ACOUSTICS 2017 PERTH
SOUND, SCIENCE AND SOCIETY

Intra-walker variability of footfall vibration and the effects of walkers' mass and carrying loads

Jason Qian (1), Aaron Miller (1) and Dominik Duschlbauer (1)

(1) Structural Dynamics, SLR Consulting Australia Pty Ltd, Lane Cove, Australia

ABSTRACT

Excessive floor vibration in buildings can make occupants uneasy and many prediction methods of varying degree of sophistication have been developed over the years to assist engineers in the prediction of footfall vibration. Prediction methods categorised as "impulse response" are often applied to relatively stiff floors. For impulse response methods, the predicted footfall vibration is proportional to a nominal walker impulse which is determined by the walker characteristics (such as stepping frequency), as well as the underlying floor parameters (such as modal mass and fundamental frequency). Among the reviewed impulse response methods, the dependence of the mass of the walker on the impulse is not implemented unanimously.

This paper examines the influence of walker mass on the response of a relatively stiff floor. Up to 10 walkers of varying mass are considered, with each walker traversing the bay of interest at different stepping frequencies and carrying varying loads within a backpack. For each configuration, the walker traverses the bay at least 10 times to account for intra-walker variations between traversals, which are also explored.

1 INTRODUCTION

Numerous models for predicting footfall vibration have been proposed over the last decades. The design is typically based on a nominal walker mass for resonant floors and a constant stepping frequency for resonant and impulse response floors. Many of the prediction methods for impulse response floors, which are also known as high frequency floors are summarised within Brownjohn and Middleton (2007). No special allowances are made for walkers carrying load, walkers' footwear or for individuals' walking styles. It must be assumed that such effects are covered by underlying statistics ie working with high percentiles rather than averages.

Of particular interest was the effect of walker weight on footfall vibration. In this paper the variability in footfall vibration induced by single persons are studied. The effect of carrying loads of 5-10 kg is also addressed as well as how the variability and load impact on footfall vibration when walking at a leisurely pace and fast pace.

This paper focuses on footfall vibration with respect to human comfort considerations and as such Vibration Dose Values (VDVs) are primarily reported. Miller and Duschlbauer (2013) have previously discussed acceptance criteria for human comfort, and consider VDVs to be a better assessment metric for assessing the effects of vibration on humans than using one-third octave spectra as required when working with base curve methods (as advocated in AS 2670.2-1990 (this Standard has been withdrawn)).

2 Description of the Tests

2.1 Walkers

Nine men and women participated in the tests. Their weight ranged from 65 kg to 123 kg. Each walker completed the same test program which consisted of crossing the test bay ten times to get results for one measurement configuration. A least 10 crossings were required to allow for extracting statistically meaningful parameters (Bates et al, 1983).

A total of four measurement configurations were tested for each walker. Two discrete walking speeds referred to as 'slow walking' and 'fast walking'. At each speed the walkers carried no extra weight ('no additional mass') initially and then repeated the test at the same speed with extra weight ('with additional mass').

The walkers were asked to walk at a pace they were most comfortable with ('slow walking') and, in addition to that, at a quick pace ('fast walking'). No further instructions were given and the use of a metronome was intentionally discarded to ensure the subjects walked naturally. Most subjects repeated the test program with a 5 kg backpack strapped to their backs and two walkers used a 10 kg backpack. Some walkers volunteered to do the tests with different shoes as well.

The tests were undertaken out of office hours to ensure very low ambient vibration levels.

2.2 Test Bay

The test bay was located on Level 2 of SLR's Sydney office and the column spacing was 11 m by 11 m. The test bay accommodated desks and book shelfs. Carpet tiles were laid. The test bay had a dominant response at 8.4 Hz and its drivepoint mobility in the centre of the bay is shown in Figure 1. The damping was calculated to be 2.5 % critically damped. At 8.4 Hz the modal mass is approximately 50 tonnes and the dynamic stiffness is 175 MN/m. The floor's response to footfall vibration is considered to be consistent with impulse response floors, ie an absence of a resonant build-up of footfall vibration.

