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Original research papers

WAVELET ANALYSIS OF THE VERTICAL GROUND REACTION FORCE ACTING ON THE FOREFOOT (vGRF_F) DURING THE ROMBERG TEST

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Abstract

Introduction. The primary objective of this study was to perform a wavelet analysis of the time-course of the vertical ground reaction force acting on the forefoot (vGRF_F) during the Romberg test. The secondary objective was to conduct a time-frequency energy analysis of this signal. ***Material and Methods.*** The study included 93 female volleyball players (age: 15.29 ± 0.49 years, body height: 174.14 ± 7.36 cm, body mass: 62.67 ± 9.41 kg). The participants performed the test on a treadmill (Noraxon FDM-T) equipped with a high-resolution pressure sensor matrix. A time-frequency analysis of the signal originating from the treadmill was conducted using the Morse wavelet. ***Results.*** The average percentage contribution of signal energy in three analyzed frequency bands and the inter-band energy flow were determined as a function of eye status (open vs. closed) during the Romberg test. ***Conclusions.*** Appropriately preprocessed, the vGRF_F signal can serve as a viable alternative to traditional stabilographic metrics. It possesses high discriminative capability, particularly within the low-frequency range of 0.05 to 1 Hz.

Keywords: postural control, Romberg test, wavelet analysis

Introduction

Beginning with the pioneering ground reaction force measurements conducted by Basler [1] and the first experimental determination of the trajectory corresponding to the modern concept of the center of pressure (COP) reported by Elftman and Manter [2] and further developed by Elftman [3], COP analyses have formed the foundation of human postural control research [4, 5]. In addition to the traditional COP parameters discussed in these review papers, spectral analyses of COP(t) trajectories [6, 7] as well as time-frequency analyses [8, 9, 10, 11] have been carried out for many decades, following the observation that COP(t) signals exhibit non-stationary characteristics [12, 13, 14].

Spectral analyses have demonstrated that frequencies below 0.1 Hz may be related to visual control, frequencies in the range of 0.1–0.5 Hz to the vestibular system, while higher frequencies up to approximately 1 Hz are attributed to the somatosensory system [8, 15, 16]. However, it should be explicitly emphasized that although these boundaries are conventional and specific frequency threshold values vary across different authors, they nevertheless serve as well-documented reference levels in the assessment of postural control.

New opportunities for assessing postural control emerged with the introduction of devices equipped with a high-resolution pressure sensor matrix. While early advancements in digital pedobarography were pioneered by companies such as Tekscan, Inc. (South Boston, MA, USA) in the late 1980s, the integration of these high-resolution matrices into clinical and biomechanical assessment reached a significant milestone in 2007. At this time, Zebris Medical GmbH (Isny, Germany) introduced its FDM series, establishing a new standard for combined gait and posture analysis on treadmill and platform systems.

Such devices complement traditional force plate measurements by determining the plantar pressure distribution across different anatomical regions of the foot [17]. In our recent study [18], we utilized wavelet analysis to examine the time-course of the resultant ground reaction force acting on the hindfoot during the Romberg test, evaluating the discriminatory capacity of this signal under varying visual conditions. It is well established that the hindfoot primarily transmits low-frequency components associated with postural control, which is a biomechanical consequence of the Center of Mass (COM) alignment relative to the ankle joint during quiet upright standing [19]. In this context, performing a spectral analysis of the signal derived from the forefoot appears highly justified, as it could provide a more comprehensive overview of the oscillations acting on the foot during the Romberg test.

Driven by these considerations, the primary objective of this study was to perform a wavelet analysis of the time-course of the resultant ground reaction force acting on the forefoot during the Romberg test. The secondary objective was to conduct a time-frequency energy analysis of this signal.

