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A METHOD FOR CONTINUOUS MONITORING OF THE GROUND REACTION FORCE DURING DAILY ACTIVITY

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INTRODUCTION

Theoretical models and and experimental studies of bone remodeling have identified peak cyclic force levels (or cyclic tissue strain energy density), number of daily loading cycles, and load (strain) rate as possible contributors to the bone modeling and remodeling stimulus[1,2,3]. To test our theoretical model and further investigate the influence of mechanical forces on bone density, we have focused on the calcaneus as a model site loaded by calcaneal surface tractions which are predominantly determined by the magnitude of the external ground reaction force (GRF).

During daily activity the body is subjected to a random external loading history supplied primarily by the GRF consisting of body weight (BW) plus inertial forces (related to intensity of activity) accelerating the body center of mass. We have hypothesized that monitoring the vertical component of the GRF (GRF_Z) may provide a useful method of quantifying activity level in order to investigate the influence of mechanical forces on muscle and bone. GRF loading histories among individuals are known to vary greatly in peak force levels and daily cycles and we suggest these differences may be reflected in differences in lower limb musculoskeletal properties.

We report here development of instrumentation to monitor the vertical component of the ground reaction force during normal daily activity.

METHODS

The components of the force measuring system are shown in Figure 1. The system is composed of a capacitance insole force sensor and battery powered data processing/storage unit. RS 232 communication transfers data to a workstation for display and further analysis. Combined dimensions of processor, memory, and signal conditioner are approximately 3"x3"x1".

Sensor calibration:

Sensor force output, calibrated by standing and jumping on a force plate at different force magnitudes (~0.0 to 3.0 BW) correlated to force plate vertical force (F_Z) with r= 0.98. (Additional calibration procedures are planned which will examine whether insole shear forces contribute to the output signal.)

No significant changes in calibration occurred over a continuous 15 hour trial limited to walking, but sensor leads failed during two short bouts of vigorous activity (running and tennis). We believe these problems are solvable, but long duration (2 week) sensor stability remains to be determined.

Data recording:

The GRF is sampled at a frequency of 100 Hz to detect peak force levels and load rates during high intensity activities such as running. Incoming GRFz data are filtered in the time interval between sampling. The processing unit is designed to operate continuously for approximately 2 weeks without the need to retrieve data or replace batteries.

Data reduction:

The microprocessor continuously filters [4] the digitized GRF_Z for "significant" peaks (P= force level at the peak) and valleys (V= force level at the valley) in the force-time history, storing peaks and valleys contributing to a force magnitude, |P-V| or |V-P|, greater than a minimum selectable level (e.g., 0.2 body weight). In addition, the processor continuously time-differentiates the force and saves the maximum load rate ($dGRF_Z/dt$) between each significant peak and valley. The data logger also stores the time of occurrence of the significant event *and* the total daily duration at force levels partitioned into 0.1 BW intervals.

Figure 2 illustrates the filtering process applied to a 12 second GRFz record of standing, walking, and jogging. The significance level was set at 0.2 BW. Note that many of the force reversals occurring during standing and walking did not meet the significance criterion of 0.2 BW and were rejected. Note also that walking is characterized by a significant mid-stance phase dip or valley in the force-time curve.

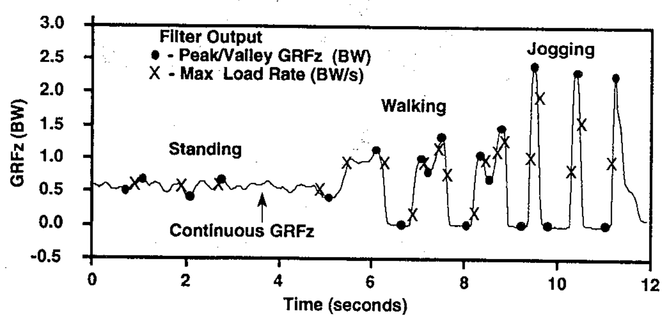

Figure 2. Continuous and filtered output record from the system.

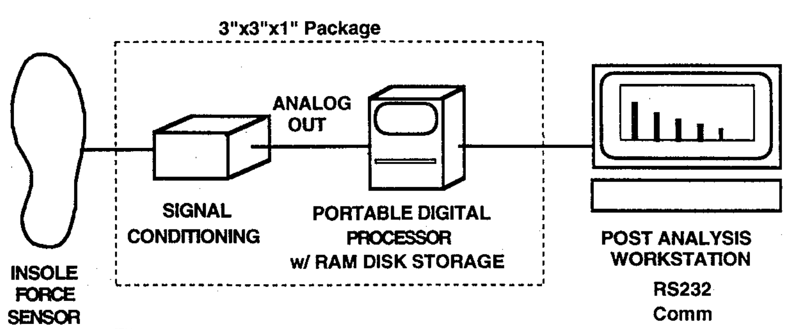

Figure 1. Insole force sensor and data acquisition system.

