Published in final edited form as:

J Appl Biomech. 2014 October ; 30(5): 668–674. doi:10.1123/jab.2014-0037.

Assessment of Gait Kinetics Using Tri-Axial Accelerometers

Emma Fortune, Melissa M. B. Morrow, and Kenton R. Kaufman*

Department of Orthopedic Surgery, Mayo Clinic, Motion Analysis Laboratory, Rochester, MN 55905 USA

Abstract

Repeated durations of dynamic activity with high ground reaction forces (GRFs) and loading rates (LRs) can be beneficial to bone health. To fully characterize dynamic activity in relation to bone health, field-based measurements of gait kinetics are desirable to assess free-living lower-extremity loading. The study aims were to determine correlations of peak vertical GRF and peak vertical LR with ankle peak vertical accelerations, and of peak resultant GRF and peak resultant LR with ankle peak resultant accelerations and to compare them to correlations with tibia, thigh, and waist accelerations. GRF data were collected as ten healthy subjects (26 (19–34) years) performed 8–10 walking trials at velocities ranging from 0.19–3.05 m/s, wearing ankle, tibia, thigh, and waist accelerometers. While peak vertical accelerations of all locations were positively correlated with peak vertical GRF and LR ($r^2 > 0.53$, $P < 0.001$), ankle peak vertical accelerations were the most correlated ($r^2 > 0.75$, $P < 0.001$). All peak resultant accelerations were positively correlated with peak resultant GRF and LR ($r^2 > 0.57$, $P < 0.001$) with waist peak resultant acceleration being the most correlated ($r^2 > 0.70$, $P < 0.001$). The results suggest that ankle or waist accelerometers give the most accurate peak GRF and LR estimates and could be useful tools in relating physical activity to bone health.

Keywords

ground reaction force; loading rate; body-worn sensors; ankle acceleration; vertical axis

Introduction

Repeated short durations of dynamic activity with high impact forces and loading rates (LRs) have been shown to increase bone mineral density (BMD).¹ Characterizing dynamic activity with measures of ground reaction force (GRF) and peak LR is commonly performed using clinical gait analysis.² However, evaluating GRFs and LR during dynamic activity in the free-living environment is not being done and could highlight a need for changes in activity intensity to maintain bone health. Body-worn accelerometers are accurate and useful tools for tracking physical activity,³ and may provide the means to indirectly assess GRF

Correspondence Address: Kenton R. Kaufman, Ph.D., P.E., Mayo Clinic, 200 First Street SW, Rochester, MN 55905, Phone: 507-284-2262, Fax: 507-266-2227, Kaufman.kenton@mayo.edu.

Conflict of Interest Disclosure: None of the authors has a conflict of interest to declare, and all authors were involved in the study design, data collection and interpretation, and contributed to the writing of the manuscript. This manuscript is not currently being considered for publication by another journal.

and LR in the field. A small number of studies have shown positive correlations of peak accelerations, measured with body-worn accelerometers, with peak vertical and resultant GRF and LR in both adults⁴⁻⁶ and children.⁷ However, these studies used accelerometers placed on the hip, thigh, tibia, and/or wrist but did not investigate the relationship of ankle accelerations with peak GRF and LR. Since peak LR is a key indicator of loading underfoot⁸ and the ankle is closer in location to ground contact, ankle peak accelerations may provide higher correlations with peak GRF and LR. As an individual's gait velocity and, therefore, peak heel-strike acceleration can be highly variable in the free-living environment, it is important to determine the correlations with peak GRF and LR across a wide range of gait velocities. Previous studies have not investigated a wide range of gait velocities or gait velocities less than 0.67 m/s.^{4-6,9,10} Normal gait velocities of less than 0.69 m/s have been characterized as a risk factor for fractures.¹¹

The aims of this study were to determine the correlations of peak vertical and resultant GRF and LR with accelerations recorded from accelerometers worn at the ankles during walking at a wide range of gait velocities and to compare them to correlations with accelerations recorded from the tibia, thigh, and waist. As previous studies have demonstrated positive correlations peak vertical and resultant GRF and LR with waist, thigh, and tibia accelerations⁴⁻⁷ and the ankle is closest in location to ground contact, we hypothesized that ankle accelerations would have higher positive correlations than waist, thigh, or tibia accelerations.

