimpedance and Joint Acoustic Emissions:

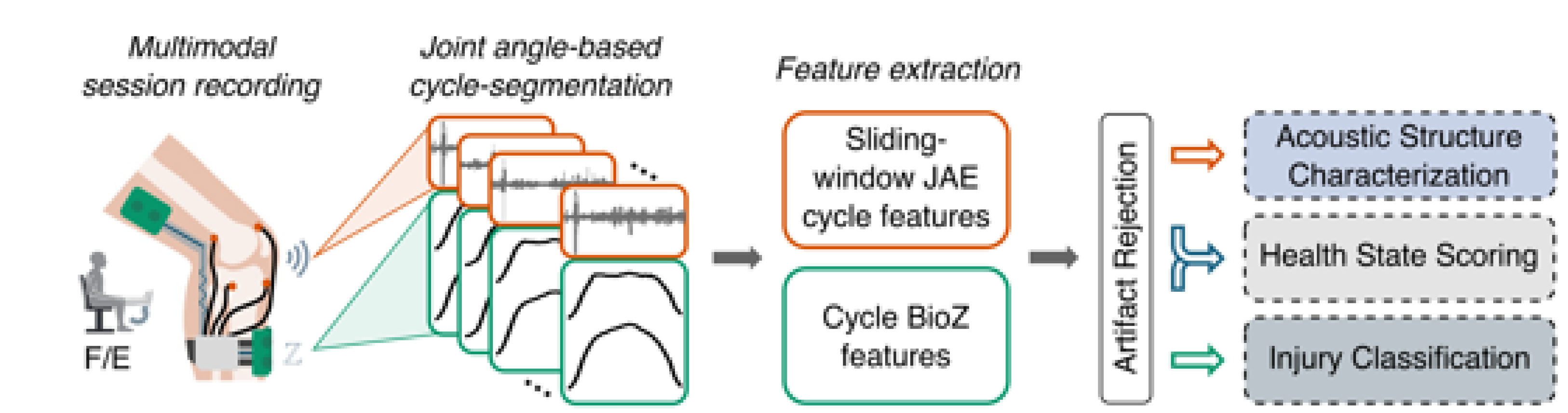
- Bi-weekly measurements of knee and ankle bioimpedance using Dual Frequency Bioimpedance Analysis (DFBIA) system.
- Concurrent bi-weekly measurements of knee acoustic emissions using vibroacoustic sensor.
- Measurements were extracted for scripted maneuvers i.e. loaded calf-raises for ankle data and flexion-extension and squat cycles for the knee.

Cardiovascular Fitness:

- Subjects performed a controlled run economy test on treadmill: 4×4-minute submaximal runs at increasing speeds ranging from the subject's training pace up to the designated race pace. Subjects used the Cosmed K5 wearable metabolic system to record expired gases.
- Subjects were requested to record their Garmin watch and HIPS chest sensors on outdoor runs during the training season.

Modeling Approaches and Data Analysis

Bioimpedance and JAE Models

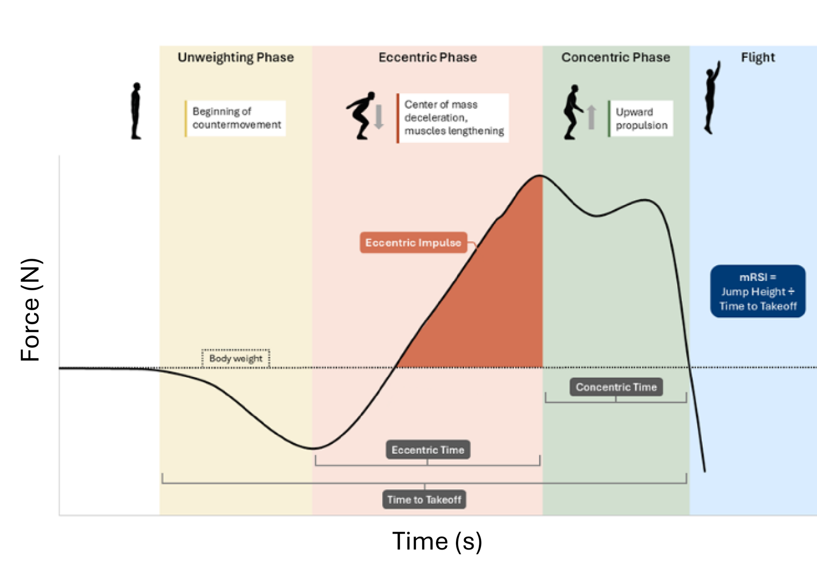


Bioimpedance Feature Extraction: 8 metrics were derived from the raw bioimpedance waveforms collected across movements, including resistance means and dynamic ranges, intracellular resistance (ICR), and ratio of resistances $\frac{R_{5kHz}}{R_{100kHz}}$.