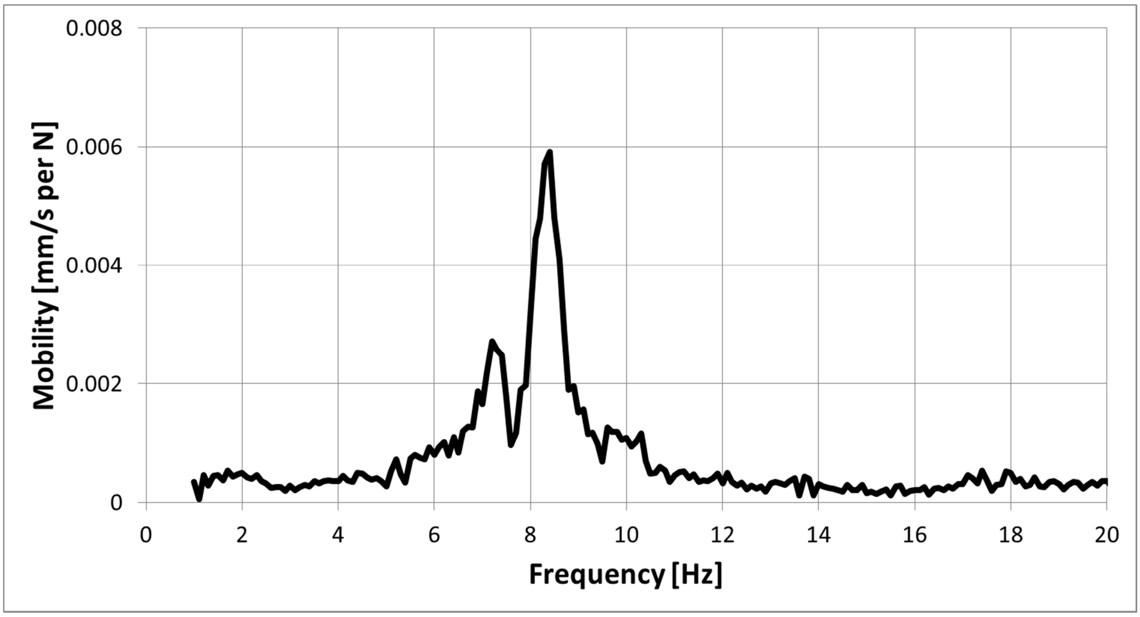

Figure 1: Mobility

2.3 Data Acquisition and Signal Processing

Unweighted raw-acceleration was measured in the centre of a bay. A 10 V/g Wilcoxon accelerometer was hot-glued to the centre of the bay and a Rion DA-21 4-channel data recorder were used. The sampling frequency was 256 Hz and matching 100 Hz anti-aliasing low-pass filters were used.
The raw acceleration was W_b-weighted (BS 6472-1:2008) and the VDVs for each individual crossing were calculated. The raw acceleration was also integrated to velocities and the maximum 1 s root-mean-square (RMS) velocities for each crossing were calculated.

3 Results

The result sets using the VDV metric are presented in Figures 2 to 7. Results in 1 s RMS values are attached as Appendix A (Figures 8 to 11). The data set for each walker in a particular configuration is shown as an average for all ten crossings (symbol) and the highest and lowest individual VDV (error bars).
Assessing the results in terms VDVs and 1 s RMS values shows similar trends and analogous observations would be made. For this reason the discussion will focus on VDVs only. It is only noted that the measured 1 s RMS velocities are generally consistent with the footfall vibration that can be expected in the test bay based on its dynamic properties (as reported in Duschlbauer and Miller (2014)).