Material and Methods

Participants

The study included 93 female volleyball players aged 15.29 ± 0.49 (body height: 174.14 ± 7.36 cm, body mass: 62.67 ± 9.41 kg) attending sports-profiled volleyball classes. Parents/legal guardians provided written informed consent for the young athletes' participation in the postural stability assessments and were informed about the testing procedures, as well as the potential risks and benefits of the project. The research protocol was approved by the Senate Ethics Committee of Józef Piłsudski

University of Physical Education in Warsaw (SKE 01-15/2023). The study was conducted at the Regional Center for Research and Development, Faculty of Physical Education and Helath in Biała Podlaska, in the Biomechanics Laboratory.

Measurements

The participants performed a 30-second classic Romberg test with their upper limbs extended forward, parallel to the ground, on a treadmill (Noraxon FDM-T) equipped with a high-resolution pressure sensor matrix (5376 sensors with a sampling density of 1.4 sensors/cm² and a measurement range of up to 120 N/cm²). The sampling frequency of the platform was 100 Hz. The Romberg test was performed in a randomized order under both open-eyes and closed-eyes conditions. Prior to both tests, the participants completed a 20-second open-eyes trial to familiarize themselves with the treadmill surface and the required body configuration. All trials were preceded by an auditory 'START' command issued by the investigator.

Data processing and computing

As part of the numerical processing, the treadmill signal in the form of the vertical ground reaction force acting on the forefoot of the right foot (vGRF_F) with a length of 3,000 samples was detrended (Fig. 1), smoothed with a low-pass filter with a cutoff frequency of 10 Hz, and then zero-padded on both sides to a total length of 9,000 samples. A Tukey window of length 3000 with a taper ratio of 0.05 was introduced to eliminate signal jumps at the beginning and end of the sample. The frequency band was divided into three left-closed, mutually complementary intervals: Band 1 ($0.05 \leq f < 0.1$ Hz), Band 2 ($0.1 \leq f < 1$ Hz), and Band 3 ($1 \leq f < 10$ Hz). For each interval, the total energy and the percentage contribution of individual components to the total energy were determined for the Romberg test under both eyes-open and eyes-closed conditions.

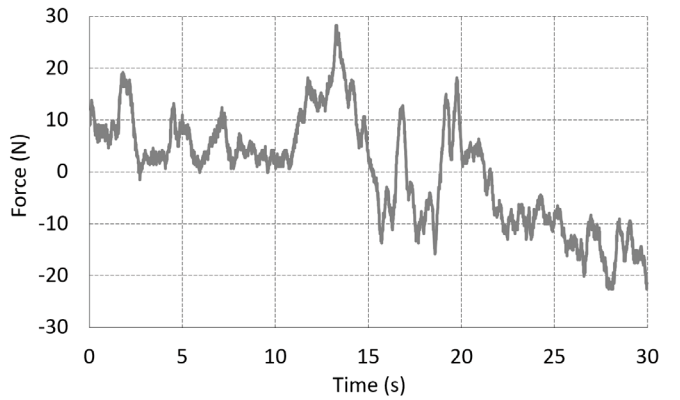


Fig. 1. Detrended vGRF_F time course of a volleyball player with eyes open.

The calculations utilized the continuous wavelet transform cwt from MathWorks' MATLAB, using the built-in filter bank based on a Morse wavelet with a symmetry parameter of 3 and a time-bandwidth product of 60. To eliminate the cone of influence, a custom algorithm, detailed in our previous work [18], was applied. When determining the instantaneous energy profiles, we modified the computational algorithm presented in the cited study by enforcing L2 norm conservation. In contrast, the frequency-dependent trends of the average energy percentage shares within the three bands were calculated in accordance with the previous algorithm [18] to compare the results obtained in both studies.

Statistical analysis

To account for the compositional nature of the data (where the energy bands sum up to 100%), and given that the variance of Band 3 remained an order of magnitude smaller across both conditions, the analysis focused on the dynamic shift between Band 1 and Band 2. To avoid the sub-compositional coherence issues and the 'closure effect' inherent to percentage data, a log-ratio transformation was applied. For each of the N = 93 participants, the relative balance between the two bands was operationalized as $LR = \ln(\text{Band 1}/\text{Band 2})$ for both eyes open and eyes closed conditions. Group-level shifts between the two states were evaluated using a paired samples t-test, following the verification of normality for the log-ratio differences via the Shapiro-Wilk test.