Acoustic Structure Characterization: Graph Community Factor based approach with cycle-level quality control to examine health state partitioning.

Injury Classification and Health State Scoring: Logistic Ridge Regression was used on unimodal and fused feature sets for injury classification. Posterior probabilities generated by regression are used to generate individualized health state scores **[0, 1]** for **[healthy, injured].**

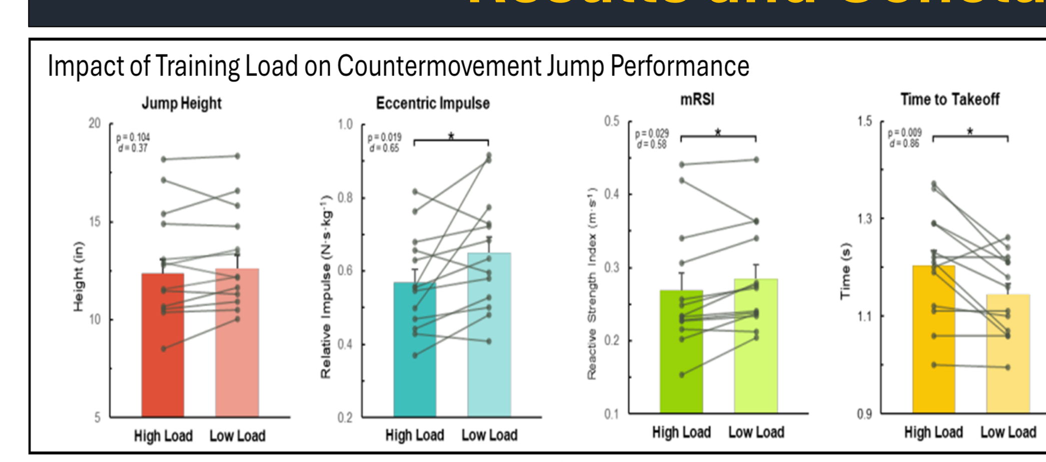
Statistical Analysis of Countermovement Jump

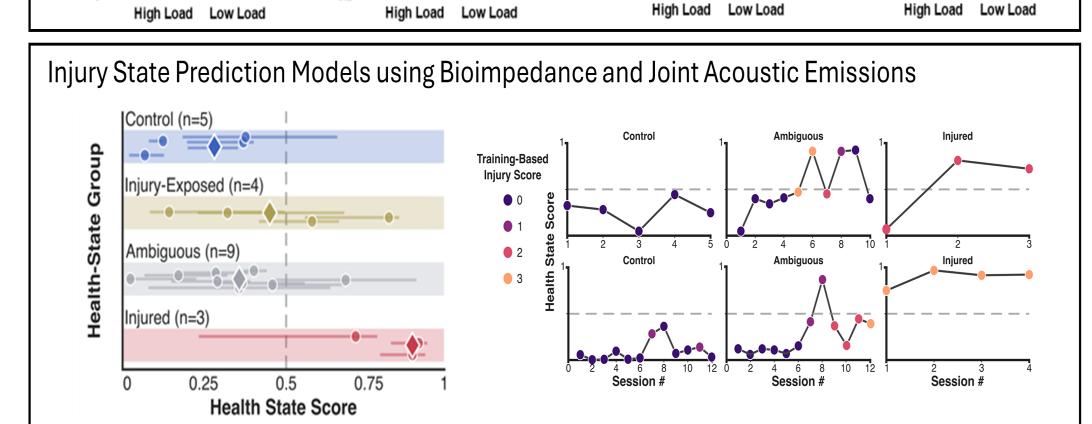


Jump performance metrics and temporal variables derived from the force-time curve: **jump height** (in), **eccentric impulse** (N·m·kg-1), **modified reactive strength index (mRSI**; m·s-1), **time to takeoff** (s), **eccentric time** (s), **concentric time** (s).

Paired sample t-tests compared measures following periods of high and low training load within subjects.

Results and Conclusions





- CMJ features mRSI, Eccentric Impulse, and Time to Takeoff correlate with training load.
- Fused BioZ + JAE model offer longitudinal musculoskeletal injury tracking and assessment – **transferrable to military populations.**
- Cardiovascular models currently under development.