3.1 Stepping Frequencies

Measured VDV ranges versus average stepping frequencies (averaged over the ten crossings of a configuration) are shown in Figures 2 and 3.
The stepping frequencies for comfortable walking (referred to as 'slow') for the walkers fell typically between the 1.6 Hz to 1.8 Hz range (or 96-108 beats per minute (bpm)). The fastest slow walking pace was just below 2.1 Hz. When asked to walk fast, the walking frequency range increased to 1.8 Hz to 2.4 Hz (or 108-144 bpm).
Walking with additional mass (Figure 3) appears to have caused the walkers to walk slightly faster compared to no additional mass (Figure 2).
For walking without additional mass (Figure 2) there is no clear trend of the VDVs increasing with stepping frequencies, however, for walking with additional mass (Figure 3) a slight general upward trend can be identified. However, the increase in average levels (symbols) with frequency is much less than the error bands (ie the intra-walker variability).

The dominant floor mode is 8.4 Hz and the fourth and fifth harmonic would excite the floor mode at stepping frequencies of 2.1 Hz and 1.68 Hz, respectively. However, results for stepping frequencies close to 1.68 Hz and 2.1 Hz are not significantly higher than at other frequencies. This observation is consistent with impulse response floors.

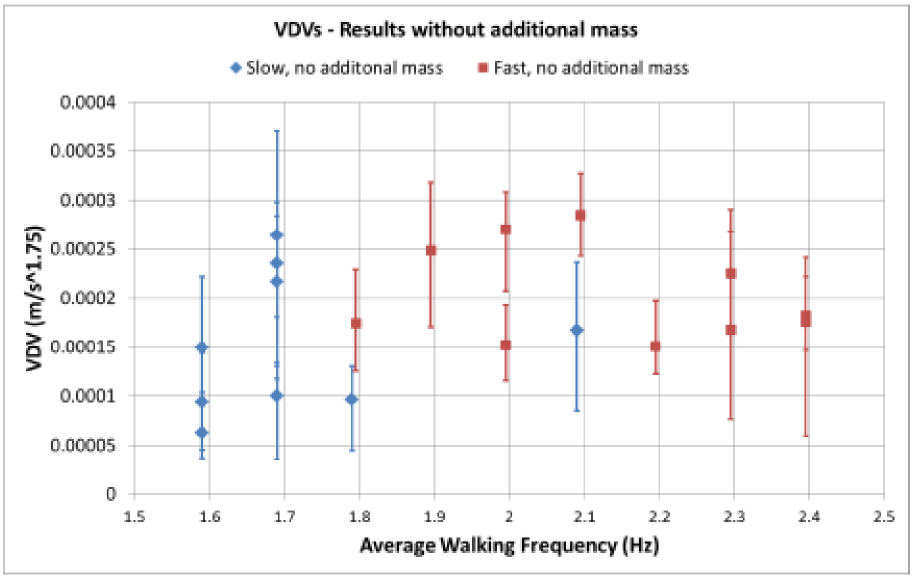

Figure 2: VDV Results versus Stepping Frequency (no additional mass).

