Repeatability Assessment and Variability Measures of GRF in Able-Bodied Gait

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Introduction: Ground reaction forces (GRF) are used in a number of ways for human gait analysis, from simple comparisons between normal and pathological gait conditions, evaluation of pre- and post-intervention conditions, functional sidedness and asymmetry assessment, and as inputs into inverse dynamic models for the derivation of variables such as joint forces, moments and powers. Investigators for the above purposes often use discrete parameters of the GRF-time patterns, such as peak forces and time-to-peak forces [1-3], time integrated parameters such as impulse (force-time integrals) over the stance phase, force-time waveforms [4], and the Fourier coefficients derived from waveform frequency domain analysis [5,6]. The criterion for the choice of the parameter to use is often based on earlier research or on a preset acceptable variability limit. The most common statistics used for parameter waveform variability assessment [7-9] are the coefficient of variation (CV), the average standard deviation (aSTD), and the variability ratio (VR). The objective of the present study was to determine the differences in the repeatability assessment, on the GRF components in able-bodied gait, resulting from each of the above statistics.

Statement of Clinical Significance: The statistic used for variability quantification, along with biases and limitations associated with it, can have a significant impact on the results and on the subsequent conclusions made. For clinical decision making, are any of these statistics appropriate for comparative repeatability measurements among parameters?

Methodology: Forty-five volunteers 21 to 83 years old, free from neuromuscular disorders of the locomotion system participated in the present study. The subjects were recruited from the university surrounding community, and an informed written consent was obtained from each. Upon the arrival of each volunteer to the biomechanics laboratory he/she was asked to walk (practice) a number of times along a 10m walkway at his/her own self-selected cadence. A number of familiarization trials were necessary to ensure constant velocity of progression and good force plate contact. Once familiarization with the protocol was achieved 6-8 good trials with right-foot force plate contact were captured. Five trials for each individual similar in gait speed (within 0.1 m/s) were used for further analysis. An AMTI strain gauge force plate (AMTI Inc, MA) sampling at 1200 Hz was used to measure the ground reaction forces. The stance phase of each of the five trials was time normalized to 100%. The ensemble set for each individual of the 5 trials of each of the 3 GRF waveforms (in body weights, BW), was subjected to the waveform variability quantification algorithms (CV, aSTD, and VR):

$$CV = \frac{\sqrt{\frac{1}{T}\sum_{t=1}^{T}\sigma_t^2}}{\frac{1}{T}\sum_{t=1}^{T}\left|\overline{X_t}\right|} \quad , \quad aSTD = \frac{1}{T}\sum_{t=1}^{T}\sigma_t \quad , \quad VR = \frac{\sum_{t=1}^{T}\sum_{n=1}^{N}(X_{nt}-\overline{X_t})^2 \,/\, T(N-1)}{\sum_{t=1}^{T}\sum_{n=1}^{N}(X_{nt}-\overline{X})^2 \,/\, (TN-1)}$$

where, $\boldsymbol{T}$ is the number of points in the waveform (100 in this case), $\boldsymbol{t}$ refers to a single point in time, $\boldsymbol{N}$ is the number of trials (5 in this case), $\boldsymbol{n}$ refers to a single trial, $\boldsymbol{X_{nt}}$ and $\boldsymbol{\sigma_t}$ refer to the value of a given waveform and the standard deviation of the ensemble at $\boldsymbol{t}$. The calculated statistics were plotted against the range and the mean absolute amplitude of the waveform ensemble in an attempt to identify biases and limitations of these algorithms. Changes in the repeatability of the GRF components with age were used for data interpretation purposes.