Methods

Ten (four males, six females) healthy adults were included in this study. At the time of evaluation, the median (range) age, mass, and height of the subjects were 26 (19–34) years, 66.4 (45.2–97.3) kg, and 1.75 (1.54–1.88) m, respectively. All subjects wore their own athletic shoes. Exclusion criteria were musculoskeletal deficits history, neurological impairment or lower extremity surgery. The study protocol was approved by the Mayo Clinic Institutional Review Board and each subject provided written informed consent before participating.

Accelerometer data were captured from each subject using custom-built activity monitors developed at the Mayo Clinic.¹² Subjects wore activity monitors, secured with straps, below the navel on the waist, on the midpoints (between the lateral epicondyle and the greater trochanter) of the bilateral thighs, on the right and left tibial tubercles, and on the lateral malleoli of the ankles. Each activity monitor incorporated a tri-axial MEMS accelerometer (analog, $\pm 16g$ (where $g=9.81 \text{ m/s}^2$), Analog Devices) and each axis was sampled at 100 Hz. In the neutral anatomical position, the y-axis of the activity monitor local coordinate system was aligned with the superior-inferior anatomical axis of each body segment. Proper alignment of the activity monitor was visually confirmed by study investigators. Gait velocities were calculated based on the distance travelled and the time duration recorded by photocells placed at either end of the walkway. GRF data were collected at 600 Hz from five force plates (AMTI Inc., Watertown, MA; Kistler Instruments, Winterthur, Switzerland). 2D video data were simultaneously acquired at 60 Hz.

Accelerometer, force plate, and video data were acquired as subjects performed 8 to 10 walking trials in a straight line over a 30 m walkway (with additional room to accelerate and decelerate). For the initial trial, subjects were asked to walk at their self-selected normal gait velocity. Following each trial, subjects were given instructions to walk slower or faster than the previous trial, until a wide range of gait velocities was obtained for each subject (mean (SD) range: 0.54 (± 0.27) m/s to 2.24 (± 0.38) m/s). A total of 87 trials were recorded.

All post-processing of accelerometer and force plate data were performed offline using MATLAB (Version 7.11.0, Mathworks, Natick, MA, USA). Accelerometer data were calibrated to derive the acceleration vector with respect to the sensor unit coordinate axis. Video data were synchronized to accelerometer data by three vertical jumps performed by subjects prior to the described protocol. Video data were analyzed to determine which steps corresponded to the force plate strikes for each trial so that accelerometer and force plate data could be synchronized. Force plate data were collected for one to five steps per trial and were filtered using a 4th order low-pass butterworth filter with a cut-off frequency of 30 Hz to eliminate baseline noise in LR calculations. Peak vertical and peak resultant impact GRF and LR (both normalized to body weight (BW)) were estimated from the force plate data. Peak vertical LR, $LR_{z,max}$, was calculated as in Liikavainio et al.⁶:

$$LR_{z,max} = max \left\{ \frac{dF_z(t)}{dt} \right\} \quad (1)$$

where F_z is the vertical force and t is time. Similarly, peak resultant LR, LR_{max} , is calculated using

$$LR_{max} = max \left\{ \frac{dF(t)}{dt} \right\} \quad (2)$$

where F is the resultant force. Heel-strike impact acceleration regions were detected visually from graphical representations of both the vertical and resultant accelerometer data. The maximum vertical acceleration point in the heel-strike region of the data was taken as the peak vertical acceleration and the maximum resultant acceleration point in the heel-strike region of the data was taken as the peak resultant acceleration. All steps, where it was determined, using video data, that 100% of the heel contact with the ground occurred with one or two force plates, were included in the analyses.