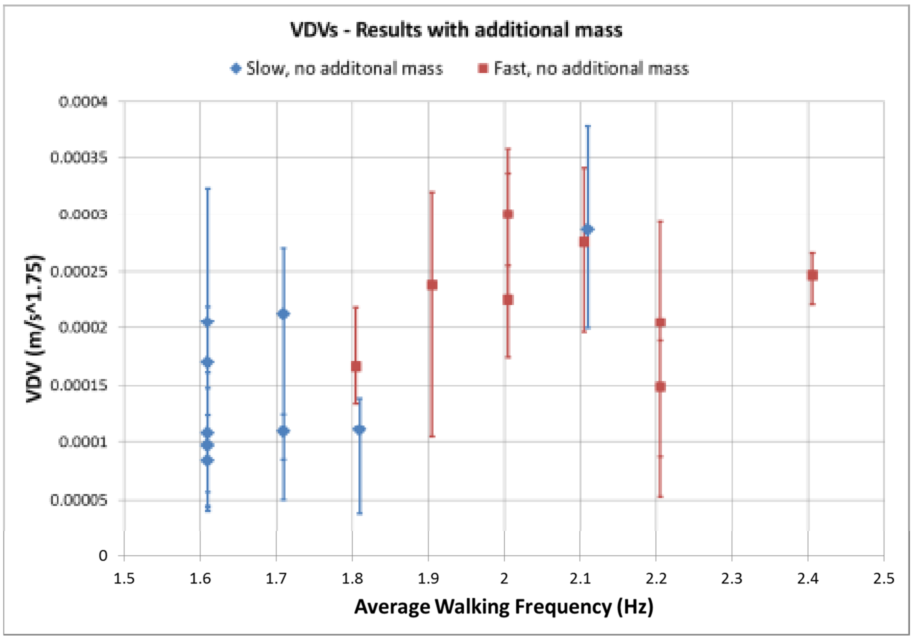

Figure 3: VDV Results versus Stepping Frequency (with additional mass).

3.2 Effect of Mass

Measured VDV ranges versus walker weight are shown in Figures 4 to 7.

The surprising outcome of this investigation is that there is no correlation between walker mass and floor vibration. Unlike for soft, resonant floors where the walker mass is directly proportional to the predicted floor vibration levels, most prediction methods for stiff floors do not explicitly account for the walker mass. This omission of the dependence on the walker mass is consistent with the observed lack of correlation of vibration with walker mass. This lack of correlation between walker mass and floor vibration is also exhibited in the results for walkers carrying extra weight. For some walkers floor vibration increases with extra weight and for some walkers floor vibration decreases with extra weight. The difference in the averaged vibration levels with and without extra weight is much less than the intra-walker variability. The intra-walker variability is surprisingly large and possibly originates from slight differences in gait and walking speed and how the foot makes contact with the floor.

The two data point pairs above 120 kg are one person walking in stiff dress boots and running shoes. The average VDVs for this person walking in dress boots are less than half of the VDVs when the same person was wearing running shoes. The walker did step at the same stepping frequencies with both types of shoeware. This shows that, at least for stiff floors, either the effect of shoes or the effect the shoes have on a person's walking style can have a large impact on the resulting floor vibration levels. These effects are completely ignored in all prediction methods known to the authors.

Given the large intra-walker variability in footfall vibration, the authors believe precise prediction of footfall vibration based on a hypothetical individual is generally not feasible nor practical. Any design has to be inherently conservative and the degree of conservatism depends on how detrimental occasional criteria exceedances are judged.

Based on these observations the authors suspect that floor vibration will also be affected by the floor covering as this likely impacts on people's gait. However, different floor coverings may have different effects on different walkers and more work is clearly required in this area.