Results

Figure 2 illustrates the frequency responses of the average energy percentage shares within the three analyzed bands for both the eyes-open and eyes-closed conditions. For clarity, a logarithmic scale was applied to the frequency axis. In the former case, prominent peaks in the average energy percentage shares are visible at 0.064, 0.1, and 0.18 Hz, reaching a maximum value of 2.47% at the latter frequency. For the eyes-closed condition, the peak values emerged at 0.064 and 0.36 Hz, with a maximum of 2.85% recorded at the latter frequency.

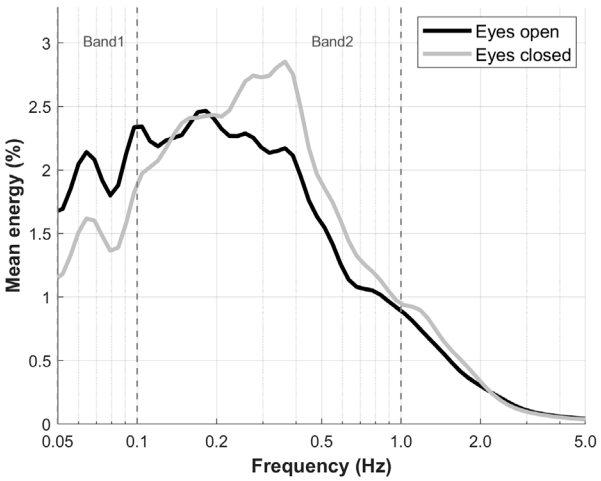


Fig. 2. Mean percentage contribution of energy within the analyzed intervals to the total energy.

Figure 3 illustrates the average scalogram for the entire study group, the instantaneous energy trajectories, and the cumulative percentage contributions of energy within each specific band relative to the total energy accumulated across all analyzed bands during the Romberg test with eyes open. Logarithmic scales are applied to the vertical axes of both plots. A high level of energy density is observable at the beginning of the trial in the second and third bands, followed by an approximately constant level of average instantaneous energy across all bands from the 5-second mark until nearly the end of the test.

Figure 4 presents the results of identical computations for the eyes-closed trial. A noticeable energy transfer from the first to the second band is apparent, along with a higher energy level across all bands compared to the eyes-open trial.

