Estimating ground reaction forces from accelerations during prolonged load carriage

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Introduction

Ground reaction forces (GRFs) are the forces exerted onto the ground, in the vertical (GRF_{vert}) and horizontal (GRF_{brake}) directions, by the body's center of mass. Activity monitors (AM) measure accelerations related to ground contact in the vertical (ACC_{vert}) and horizontal (ACC_{brake}) directions. Accelerations have been related to GRF_{brake} while walking and running (Neugebauer, Collins, & Hawkins, 2014) and GRF_{vert} while walking and carrying load (Neugebauer & LaFiandra, 2018).

Greater GRFs can take a significant toll on one's body and this research informs people on the risks of undergoing rapid accelerations while carrying heavy loads and how these factors affect the forces exerted onto oneself. If applied correctly, physicians could adapt the results of this research, identifying possible causation of an injury as a result of increased GRFs. Prior to this study, no one has examined the relationship between accelerations and prolonged load carriage on GRFs. Therefore, the purpose of this experiment was to determine an equation identifying the relationship between GRFs and accelerations, during prolonged load carriage.

Materials and Methods

The materials implemented in this experiment were a force plate treadmill, loaded combat vests and rucksacks (figures 1 and 2), and an accelerometer contained within a tri-axial ACTi-Graph GT3X+ activity monitor (figure 3). The force plate treadmill was utilized to measure each subject's vertical and braking GRFs, which were collected through the data processing program, Cortex©. Variable loads were implemented to investigate how carried mass affects vertical and braking GRFs.

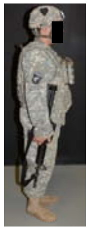


Figure 1 (left): Subject wearing the 26.1 kg load combat vest.

Figure 2 (right): Subject with the 48.5 kg combat vest and rifleman load.

Figure 3 (above): The tri-axial ACTi-Graph GT3X+ activity monitor, placed over the subject's left hip.

Twelve active duty, male soldiers participated in data collection at the SPEAR cross country (XC) course and rifle range (RR) on Aberdeen Proving Ground.

Materials and Methods (cont.)

The subjects walked the following course, going over the force plate treadmill (figure 4) at each distance increment: starting at the force plate (mile 0), completing the XC course (figure 5, mile 2.7), walking to a rifle range (mile 3.7), resting, then walking the XC course a second time (total 6.3 mi). Each subject walked two days. On day one, the subject carried the 26.1 kg load; on day two, the subject carried the 48.5 kg load.

Figure 4 (left): A full body view of the subject walking over the force plate treadmill with the 48.5 kg load.

Figure 5 (right): The subject depicted marching though the unaltered XC trail with the 48.5 kg load.

Trials were completed at self-selected walking speeds (3.0 ± 0.2 mph). Acceleration data was collected by the AM from five seconds before to five seconds after the subject's initial contact with the force plate treadmill. The subject's vertical and braking GRFs were the only inputs. The average peak acceleration values, ACC_{vert} and ACC_{brake}, and the average peak ground reaction force values, GRF_{vert} and GRF_{brake} were determined.

The collected data was fitted to previously published equations estimating GRF_{vert} and GRF_{brake} (figure 6).

$$\ln(GRF_{vert}) = 5.675 + (0.255 \times ACC_{vert}) + (0.095 \times mass_{load}) + (0.006 \times mass_{body}) + (0.003 \times ACC_{vert} \times mass_{load})$$

$$\ln(GRF_{brake}) = 3.773 + (0.665 \times ACC_{brake}) + (0.011 \times mass_{body})$$

Figure 6 (above): The equation estimating GRF_{vert} while walking with load and the equation estimating GRF_{brake} while walking and running (Neugebauer et al., 2014; 2018)

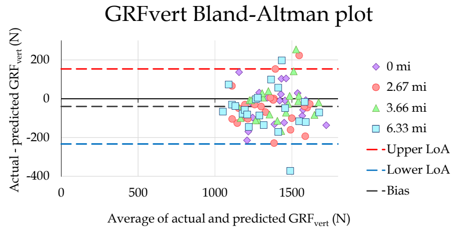
After the data was fitted to the previously published equations, Bland-Altman plots with the collected data were developed, displaying the differences between observed versus predicted GRF_{vert} and GRF_{brake} data. A mixed linear model regression was run in the statistical computing program, R©, to determine the significance of distance in predicting GRF_{vert} and GRF_{brake} with significance defined as $p < 0.05$.

Results

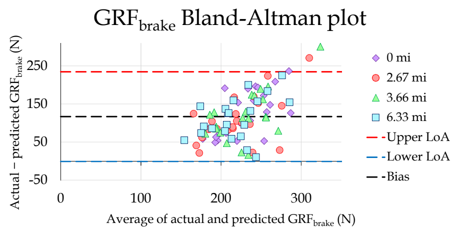
A mixed linear model in R was implemented to verify that distance was insignificant in predicting both GRF_{vert} ($p = 0.12$) and GRF_{brake} ($p = 0.39$). Generally, GRF_{vert} increased as ACC_{vert} increased. The data predicted using the previously published GRF_{vert} equation versus the actual data was associated with a percent error of 6.1% (Graph 1).

Results (cont.)

The data predicted using the previously published GRF_{brake} equation versus the actual data was associated with a percent error of 39.3% (Graph 2). An accurate model is characterized by a Bland-Altman plot bias closer to zero and a smaller distance between the limits of agreement (LoA).



Graph 1 (left): The GRF_{vert} Bland-Altman plot with bias of −40.00 N suggests that the model has a mean overprediction of 40 N, when estimating GRF_{vert}.



Graph 2 (left): The GRF_{brake} Bland-Altman chart with a bias of 116.72, suggests that the model has a mean underprediction of 116.72 N, when predicting GRF_{brake}.

Conclusion

Distance was not supported as a significant variable in predicting GRF_{vert} or GRF_{brake}. The previously published GRF_{vert} equation (Neugebauer & LaFiandra, 2018) was adequate to predict GRF_{vert}, whereas the previously published GRF_{brake} equation (Neugebauer, Collins, & Hawkins, 2014) did not accurately predict GRF_{brake} for this dataset, over a 6.33 mile distance rucksack march. A probable reason for this is the lack of running trials during this study, which the 2014 research included. A new equation is required to predict GRF_{brake}.

References

Neugebauer, J. M., Collins, K. H., & Hawkins, D. A. (2014). Ground reaction force estimates from ACTi-Graph GT3X+ hip accelerations. *PLoS ONE 9*(6): e99023. https://doi.org/10.1371/journal.pone.0099023

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