Froude number (FR) was used instead of gait velocity when investigating the relationships between speed, peak GRF, peak LR, and accelerations to exclude any influence of individuals' leg lengths.¹³ FR was calculated for each trial based on the gait velocity recorded and the subjects' leg lengths (measured from the greater trochanter to the floor).¹³

Linear regression with Pearson correlation analysis was used to assess the correlations of peak vertical GRF and LR with peak vertical acceleration values, of peak resultant GRF and LR with peak resultant acceleration values, and of FR with peak vertical and resultant GRF, peak vertical and resultant LR, and peak vertical and resultant acceleration values (waist, thigh, tibia, ankle) across all subjects using JMP Pro 9.0.1 (SAS Institute Inc., Cary, NC,

USA). As different numbers of data points were used per subject (18–33; a mean of 22 data points per subject), Fisher z transformations¹⁴ were calculated while excluding data from any one subject at a time to determine if individual subjects were dominating the trend. One subject was identified as an outlier reducing the correlations between ankle acceleration and both GRF and LR ($|z| = 2.56$ and 2.14). Another subject was identified as an outlier reducing the correlations between thigh acceleration and LR ($|z| = 2.13$). The data points from these subjects were excluded in the analyses for those respective accelerometer locations, meaning that 9 subjects were retained for the analyses of the ankle and thigh accelerations, while 10 subjects were retained for the analyses of the tibia and waist accelerations.

Results

Ankle, tibia, thigh, and waist peak vertical accelerations all demonstrated moderate to high positive correlations¹⁵ with peak vertical GRF and peak vertical LR for a range of FR from 0.0046 to 1 (Figure 1 and 2, Table 1). Consistently, ankle, tibia, thigh, and waist peak vertical accelerations, peak vertical GRF, and peak vertical LR were all positively correlated with FR (Figure 3, Table 1). The root mean square error (RMSE) values for predicting peak vertical GRF using the ankle, thigh, or waist peak vertical acceleration were 11% of BW and the mean (SD) absolute differences between the actual and predicted peak vertical GRF were 7.5% (6.6%) (Figure 1). The RMSE values for predicting peak vertical LR using the ankle, tibia, thigh, or waist peak vertical acceleration were 7.74 BW/s. The mean (SD) absolute differences between the actual and predicted peak vertical LR were 26.4% (26.0%) using ankle or waist accelerometers but were as large as 46.1% (50.5%) using tibia or thigh accelerations (Figure 2). Similarly, ankle, tibia, thigh, and waist peak resultant accelerations all demonstrated moderate to high positive correlations¹⁵ with peak resultant GRF and peak resultant LR for a range of FR from 0.0046 to 1 (Table 1). Ankle, tibia, thigh, and waist peak resultant accelerations, peak resultant GRF, and peak resultant LR were also all positively correlated with FR (Table 1). The waist and ankle peak vertical accelerations demonstrated the highest correlations with peak vertical GRF and peak vertical LR. In the resultant direction, waist peak resultant accelerations demonstrated the highest correlations with peak resultant GRF and peak resultant LR due to the higher correlations of FR with peak resultant GRF and peak resultant LR.

Discussion

The purpose of this study was to determine the correlations between accelerations measured from body-worn accelerometers and GRFs and LR measured from floor-embedded force plates during walking over a range of gait velocities. Correlations of peak GRF and LR with ankle acceleration have not been previously investigated and may give additional bone loading information since the ankle location is closer to the point of ground impact than the previously investigated hip, thigh or tibia.

It is important to note that the vertical axis of the accelerometer, which aligns with the longitudinal axis of the limb segment, does not correspond to the vertical axis of the force plate. However, the majority of loading is in line with the vertical vector of the accelerometers⁵ and heel impact vertical accelerations have been shown to correlate with

changes in BMD.¹⁶ Therefore, relating peak vertical GRF and LR to the acceleration impacts in the longitudinal axis of the bone, which aligns with the vertical axis of the accelerometer, may provide higher correlations with BMD, although the correlation between resultant acceleration and BMD has not yet been investigated. As such, even though tibia, thigh, and waist accelerations gave similar or higher correlations with peak GRF and peak LR in the resultant direction than in the vertical direction, analysis along the resultant direction may be less representative of BMD than analysis along the 'vertical' direction. Ankle peak vertical accelerations were more highly correlated with peak vertical GRF and peak vertical LR than tibia, thigh, or waist peak vertical accelerations due to the very high correlations of FR with peak vertical GRF, peak vertical LR, and ankle peak vertical accelerations and also to the closer proximity of the ankle to underfoot loading. The correlations between waist peak vertical acceleration and peak vertical GRF and peak vertical LR in this study were comparable to correlations obtained in similar studies.^{4,5}

