# Physics-Informed Multi-Sensor Fusion Network for Estimation of Gait Energy Expenditure

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***Abstract*—Gait analysis provides critical insights into locomotor function, especially when considering biomechanical features such as energy expenditure during gait. However, traditional spatiotemporal, time-varying, and kinematic metrics often fail to capture the underlying metabolic characteristics. To address this challenge, we present a physics-informed neural network for estimating energy consumption during gait. This model is implemented using electromyography (EMG) and inertial measurement unit (IMU) signals collected from wearable sensor devices. Unlike purely data-driven models, our proposed framework incorporates physics-based constraints from the Umberger and Bhargava metabolic models, ensuring bio-mechanically plausible predictions of energy cost. The estimated energy consumption is validated in a secondary classifier to distinguish gait performed under strain from gait without strain. Experimental results on treadmill-based gait recordings from 20 subjects demonstrate that the physics-informed approach achieves improved accuracy and generalization compared to conventional deep learning baselines. The proposed method highlights the synergy between wearable sensing, biomechanics, and deep learning, advancing interpretable and physiologically grounded approaches for gait analysis.**

***Index Terms*—Gait Energy Expenditure, Physics-Informed Gait Analysis, Electromyography(EMG), Inertial Measurement Unit(IMU), Strain Classification, Physics-Informed Neural Network (PINN)**

## I. Introduction

Gait analysis [1] plays a crucial role in biomechanics and clinical diagnostics, providing insights into musculoskeletal function, rehabilitation outcomes, and disease progression. [2] [3]. Traditional such as spatiotemporal parameters [4] or kinematic and kinetic features [5] [6], may not sufficiently capture the underlying metabolic and mechanical demands of gait. A potential alternative approach involves estimating the energy cost of locomotion [7] [8], which indicates both the efficiency and the physiological strain associated with walking or running. Energy consumption has been shown to be a robust and physiologically meaningful metric that correlates with fatigue, motor impairment, and gait abnormalities. Thus, it can serve as a discriminative feature to distinguish between gait performed under strain and without strain [9] [10].

In this work, we develop a physics-informed deep neural network that estimates energy cost from synchronized Electromyography (EMG) and Inertial Measurement Unit (IMU) recordings from wearable sensors. We use the concept of a Physics-Informed Neural Network (PINN) where Physics-informed loss, derived from the Umberger and Bhargava metabolic models [11] is embedded into the learning process. This ensures that the model predictions remain consistent with known principles of muscle activation and mechanical work. This coupling of sensor-derived data with biomechanical models enables efficient and physiologically valid estimation of gait energy expenditure. Furthermore, we introduce a secondary classification task that evaluates the ability of the predicted energy cost to discriminate between gait performed under strain and gait performed without strain. The accuracy of this classifier provides an indirect measure of both the informativeness of energy consumption as a feature and the efficiency of the proposed PINN framework.

The primary contributions of this paper are as follows:

- Development of a biomechanically relevant preprocessing technique for both IMU and EMG sensor data.
- Mathematical formulation of a neural network that integrates metabolic energy models into deep learning with the help of the Umberger and Bhargava metabolic equations [11].
- Estimation of the energy expenditure as an effective biomarker for distinguishing strain-related gait patterns.

The proposed framework highlights the synergy between wearable sensing, deep learning, and biomechanical modeling, advancing the development of interpretable and physiologically grounded methods for gait analysis.

The remainder of this paper is organized as follows: Section II reviews the related work on gait analysis and pattern classification. Section III describes the methodology, including the data preparation steps, energy calculation methods, and the architecture of the proposed PINN. Section IV presents the experimental results and comparison analysis. Finally, Section V discusses the implications of our findings and potential applications.

## II. Literature Review

Gait analysis has been proven to be an effective biomarker for identity, gender, and neurological disorders, making it both essential and diverse. Researchers have explored a wide range of sensing modalities [12] [13], from vision-based systems and Ground Reaction Force (GRF) [14] [15] platforms to more recent wearable sensors that offer affordability and simplicity. To demonstrate, Morbidoni *et al.* [16] demonstrated that surface EMG signals can be effectively leveraged to predict gait events in children with cerebral palsy, highlighting the discriminative power of neuromuscular activation patterns. Similarly, Hutabarat *et al.* [17] provided a comprehensive review of wearable IMU-based gait analysis, emphasizing their effectiveness in extracting spatiotemporal parameters such as stride length and cadence. Joshi *et al.* [18] further validated the utility of EMG in gait phase classification, particularly