**Development and validation of FootNet, a new kinematic and deep learning-based algorithm to detect foot-strike and toe-off in treadmill running**

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## Summary

Foot-strike and toe-off detection is often critical in the assessment of running biomechanics. The onset and offset of the vertical ground reaction force is regarded as the "gold standard" method for step event detection, but several kinematics-based algorithms have been proposed to detect foot-strike and toe-off in the absence of force plates. However, the accuracy and generalisability of kinematics-based methods are often limited. Therefore, we developed FootNet, an algorithm using kinematic input and deep learning, to improve the detection of foot-strike and toe-off events during treadmill running in a variety of speed, foot-strike angle and incline conditions.

## Introduction

The accurate detection of foot-strike and toe-off events based on kinematics has historically proved a challenging problem within locomotion biomechanics. Although several marker trajectory-based and segment/joint kinematics-based algorithms exist, these methods typically require markers to be affixed to highly deformable areas of the shoe which can be problematic. The accuracy of these methods can also be affected by running speed and a runner's preferred foot-strike pattern (foot landing angle). Further, algorithm development and validation has typically been conducted in a single laboratory, potentially limiting their generalisability [1].

The purpose of this study was to develop and evaluate FootNet, a new kinematics and deep learning-based algorithm to detect foot-strike and toe-off in treadmill running.

## Methods

Five treadmill-running datasets from three independent laboratories with different motion capture systems and instrumented treadmills were gathered from previous studies. These datasets included kinematics and kinetics of athletes of different abilities and foot-strike patterns running at multiple speeds and on different inclines. Marker trajectories were processed to calculate leg, foot and ankle kinematics. Running trials were divided in cycles and the non-contact and contact phases within each cycle were detected using the raw vertical ground reaction force (non-contact: vGRF < 50 N; contact: vGRF ≥ 50 N).

FootNet is based on a recurrent neural network with long, short-term memory (LSTM) units [2]. The network takes the distal tibia anteroposterior velocity, ankle dorsi/plantar flexion angle, and the anteroposterior and vertical velocity of the foot centre of mass as input features (entire time-series of a cycle) and predicts whether each time point belongs to the contact or non-contact phases. Foot-strike and toe-off can then be simply identified by finding the first and last timepoints identified as contact. We used the five datasets for model development (70% participants from each set) and testing (30% participants of each set). The model underwent 5-fold cross-validation and the best set of weights was selected for final model testing.

Non-parametric Bland-Altman analyses (median bias and 2.5$^{th}$ and 97.5$^{th}$ percentile as 95% limits of agreement, 95LA) [3] and root mean squared error (RMSE) were used to assess the performance of FootNet against the onset and offset of the vertical ground reaction force method for the detection of foot-strike, toe-off and contact times. The linear association between detection errors and running speed, foot-strike angle and incline respectively were also investigated.

## Results and Discussion

FootNet achieved close agreement with the force plate method (Figure 1), with a median bias of 0 ms for foot-strike (95LA = [-10, 7] ms, RMSE = 5 ms), toe-off (95LA = [-10, 10] ms, RMSE = 6 ms) and contact time (95LA = [-15, 15] ms, RMSE = 8 ms). These errors were two to four times smaller than those previously reported in the literature [1]. Linear associations between detection errors and running speed, foot strike angle and incline were small and practically negligible. Thus, FootNet seems robust to different running speeds, foot strike patterns and treadmill gradients, one of the main limitations highlighted in previous research.

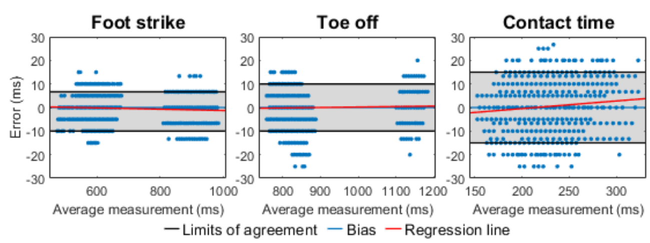


**Figure 1**: Bland-Altman plots.

## Conclusions

FootNet improves the detection of foot-strike and toe-off events in treadmill running, and is robust to different speeds, foot-strike patterns and inclines. FootNet and its source code is publicly available for the biomechanics community.

## References

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