Stiles et al. (2013) reported positive correlations between hip peak vertical acceleration and peak vertical GRF ($r^2 = 0.75$ to 0.77 , $P < 0.001$) and hip peak vertical acceleration and peak vertical LR ($r^2 = 0.51$ to 0.54 , $P < 0.001$).⁴ Rowlands et al. (2012) reported positive, but not significant, correlations between hip peak vertical acceleration with peak vertical GRF ($r^2 = 0.53$).⁵ In these studies, walking, running, and jumping activities were included. While this provided a large range of acceleration values, the relationship between GRF and acceleration may vary, resulting in lower correlations compared to obtaining a large range of accelerations for one activity. Liikavainio et al. (2007) demonstrated positive correlations of peak vertical GRF with tibia peak vertical acceleration ($r^2 = 0.78$, $P < 0.01$), of peak vertical LR with tibia peak vertical acceleration ($r^2 = 0.84$, $P < 0.001$), and of peak vertical LR with tibia peak resultant acceleration ($r^2 = 0.92$, $P < 0.001$).⁶ These correlations are higher than those obtained with tibia accelerations in this study. The reasons for these differences are not readily apparent; however, as only 10 subjects were included in both studies, it is possible that the results could converge if larger sample sizes had been included. Another possible reason is that in Liikavainio et al. (2007), both accelerometer and force plate data were sampled at higher frequencies (2000 Hz). Some studies have investigated the use of ankle or tibia accelerometers to identify where foot strike occurs and used the corresponding acceleration value recorded by a waist accelerometer to calculate peak vertical GRF using fixed effects regression models with average absolute differences of 5.2%–10.5%.^{9,10} However, the results from the current study suggest that peak vertical GRF could be assessed with the use of an ankle accelerometer alone with a mean (SD) absolute difference of 6.6% (5.8%). While the mean (SD) absolute differences between predicted and measured peak vertical LR for the ankle and waist accelerometers were between 23.4% (20.5%) and 26.4% (26.0%), the high correlations between both ankle and waist peak vertical accelerations and peak vertical LR suggest that ankle or waist accelerometers could be used to accurately assess changes in peak vertical LR.

This study reports accelerometer and force plate measure correlations over a wide range of gait velocities from ten young, healthy subjects. Further investigation is needed to validate the use of ankle or waist accelerometers in loading assessments for the general population, and, in particular, for both older healthy and patient populations. In conclusion, ankle, tibia, thigh, and waist accelerations all demonstrated moderate to high correlations with peak

vertical GRF, peak resultant GRF, peak vertical LR, and peak resultant LR, with the highest correlation being observed between ankle peak vertical acceleration and peak vertical LR. This suggests that they could successfully be used to assess dynamic loading in the free-living environment using an automated heel-strike detection algorithm¹⁷ in combination with regression equations, such as those developed in this study, to estimate GRFs and LR.

Acknowledgments

Study funding was provided by DOD DM090896 and NIH K12 HD065987. The body-worn motion detection and recording units were provided by Dr. B.K. Gilbert, J.E. Bublitz, K.J. Buchs, C.A. Burfield, C.L. Felton, Dr. C.R. Haider, M.J. Loring, S.M. Schreiber, S.J. Schuster, and D.J. Schwab from the Mayo Clinic Special Purpose Processor Development Group. The information or content and conclusions do not necessarily represent the official position of, nor should any official endorsement be inferred by the National Institutes of Health, the United States Navy, the Department of Defense, or the U.S. Government.

Funding: Funding for this project was provided by the Department of Defense (DM090896) and the National Institutes of Health (K12 HD065987).

