# BEYOND GROUND REACTION FORCES: TOWARDS WEARABLE TECH TO MONITOR BONE LOADING & PREVENT INJURY

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## INTRODUCTION

Bone stress injuries (BSI) can result from repeated submaximal bone loading that causes an accumulation of microdamage. There is a high prevalence of BSI, particularly tibia stress fractures, in military trainees, recreational runners, and certain industrial workers. BSI can result in pain, missed work, reduced physical activity, decreased productivity and substantial healthcare costs.

We predict that BSI could be prevented if one could monitor bone loading in daily life, identify potentially injurious loading conditions, and then intervene before an excessive accumulation of bone microdamage. However, monitoring bone loading is challenging, particularly if the goal is to do so in daily life outside of a motion analysis lab. An ideal solution would be a wearable, non-invasive device that serves as an injury prevention tool for military trainees, runners and industrial workers.

Various researchers have attempted to understand BSI by measuring ground reaction forces (GRFs), with the hope that GRF peaks or loading rates might reflect bone loading. GRFs are appealing because, in contrast to bone loading, they can be measured directly and non-invasively; however, it can be shown analytically (via Newton-Euler laws of motion) that bone forces are a function of more than just GRFs. Typically, the vast majority of bone loading is due to muscle contractions. GRF magnitude is generally only a small fraction of the total bone loading. For instance, during running peak GRFs are typically 2-3 times body weight (BW), whereas peak tibia bone forces are typically 8-12 times BW, as evidenced by gait analysis [1], cadaver [2] and modeling studies. Moreover, peak bone loading occurs in midstance, while GRF impact peaks occur near initial foot contact.

Nevertheless, it is plausible that for a certain subset of tasks (e.g., running over a limited range of speeds) that GRF might positively correlate with bone loading, and thus still be a useful indicator of increases/decreases in bone loading. Given the ability to measure GRFs directly with wearable sensors, this possibility is worth exploring before investigating more complex multi-sensor solutions.

The purpose of this study was to determine if increases in GRF peaks or loading rate were correlated with increases in peak tibia bone loading during running. We focused on running and tibia bone loading, because of the high prevalence of tibia stress fractures in runners. We hypothesized that increases in common GRF metrics (impact and active peaks, impact loading rate) would not be strongly correlated with increases in peak tibia loading as runners varied speed, step frequency and terrain slope (i.e., $r<0.8$). The absence of strong correlation would suggest the need to fuse data from additional/alternative sensors, moving beyond GRF measures, to non-invasively monitor bone loading.

## METHODS

Three healthy subjects (2 M, 1 F, height 1.8 ± 0.1 m, weight 66.8 ± 7.0 kg, age 24.6 ± 1.5 years) have participated in this ongoing study. Subjects performed various running trials on a treadmill: (i) 20 total trials at 4 different speeds, ranging from 2.0-3.0 m/s, using self-selected step frequency at each speed, and 5 different slopes ranging from –6 to +6 degrees, (ii) 7 trials at 2.6 m/s but varying step frequency from -15% to +15% of their self-selected step frequency (enforced via metronome). Parameter ranges were selected to reflect variability that a recreational runner might encounter.

<u>Data collection & processing:</u> Unilateral lower-limb kinematics (100 Hz) and GRFs (1000 Hz) were collected. Subjects provided informed consent prior to participation. For each trial, data were collected for 20 seconds, individual steps were

parsed out, and outcome metrics were computed on a step-by-step basis and then averaged.

*Tibia bone loading:* An established inverse dynamics analysis was used to estimate the total tibia compression force ($F_{total}$, Fig. 1a), due to internal (muscle) and external (GRF) sources [1]. The external contribution ($F_{ext}$) was calculated as the measured GRF projected onto the long axis of the tibia. The internal force contribution ($F_{int}$) was calculated as the estimated ankle moment divided by the Achilles tendon moment arm (5 cm, assumed constant). Peak tibia force ($F_{total,max}$) was calculated as the maximum of $F_{total}$ across stance. Forces were normalized by subject BW.

*GRF:* Three common GRF metrics were calculated: $F_{active}$ (vertical GRF active peak), $F_{impact}$ (vertical GRF impact peak) and VALR (vertical GRF average loading rate, Fig. 1b). For each subject, individual GRF metrics were linearly correlated to peak tibia force. The Pearson correlation coefficient (r) was computed for all trials, and also for each parameter sweep, then averaged across subjects.

