Wearables and injury prevention: the pitfalls and opportunities for monitoring musculoskeletal loading

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Summary

In scientific studies and in commercial wearable devices it is often assumed that increases in ground reaction forces (GRF), or in GRF-correlated signals from pressure-sensing insoles and inertial measurement units (IMUs), indicates increases in musculoskeletal loading or overuse injury risk (e.g., bone stress fracture risk). Here we summarize our recent empirical findings on tibia stress fracture risk and running that demonstrate that this common assumption is flawed. Specifically, we show that GRF metrics are not strongly correlated with tibial bone forces across a range of running speeds and slopes. Next, we outline a new approach: using data from multiple wearable sensors on the foot and shank and a musculoskeletal model to better estimate loading on the tibia bone. Our preliminary feasibility assessment indicates this multi-sensor data fusion approach can outperform conventional GRF metrics, offering a promising solution for monitoring musculoskeletal forces unobtrusively in daily life.

Introduction

Tibial stress fractures are a common overuse injury due to repeated bone loading. More than 50 scientific publications per year report or interpret increases in GRF metrics (e.g., impact peaks, loading rates) or GRF-correlated signals (e.g., tibial shock) to signify increases in injury risk or forces on internal biological structures such as the tibial bone [1]. This literature, along with the convenience of estimating GRF metrics using portable pressure-sensing insoles or IMUs, has motivated the development of various commercial wearable devices that claim to provide feedback on musculoskeletal loading or injury risk to runners/athletes. However, the key underlying assumption that increases in GRF metrics reflect increases in loading inside the body, and thus increased overuse injury risk, has not been validated. Therefore, the objective of our first study was to evaluate this assumption for running. Based on our results (namely the lack of strong correlations between GRF metrics and tibial forces when running across speeds and slopes) we began exploring an alternative solution for monitoring bone forces: integrating kinematic and kinetic data from multiple wearable sensors with musculoskeletal modelling techniques to non-invasively estimate bone loading. The second objective of this study was to assess the feasibility of this new approach using simulated-wearable data (as outlined in Methods).

Methods

Ten recreational runners each performed thirty running conditions across a range of speeds and slopes. Lower-limb kinematics and GRFs were collected, and tibial compression force was estimated using an established model [1]. For the first study, we computed correlations between commonly-used vertical GRF metrics (impact peak, loading rate, active peak, impulse) and tibial metrics (peak, impulse) across all conditions for each subject, then computed inter-subject averages. Next, to explore a new approach for estimating tibial force outside the lab, we distilled *lab-based* data (i.e., force plate and motion capture data from our first study) into lower-fidelity *simulated-wearable* data (i.e., approximate signals we expect from wearable sensors outside the lab). For instance, pressure-sensing insoles can provide normal force and center of pressure estimates (simulated by transforming 3D force plate data into 1D normal force and center of pressure into the foot frame), and IMUs can estimate foot/shank orientations (simulated by using segment motion capture data). We used these data, with a modified musculoskeletal model, to generate a *simulated-wearable* estimate of tibial force, then computed correlations vs. lab-based tibial force (similar to first study).

Results and Discussion

We found that increases in vertical GRF metrics were not strongly correlated with increases in tibial force metrics (Table 1). Seventy-six of 80 subject-specific correlation coefficients exhibited r<0.8 [1]. These findings reinforce that commonly-used GRF metrics should not be assumed to be a surrogate for tibial force or injury risk [2]. Simulated-wearable estimates of tibial force were, on average, strongly correlated to lab-based estimates (r>0.8, Table 1). These correlations were stronger than correlations between GRF metrics and tibia force.

Conclusions

GRF metrics – particularly impact peaks and loading rates – should not be assumed to indicate tibial force during running across speeds and slopes. Fusing data from multiple wearable sensors with musculoskeletal modelling provides a feasible and promising solution for daily monitoring of tibial forces.

References

[1] Matijevich ES et al. (2019) *PLOS ONE,* 14(1): e0210000.
[2] Nigg et al. (2017), *CISS*, 2:007.

Table 1: Left: correlation coefficients (r) between *lab-based* and *simulated-wearable* estimates of tibial force metrics. Right: correlation coefficients between *lab-based* estimates of tibial force and vertical GRF metrics from the same subjects (extended results published in [1]).

correlation (r) avg ± std (N=10)		*simulated-wearable* tibial force		vertical GRF metrics			
		peak	impulse	impact peak	loading rate	active peak	impulse
lab-based tibial force	peak	0.83 ± 0.47		-0.29 ± 0.37	-0.20 ± 0.35	0.72 ± 0.42	-0.46 ± 0.40
	impulse		0.94 ± 0.55	-0.51 ± 0.53	-0.72 ± 0.41	0.03 ± 0.51	-0.11 ± 0.41