References

1. Bassey EJ, Rothwell MC, Littlewood JJ, Pye DW. Pre- and postmenopausal women have different bone mineral density responses to the same high-impact exercise. *J Bone Miner Res.* 1998; 13(12): 1805–1813. [PubMed: 9844097]
2. Sutherland DH. The evolution of clinical gait analysis part III—kinetics and energy assessment. *Gait Posture.* 2005; 21(4):447–461. [PubMed: 15886135]
3. Farr JN, et al. Physical activity levels in patients with early knee osteoarthritis measured by accelerometry. *Arthritis Rheum.* 2008; 59(9):1229–1236. [PubMed: 18759320]
4. Stiles VH, Griew PJ, Rowlands AV. Use of accelerometry to classify activity beneficial to bone in premenopausal women. *Med Sci Sports Exerc.* 2013; 45(12):2353–2361. [PubMed: 23698245]
5. Rowlands AV, Stiles VH. Accelerometer counts and raw acceleration output in relation to mechanical loading. *J Biomech.* 2012; 45(3):448–454. [PubMed: 22218284]
6. Liikavainio T, et al. Reproducibility of loading measurements with skin-mounted accelerometers during walking. *Arch Phys Med Rehabil.* 2007; 88(7):907–915. [PubMed: 17601473]
7. Neugebauer JM, Hawkins DA, Beckett L. Estimating youth locomotion ground reaction forces using an accelerometer-based activity monitor. *PLoS One.* 2012; 7(10):e48182. [PubMed: 23133564]
8. Munro CF, Miller DI, Fuglevand AJ. Ground reaction forces in running: a reexamination. *J Biomech.* 1987; 20(2):147–155. [PubMed: 3571295]
9. Neugebauer, JM. Estimating soldier ground reaction forces using an activity monitor. The Proceedings of the 37th Annual Meeting of the American Society of Biomechanics; Omaha, NE. 4–7 September 2013;
10. Collins, KH.; Neugebauer, JM.; Hawkins, DA. Estimating ground reaction forces during locomotion in adults from actigraph activity monitor data. The Proceedings of the 35th Annual Meeting of the American Society of Biomechanics; Longbeach, CA. 10–13 August 2011;
11. Taylor BC, et al. Long-term prediction of incident hip fracture risk in elderly white women: study of osteoporotic fractures. *J Am Geriatr Soc.* 2004; 52(9):1479–1486. [PubMed: 15341549]
12. Bliley KE, Kaufman KR, Gilbert BK. Methods for validating the performance of wearable motion-sensing devices under controlled conditions. *Meas Sci Technol.* 2009; 20(4):045802.
13. Vaughan CL, O'Malley MJ. Froude and the contribution of naval architecture to our understanding of bipedal locomotion. *Gait Posture.* 2005; 21(3):350–362. [PubMed: 15760752]
14. Fisher RA. Frequency distribution of the values of the correlation coefficient in samples from an indefinitely large population. *Biometrika.* 1915; 10(4):507–521.
15. Vincent, W.; Weir, J. Statistics in Kinesiology. 4. Champaign, IL: Human Kinetics; 2012.

16. Jamsa T, et al. Effect of daily physical activity on proximal femur. Clin Biomech (Bristol, Avon). 2006; 21(1):1–7.
17. Fortune, E.; Lugade, VA.; Morrow, MM.; Kaufman, KR. Validity of using tri-axial accelerometers to measure human movement - Part II: Step counts at a wide range of gait velocities. Med Eng Phys. In Press; <http://dx.doi.org/10.1016/j.medengphy.2014.02.006>

Figure 1.

Correlation between peak vertical ground reaction force (pVGRF) and peak vertical acceleration of the ankles (a), tibias (b), thighs (c), and waist (d). RMSE is the root mean square error and AD is the absolute difference of the predicted peak vertical GRF from the associated equation from the actual recorded peak vertical GRF.

Figure 2.

Correlation between peak vertical loading rate (pVLR) and peak vertical acceleration of the ankles (a), tibias (b), thighs (c), and waist (d). RMSE is the root mean square error and AD is the absolute difference of the predicted peak vertical LR from the associated equation from the actual recorded peak vertical LR.

Figure 3.

Correlations between Froude number (FR) and peak vertical ground reaction force (pVGRF) (a), peak vertical loading rate (pVLR) (b), and peak vertical acceleration of the ankles (c), tibias (d), thighs (e), and waist (f).

Table 1

Coefficient of determination (r^2) between FR, peak vertical and peak resultant GRF, LR, and accelerations. In all analyses $P < 0.001$.

Vertical	GRF	LR	FR
Ankle acceleration	0.75	0.82	0.83
Tibia acceleration	0.53	0.65	0.67
Thigh acceleration	0.58	0.74	0.82
Waist acceleration	0.72	0.77	0.76
FR	0.76	0.86	-

Resultant	GRF	LR	FR
Ankle acceleration	0.62	0.69	0.73
Tibia acceleration	0.57	0.68	0.72
Thigh acceleration	0.66	0.74	0.76
Waist acceleration	0.70	0.79	0.83
FR	0.77	0.86	-