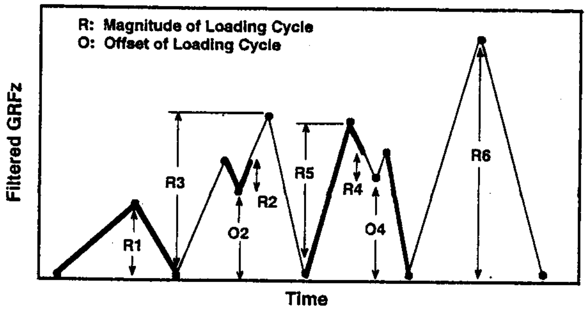

Figure 3. Illustration of the post-processing "rainflow" cycle counting algorithm.

On-board post-processing [5] sorts the loading cycles into a histogram organized according to cyclic range (|P-V|) and GRF_Z loading cycle offset. The method of "rainflow" counting of loading cycles is demonstrated in Figure 3. In this example, 6 loading cycles are shown---4 with zero offsets (R1, R3, R5, R6) and 2 with non-zero offsets (R2, R4).

RESULTS

Comparison of walking and running:

Loading history data collected while walking and jogging 800 m each are plotted in Figure 4a. The significance level was set at 0.1 BW. The sensor and filtering algorithm captured the primary and mid-stance phase load cycle of each walking step. Jogging generated one significant loading cycle per step, but at a higher GRFz level of ~ 2.3-2.4 BW. The fewer number of jogging load cycles compared to walking is attributed to longer step lengths.

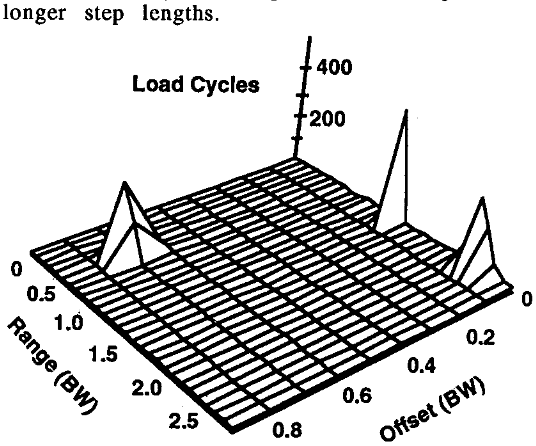

Figure 4a. Sample loading history: walking and running 800 m.

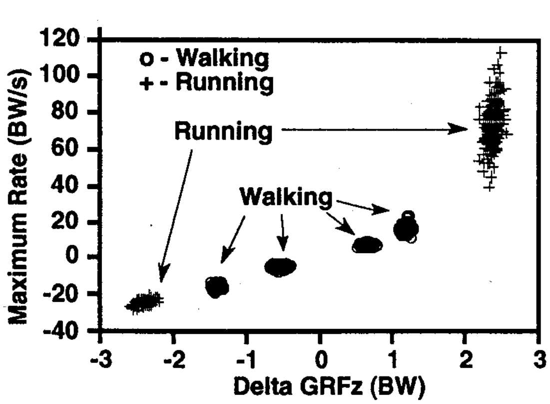

Figure 4b. Load rate record: walking and running 800 m.

Peak walking and jogging load rates, expressed in terms of body weights per second (BW/s), are plotted in Figure 4b as functions of the change in force magnitude within which the peak rate occurred. Loading of the body produces positive load rates (positive slope of the GRFz-time history) while unloading is associated with negative load rates. Two load cycles and, therefore, 4 load rates are associated with each walking step.

Preliminary trial of 1 day:

Data from a typical 'non-exercising' day revealed that, based on duration, the body was rarely loaded above ~1.0 BW (9 min. or 1% of the non-resting day). However, ~41% of the daily load cycles had a range of ~1.0 BW or greater, whereas 45% were equal to or below a range of ~0.5 BW with a GRFz offset of ~ 0.7 BW (see Figure 5).

These lower range cycles with high offset occurred primarily during the mid-stance phase of walking during a brisk walk (see mid-stance walking in Figure 2 for example). Importantly, the sensor was able to detect the few higher force (1.5-1.9 BW), non-normal walking load cycles which may contribute significantly to the daily bone maintenance stimulus. Sensor data used to estimate daily walking cycles and digital stepmeter readings, recorded simultaneously, were within 3% of each other.

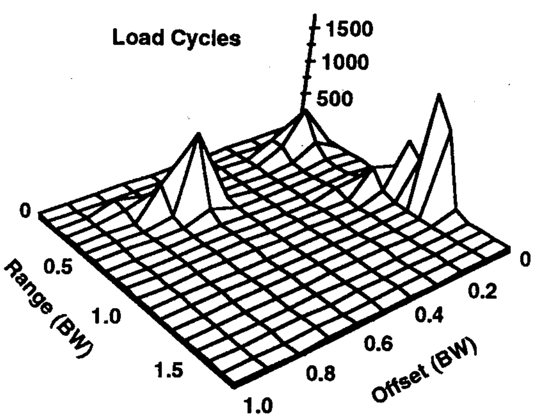

Figure 5. Loading history for one 15 hour day without exercise.

CONCLUSIONS

We believe long term monitoring of ground reaction forces to obtain habitual individual loading histories may provide new insights into the role of repetitive mechanical loading on the modeling and remodeling response of bone. This method may also be used to evaluate exercise activities in space and to establish equivalent loading histories compared to Earth activity levels.

REFERENCES

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