A Physics-Informed Generative AI Model for Decomposing Ground Reaction Forces in Each Foot During the Double Support Phase of Gait

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Summary

Measuring three-dimensional ground reaction forces (GRFs) is essential for clinical gait analysis. However, traditional methods require participants to step each foot onto separate force plates, limiting the number of collected steps and often necessitating multiple trial attempts, particularly for patients. Thus, this study presents a physics-informed AI model capable of reconstructing bilateral GRFs during gait using data from either a single forceplate or a motion capture system. Trained and validated on data from 240 individuals, this model integrates Newtonian mechanics to calculate resultant forces on both limbs and employs a generative AI to decompose these forces into individual limb contributions during the double support phase. With errors below 0.4% in GRFs, center of pressure (COP), and joint torques, the model accurately detected between-group differences in the tested pathological conditions. By eliminating the need for multiple forceplates, this approach offers a highly accurate and easily implementable solution for measuring bilateral GRFs.

Introduction

In clinical gait analysis, measuring three-dimensional GRFs is essential for understanding foot loading and calculating joint kinetics, which traditionally requires patients to step each foot consecutively onto individual floor-mounted forceplates. However, this requirement allows only the collection of a few steps and often leads to repeated attempts due to missteps and unnatural gait patterns, especially in patients with gait-related pathologies. An alternative approach is to develop methods for decomposing bilateral GRFs from resultant forces in both limbs obtained using a single forceplate [1] or a motion capture system [2]. Whereas, none of the existing methods has undergone a thorough accuracy assessment in clinical populations. Moreover, the most accurate method in the literature for healthy individuals still exhibits errors exceeding 12% [1], highlighting the challenges of practical clinical applications. Thus, this study aimed to (1) develop a physics-informed generative AI model for decomposing bilateral GRFs using data obtained from either a single forceplate or a motion capture system, and (2) compare the model-generated results against existing methods across subjects with different physical conditions.

Methods

A total of 180 healthy participants (aged 1–85) and 60 patients with pathological conditions were recruited. The pathological group consisted of four subgroups, each comprising 15 patients with hemiplegic cerebral palsy, stroke, Parkinson's disease, or Duchenne muscular dystrophy, all of whom often required clinical gait assessment. Each participant, wearing 54 skin markers, walked on a 10-meter walkway while GRFs and marker data were recorded using four forceplates and a motion capture system. The starting line was manually adjusted to ensure that, during natural walking, at least two consecutive steps fully landed on separate forceplates. These data from 4800 trials were used to train and validate a physics-informed variational autoencoder model (Figure 1). Model-predicted GRFs, COP, and joint torques were compared to the gold standard using percentage relative root-mean-squared errors (rRMSE). Independent t-tests were used to compare each pathological subgroup with age-matched healthy peers using measured and model-predicted results, respectively.

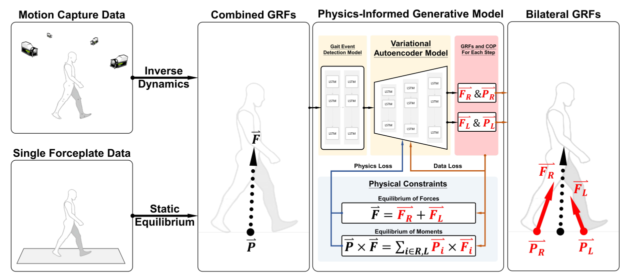

Figure 1: Flowchart of the proposed approach for estimating bilateral GRFs from a single forceplate or motion capture data.

Results and Discussion

Compared to existing methods, the model achieved significantly lower rRMSEs for GRFs, COP, and joint torques ($p < 0.01$), with mean rRMSEs below 0.29%, 0.35%, and 0.40%, respectively. Similar between-group effects were detected using both measured and predicted results, suggesting that the model is sufficiently accurate for identifying altered kinetic patterns in the tested subgroups.

Conclusions

This study is the first in the literature to integrate Newtonian mechanics with generative AI in a model capable of decomposing bilateral GRFs from a single forceplate or a motion capture system. Compared to existing methods, this approach offers a more accurate and practical solution for obtaining GRF and joint kinetics in clinical gait analysis.

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References

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