Ground reaction forces don't indicate tibial forces: implications for injury prevention, shoe design & wearable tech

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Introduction

Tibial stress fractures are a common overuse injury due to repeated bone loading. More than 50 scientific publications per year interpret increases in ground reaction force (GRF) metrics (e.g., impact peaks, loading rates) or correlated signals (e.g., tibial shock) to signify increases in injury risk or forces on musculoskeletal structures such as the tibia (Matijevich et al. 2019). In an effort to minimize injuries in runners, shoes are often designed to reduce GRF impacts or loading rates. Likewise, wearable devices use GRF-correlated signals to assess injury risks. However, the underlying assumption that GRF metrics reflect loading inside the body has not been validated.

Purpose of the study

The first objective was to evaluate if increases in GRF metrics indicate increases in tibial loading during running. Based on the lack of strong correlations we found between GRF metrics and tibial forces, we explored an alternative method for monitoring tibial force: combining data from multiple wearable sensors with a musculoskeletal model to estimate tibial force outside the lab. The second objective was to assess the feasibility of this approach using simulated-wearable data.

Methods

Ten recreational runners each performed 30 running conditions, sweeping a range of speeds (2.6-4.0 m/s) and slopes (-9° to +9°). Lower-limb kinematics and GRFs were collected, and tibial compression force was estimated using an established model (Matijevich et al. 2019). First, we computed correlations between commonly-used GRF metrics (impact peak, loading rate, active peak, impulse) and tibial force metrics (peak, impulse) across all conditions for each subject, then computed inter-subject averages. Next, to explore our alternative method for estimating tibial force outside the lab, we distilled *lab-based* data (i.e., force plate and motion capture data from first study) into lower-fidelity *simulated-wearable* data (to approximate wearable sensor signals): Pressure-sensing insoles can estimate normal force and center of pressure (simulated by transforming 3D force plate data into 1D normal force data and transforming force plate center of pressure data into the foot's reference frame), and inertial measurement units can estimate foot/shank orientations (simulated from segment kinematics from motion capture). We used these data and a musculoskeletal model to generate a simulated-wearable tibial force estimate, and computed correlations vs. lab-based tibial force.

Results

Increases in vertical GRF metrics were not strongly correlated with increases in tibial force metrics (Table 1). 76 of 80 subject-specific correlation coefficients resulted in $r<0.8$ (Matijevich et al. 2019). Simulated-wearable tibial force estimates were, on average, strongly correlated to lab-based estimates ($r>0.8$, Table 1), and these correlations were stronger than correlations with GRF metrics.

Discussion and conclusion

Our results reinforce that commonly-used GRF metrics should not be assumed to be a surrogate for tibial force or injury risk (Nigg et al. 2017). GRF metrics like impact peaks or loading rates can be negatively correlated with bone force (Table 1), highlighting their potential to misinform interpretations related to bone loading and overuse injury risk. If running shoe developers aim to minimize injury risk, they may be interested in how shoe features affect forces on specific bones, muscles and tendons; and GRF metrics may be unreliable surrogates for evaluations. Similarly, wearable devices aiming to provide injury risk feedback may benefit from targeted monitoring of musculoskeletal loading, with less emphasis on GRFs. Our feasibility assessment using simulated-wearable data indicates that fusing data from multiple wearable sensors with a musculoskeletal model is a promising solution for daily monitoring of tibial forces.

References

Matijevich, E.S., Branscombe, L.M., Scott, L.R., Zelik, K.E. (2019). Ground reaction force metrics are not strongly correlated with tibial bone load when running across speeds and slopes: Implications for science, sport and wearable tech. PLoS ONE 14(1): e0210000.

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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 GRF metrics from the same subjects (see Matijevich et al. 2019). Mean (avg) and standard deviation (std) computed using Fisher's z transformation.

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