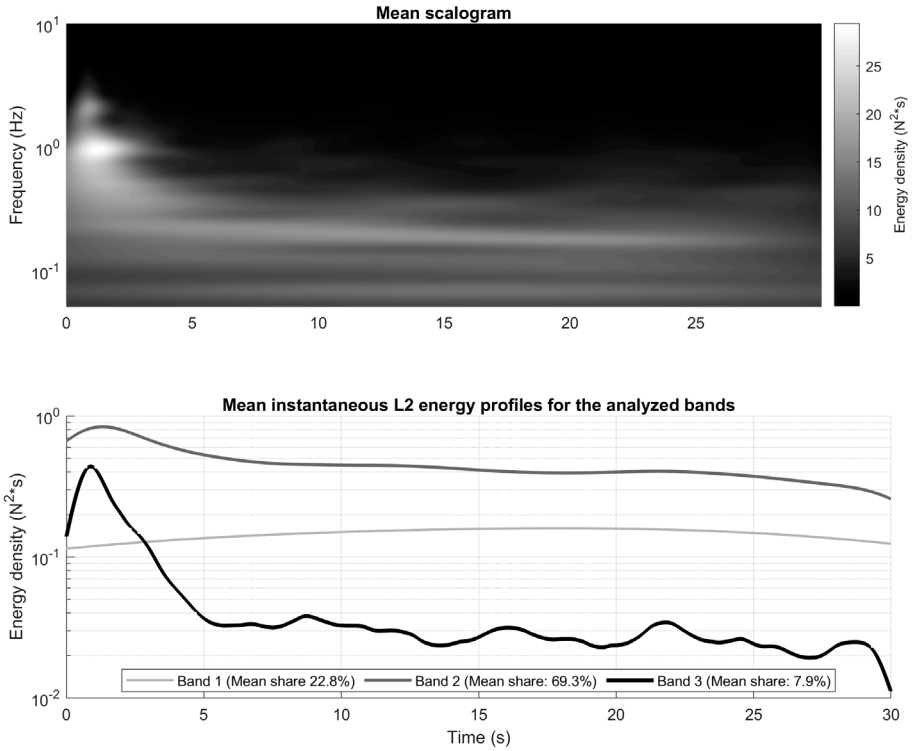


Fig. 3. Mean scalogram (top panel) and energy profiles (bottom panel) for the eyes-open condition.

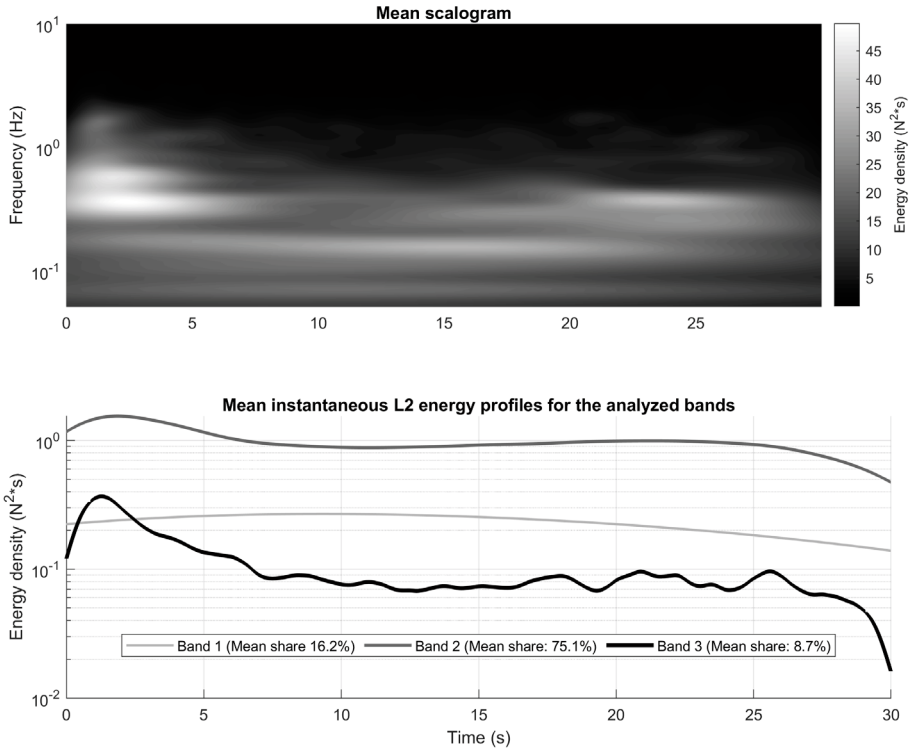


Fig. 4. Mean scalogram (top panel) and energy profiles (bottom panel) for the eyes-closed condition.

The Shapiro-Wilk test confirmed that the log-ratio differences followed a normal distribution (W = 0.988, p = 0.562). Consequently, a paired samples t-test was conducted to evaluate the change in energy distribution between the two experimental conditions. The analysis revealed a statistically significant shift in the energy balance from the eyes open to the eyes closed condition, $t(92)$ = 3.08, p = 0.003, 95% CI [0.15, 0.70], Cohen's d = 0.46, with a mean log-ratio decrease of 0.43. Given that the third energy band exhibited no meaningful variation, this substantial drop in the *LR = ln(Band 1/Band 2)* value provides robust statistical evidence of a direct, state-dependent energy redistribution (transfer) from Band 1 to Band 2 upon eye closure.