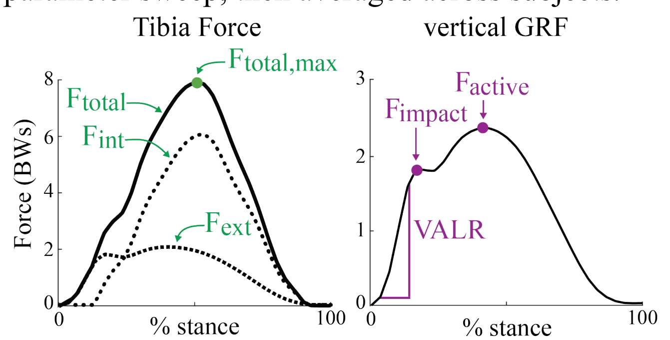


**Figure 1**. Running 2.8 m/s. (a) Total tibia load summation. (b) Vertical GRF metrics. Force in BWs

## RESULTS AND DISCUSSION

*All trials:* GRF metrics were moderately or weakly correlated to $F_{total}$ (Fig. 2). However, only the GRF active peak was positively correlated ($F_{active}$: r = 0.64 ± 0.26). Surprisingly, tibia bone force actually decreased with increases in GRF impact peak and loading rate ($F_{impact}$: r = -0.50 ± 0.29; VALR: r = -0.53 ± 0.28; Fig. 2). These preliminary results support our hypothesis. Increases in GRF metrics do not necessarily reflect increases in bone loading, signifying that GRFs alone may be of limited value in monitoring tibia loading or BSI risk. These findings complement prior evidence that higher impacts may not play a key role in the development of stress fractures [3].

*Speed sweep*: GRF metrics were strongly correlated to $F_{total}$ ($F_{active}$: r = 0.86 ± 0.11; $F_{impact}$: r = 0.86 ± 0.10; VALR: r = 0.94 ± 0.10) with increasing speed on level ground. However, $F_{total}$ was also strongly correlated to speed itself (r = 0.91 ± 0.10), which is generally easier to measure with wearable sensors.

*Slopes sweep:* $F_{active}$ had a range of correlations with $F_{total}$ (min r = -0.24; max r = 0.99), while $F_{impact}$ and VALR were negatively correlated to $F_{total}$ ($F_{impact}$: r = -0.75 ± 0.22; VALR: r = -0.78 ± 0.18). $F_{active}$ had a range of correlations with slope itself (min r = -0.47; max r = 0.95). Even with this small sample size, large variability in correlation values indicates GRF may not adequately capture subject-specific running strategies or estimate bone loading trends.

## CONCLUSIONS

Preliminary results suggest that trends in GRFs may be insufficient to track tibia bone loading. The most striking observation was that tibia loading tended to decrease with increasing GRF impact peaks and loading rates; though correlations were relatively weak. Additional or alternative measures may be needed to track tibia bone loading, with the long-term goal of predicting and preventing BSI risks.

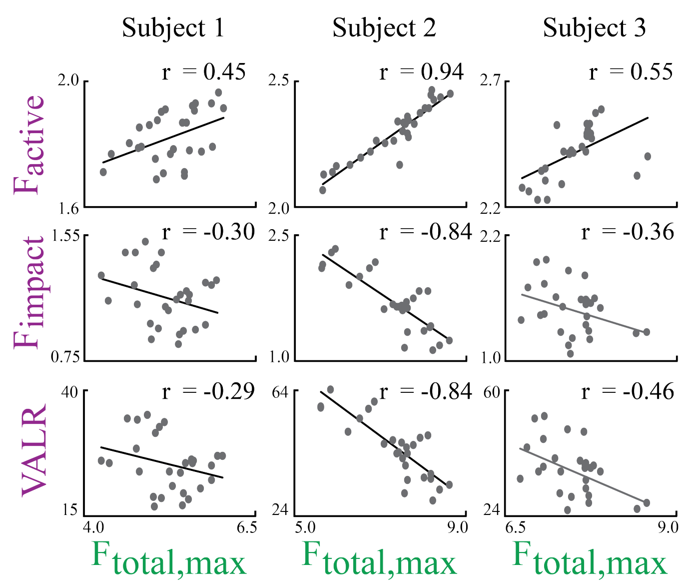


**Figure 2**. Each data point represents the average of one trial. Force in BWs. VALR in BWs/s.

## REFERENCES


1. Scott and Winter. *Med. Sci. Sports Exerc*. 1990.
2. Sharkey and Hamel. *Clin Biomech.* 1998.
3. Loundagin et al. *J Biomech Eng.* 2018.