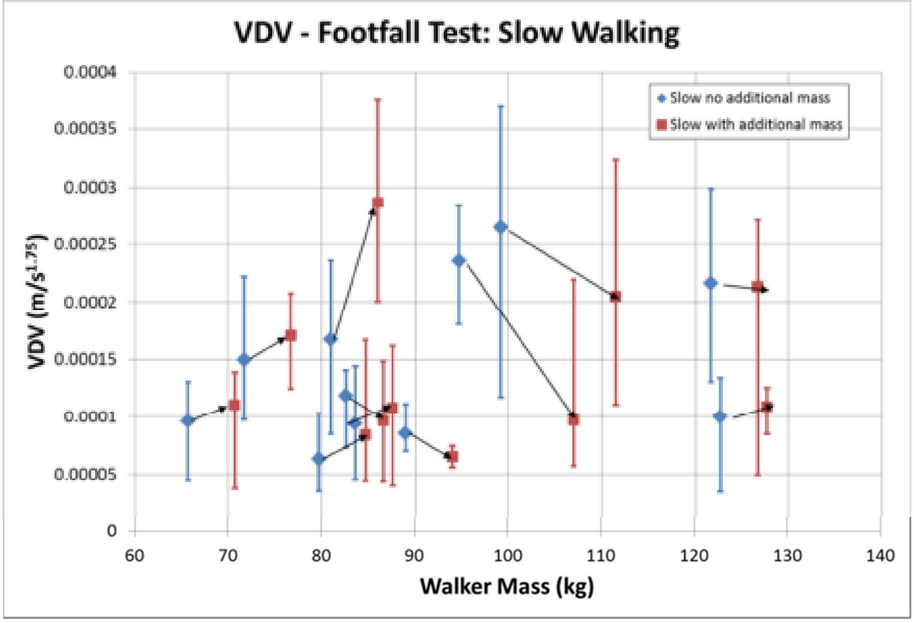

Figure 4: VDV Results – Slow Walking

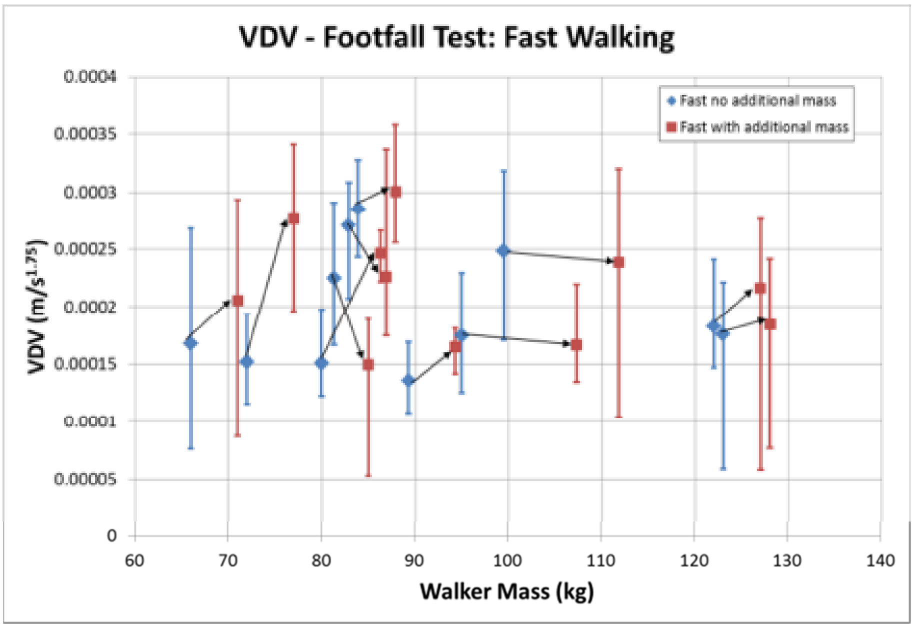

Figure 5: VDV Results – Fast Walking

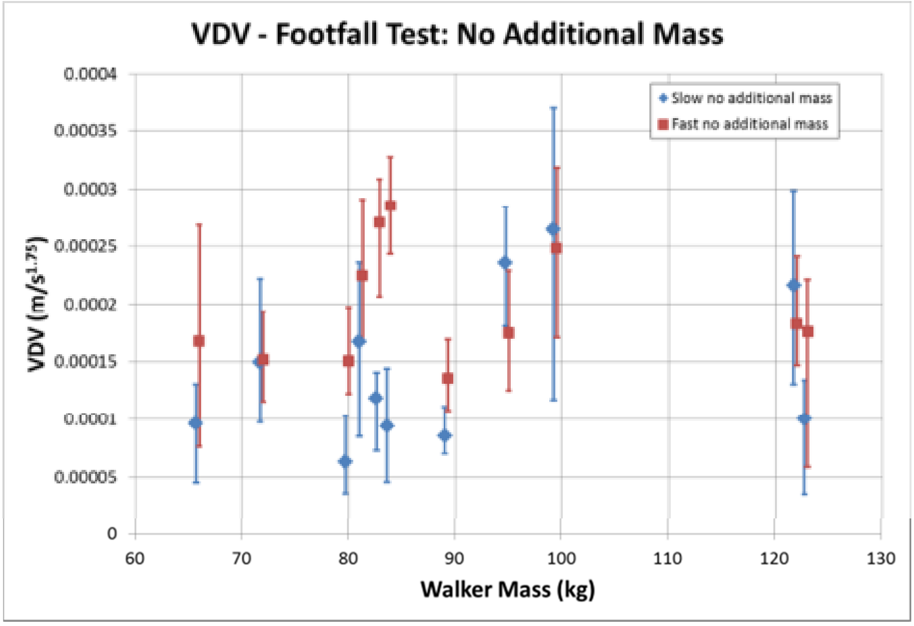

Figure 6: VDV Results – No Additional Mass

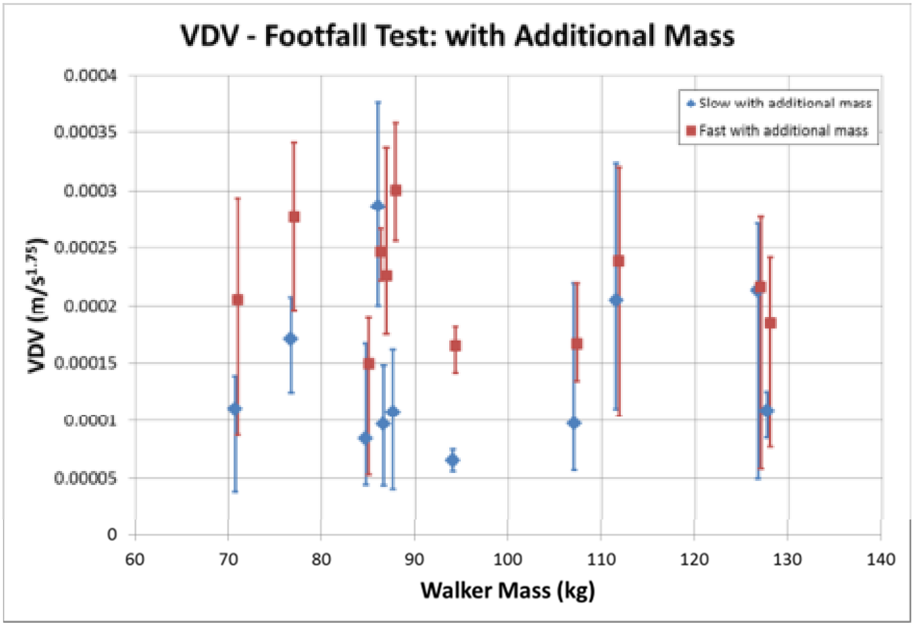

Figure 7: VDV Results – with Additional Mass

4 Conclusions

In this paper footfall vibration measurements on a stiff floor for nine different individual walkers with weight ranging from 65 kg to 123 kg are presented. Each walker crossed a test bay at least ten times in four different configurations.

The vibration measurements indicate that there is no clear correlation between walker mass and footfall vibration. Further the results show that carrying additional weights of 5 to 10 kg in backpacks does not consistently alter footfall vibration. The intra-walker variability was found to dominate the overall variability of the results.

More work is clearly required to understand the sources of the observed intra-walker variability in footfall vibration.

REFERENCES

Australian Standard 2670.2-1990 *Evaluation of human exposure to whole-body vibration Part 2: Continuous and shock-induced vibration in buildings (1 to 80 Hz)*.

Bates, B. T.; Osternig, L. R.; Sawhill, J. A. 1983. *An assessment of subject variability, subject-shoe interaction, and the evaluation of running shoes using ground reaction force data*. J Biomechanics, Vo. 16, No.3, pp.181-191.

British Standard 6472-1:2008 *Guide to evaluation of human exposure to vibration in buildings Part 1: Vibration sources other than blasting*.

Brownjohn, J. M. W.; Middleton, C. J. 2007 *Procedures for vibration serviceability assessment of high-frequency floors.* Engineering Structures Vol. 30 pp. 1548-1559

Duschlbauer, D; Miller, A.; 2014. *Modal floor parameters and their correlation with footfall vibration*. Internoise 2014 – Melbourne.