Individual trajectories for all N = 93 participants are represented by the semi-transparent grey lines, illustrating the person-specific shifts from the eyes open to the eyes closed state. The thick line with diamond markers denotes the overall sample mean trend. The vertical axis represents the log-ratio transformed values, calculated as *LR = ln(Band 1/Band 2)*. A statistically significant downward shift (p = 0.003) reflects a systematic energy transfer from Band 1 to Band 2 upon eye closure.

Discussion

The primary objective of this study was a time-frequency analysis of the vertical ground reaction force acting on the forefoot of the right lower limb (vGRF_F) during the Romberg test. Within this analysis, the mean percentage contributions of the signal energy were first determined across three frequency bands commonly utilized in spectral analyses of COP waveforms [8, 20, 11]. These contributions were quantitatively consistent with the findings for the rearfoot presented in [18]. However, a discernible shift of the dominant peak toward higher frequencies by 0.07 Hz was noted within Band 2 during the eyes-closed trial. Approximately 90% of the total signal energy, regardless of the Romberg test conditions, was concentrated in the frequency band below 1 Hz. This result deviates from the findings of COP spectral analysis in the anteroposterior (AP) plane during quiet standing, where 90% of the energy of the signal recorded by the Kistler force platform is located below 2 Hz [7]. The vGRF_F spectrum also differs from the spectrum of vertical ground reaction forces measured using traditional force platforms [21, 22], as it lacks the peaks in the 4–6 Hz range characteristic of the latter. This demonstrates that the analyzed signal reflects a distinct biomechanical profile and carries different diagnostic information than traditional signals used in posturography.

The results presented in Figures 3 and 4, which represent the averaged recordings for the entire study group (N = 93), indicate that regardless of the Romberg test variant, a distinct increase in energy density occurs within Band 2 and Band 3 during the first 5 seconds of both measurements. These values are significantly elevated relative to the remainder of the signal, where the energy density remains approximately constant. The Tukey window applied in the calculations (owing to its edge-tapering characteristics) does not mask this phenomenon within the analyzed bands. This demonstrates that the higher energy density is a direct consequence of the postural stabilization process following the 'START' command. The total mean signal energy was 1946 N²s for the eyes-open trial and 2774 N²s for the eyes-closed trial, respectively. Consequently, altering the test conditions results in an approximate 43% increase in signal energy, reflecting higher postural activity.

One of the most prominent findings of this computational phase is the significant state-dependent shift in energy distribution between the two experimental conditions. We observed