Results and Discussion: Figure 1a indicates a bias of the CV with respect to the parameter range, decreasing from the mediolateral to vertical GRF components for all the individuals. This was not expected since the CV of variation is designed to standardize the variability of the parameter to the mean absolute amplitude of the parameter. A similar pattern is found when the CV is plotted against the parameter amplitude indicating the mediolateral (M/L) as the least repeatable and the vertical as the most repeatable amongst the 3 GRF components. In this case we can argue that the CV favors the vertical GRF since its absolute mean amplitude is quite high and that of the M/L and anteroposterior (A/P) GRF components is close to zero. This finding as expected was opposite when the aSTD is considered (Figure 1b). The aSTD has been questioned since it does not take into account the amplitude of the measured parameter. Based on these findings, one may argue that both the CV and the aSTD are not good measures of variability when intended to reflect differences in repeatability between parameters of different amplitude scales. The VR of each of these parameters on the other hand displays no trend with respect to the range (Figure 1c) or the mean absolute amplitude of the parameter measured. The VR is the ratio of square deviations from the respective means and thus it is independent from the range and mean amplitude of the parameter itself. In this case the M/L is the least repeatable component and that there is no measurable difference in repeatability of the vertical and the A/P GRF components. Interestingly, the M/L GRF variability to age relationship shown in Figure 2, shown by each of these statistics, would have been interpreted differently based on the statistic chosen by the investigator.

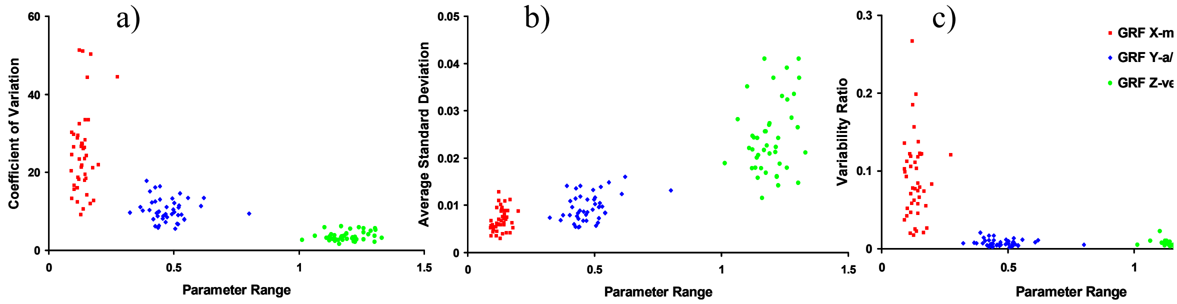

Figure 1. Data points represent: a) CV, b) aSTD, and c) VR calculated on each subjects's waveform set plotted against the range, separate for the (M/L) (■), (A/P) (♦), and vertical (●) GRF components.

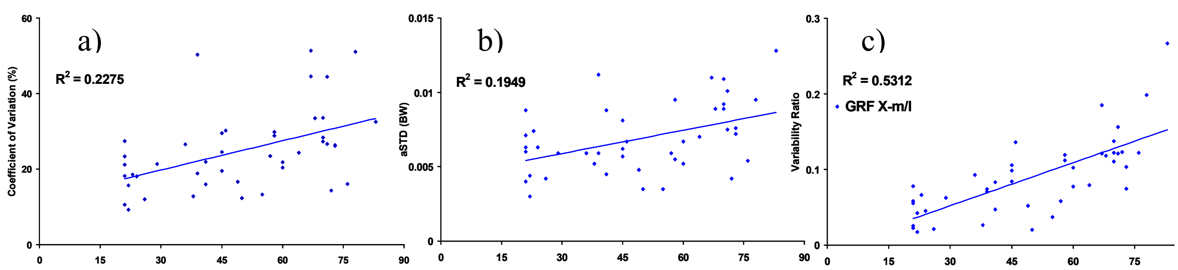

Figure 2. M/L GRF variability as related to age: a) CV, R^2=0.23, b) aSTD, R^2=0.19, and c) VR, R^2=0.53.

References: [1] Hamill et al., Res Quart, 55(3): 289-293, 1984; [2] DeVita & Bates, Hum Mov Sci, 7:73-85, 1988; [3] Hamill & McNiven, Hum Mov Sci, 9:117-131, 1990; [4] Munro et al., J Biomech, 20:147-155, 1987; [5] Patterson & Brown, IEEE Eng Med Biol, 6:12-16, 1987; [6] Giakas & Baltzopoulos, Gait & posture, 5:189-197, 1997; [7] Winter, D.A., Hum Mov Sci, 3:51-76, 1984; [8] Kadaba et al., J Orthop Res, 7:849-860, 1989; [9] Gabel & Brand, Electoenceph & Clin Neurophys, 93:188-201. 1994.