Miller, A.; Duschlbauer, D 2013. *Footfall Vibration and the Dynamic Response of Different Structures – A case study comparing predicted and measured results*. Proceedings of Acoustics 2013 – Victor Harbor.

APPENDIX A: Vibration Levels in 1s RMS Velocities

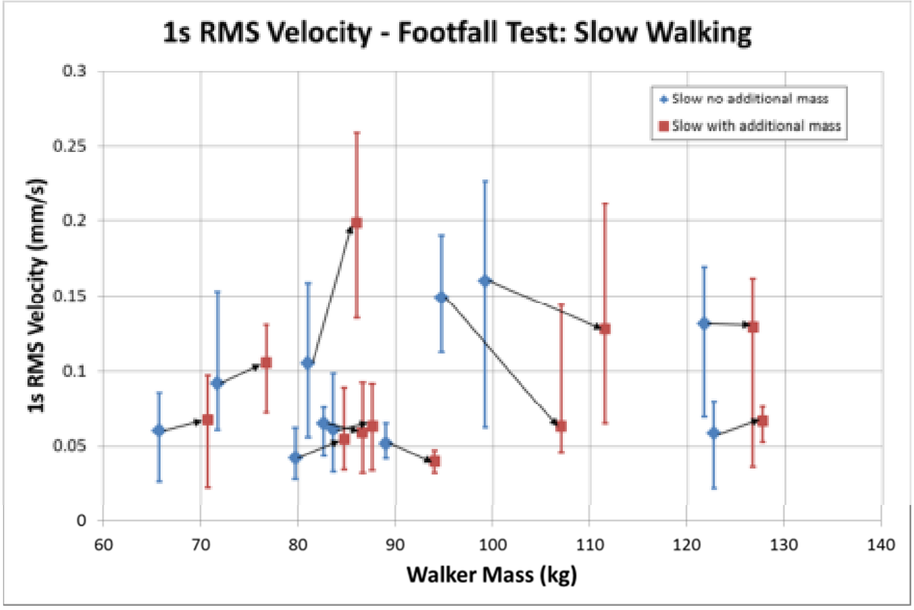