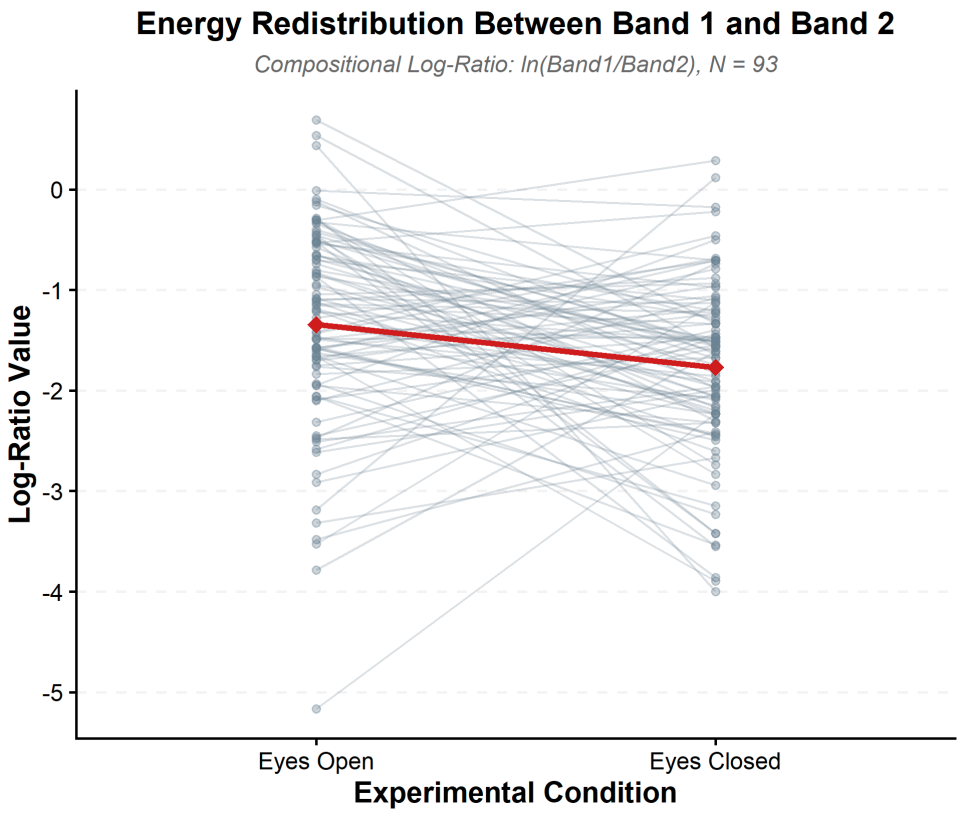


Fig. 4. Mean scalogram (top panel) and energy profiles (bottom panel) for the eyes-closed condition.

a systematic redistribution of energy characterized by a distinct transfer from Band 1 to Band 2. These changes were addressed through a log-ratio approach that allowed us to bypass the mathematical constraints of the 'closure effect' inherent to percentage data, providing a more mathematically robust representation of relative band dynamics. Given that Band 3 remained exceptionally stable, the observed drop in the log-ratio values cannot be attributed to a general baseline shift, but rather reflects a targeted, reciprocal compensation mechanism. This clear energy flow from Band 1 to Band 2 during the transition from the eyes-open to the eyes-closed state underscores a functional reorganization of neurological or physiological resources, highlighting how a simple alteration in sensory input can trigger a systematic macro-level modulation of the underlying signal structure.

In concluding the performed analyses, certain methodological limitations of the present study must be addressed. The primary limitation concerns the direct generalizability of the obtained results to alternative measurement systems. The time--series waveforms of the ground reaction forces acting on individual anatomical zones of the foot, utilized in this research, are generated by the hardware manufacturer's proprietary software. These algorithms rely on an arbitrary segmentation of the foot support area into specific zones [23], as well as distinct proprietary procedures for filtering and analog-to-digital signal processing directly from the pressure sensors.

The lack of full access to the raw data and the architecture of the computational algorithms (the so-called black-box effect) implies that the absolute energy density values and the proportions between bands may be device-specific. This could impede direct comparisons between our findings and studies conducted on platforms from different manufacturers. Nevertheless, given the large size of the study cohort (N = 93) and the fact that all participants were evaluated under identical hardware conditions, the observed trends and relative energy shifts between bands – analyzed via the log-ratio approach – maintain complete consistency and high applicational value for postural diagnostics.

Finally, a limitation of the present study is that concurrent measurements of vGRF_F and COP were not performed within the same cohort; this factor should be taken into account when interpreting the first paragraph of the discussion.

Conclusions

Appropriately preprocessed vertical ground reaction force (vGRF_F) signals can serve as a valuable complement to traditional stabilographic metrics derived from conventional force platforms routinely utilized in posturographic research.

This signal possesses high discriminative capability within the low-frequency range of 0.05 to 1 Hz, enabling a precise evaluation of postural control mechanisms and the identification of subtle shifts in balance maintenance strategies.

The proposed methodological approach opens new avenues for widely accessible clinical diagnostics, allowing for advanced postural stability analysis using more portable and cost-effective measurement systems.

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