Figure 8: 1s RMS Velocity Results – Slow Walking

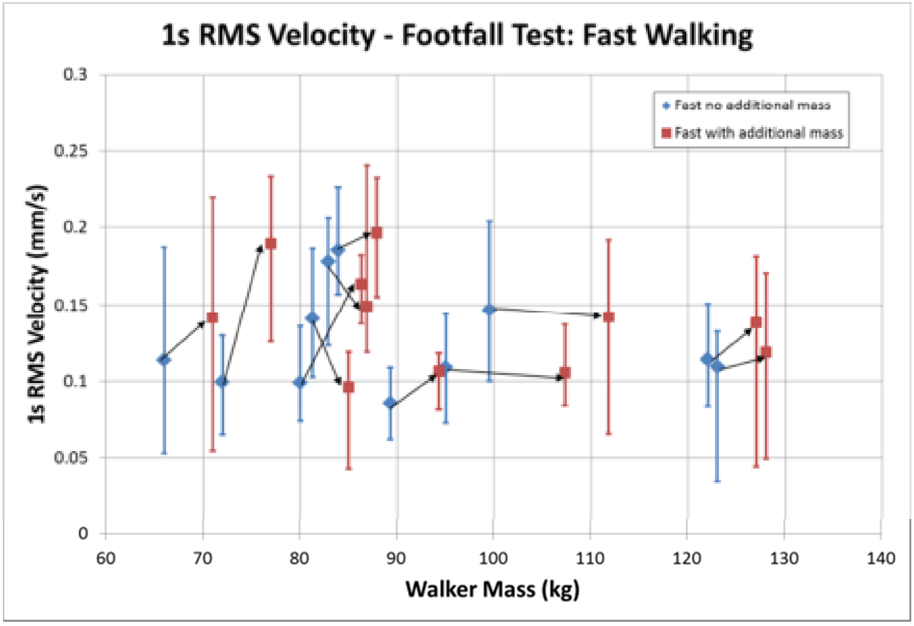

Figure 9: 1s RMS Velocity Results – Fast Walking

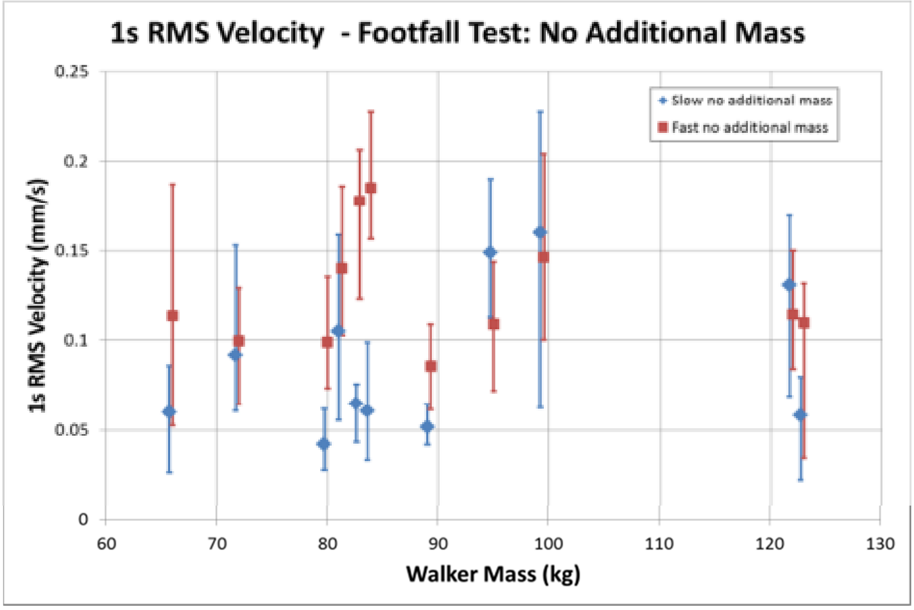

Figure 10: 1s RMS Velocity Results – No Additional Mass

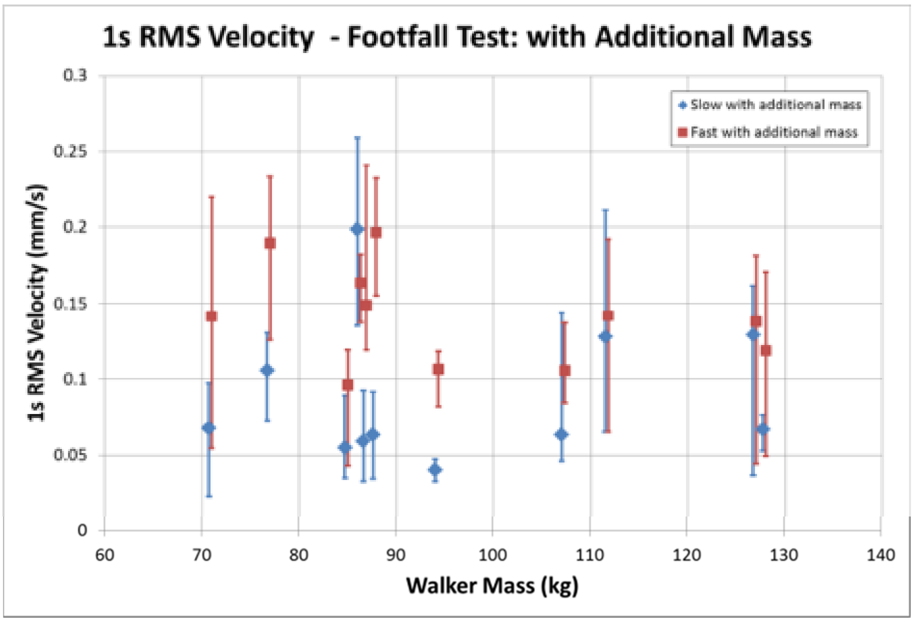

Figure 11: 1s RMS Velocity Results – with Additional Mass