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# Accelerations of the Waist and Lower Extremities over a Range of Gait Velocities to Aid in Activity Monitor Selection for Field-Based Studies

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## Abstract

This study aimed to define accelerations measured at the waist and lower extremities over a range of gait velocities to provide reference data for choosing the appropriate accelerometer for field-based human activity monitoring studies. Accelerations were measured with a custom activity monitor (±16g) at the waist, thighs, and ankles in 11 participants over a range of gait velocities from slow walking to running speeds. The cumulative frequencies and peak accelerations were determined. Cumulative acceleration amplitudes for the waist, thighs, and ankles during gait velocities up to 4.8 m/s were within the standard commercial g-range (±6g) in 99.8%, 99.0%, and 96.5% of the data, respectively. Conversely, peak acceleration amplitudes exceeding the limits of many commercially available activity monitors were observed at the waist, thighs, and ankles, with the highest peaks at the ankles as expected. At the thighs, and more so at the ankles, nearly 50% of the peak accelerations would not be detected when the gait velocity exceeds a walking velocity. Activity monitor choice is application specific, and investigators should be aware that when measuring high intensity gait velocity activities with commercial units that impose a ceiling at ±6g, peak accelerations may not be measured.

### Keywords

movement; activity monitoring; accelerometer; sport; gait

## Introduction

Accelerometry based activity monitors are recognized as validated, objective tools for quantitative assessment of free-living physical activity. [1] These portable measurement tools have been used for several decades to study gait,[2] measure tremor and motor activity in neurological patients,[3] and estimate energy expenditure.[4-6] Modern iterations of the activity



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monitor are typically small in size, capture tri-axial accelerations, store data for several days, and are water resistant. Activity monitors overcome the limitations of self-reported physical activity questionnaires that depend on subject recall and perception of activity.[7,8] These devices also provide a low cost alternative to expensive, laboratory-based assessment of movement by capturing activity in an individual's natural living environment (field-based studies).

When choosing an accelerometry based system for the assessment of physical activity, the technical requirements for high fidelity data recording need to be defined specific to the population and activity under study. Using the appropriate accelerometer amplitude range, or g-range, is crucial to capturing the full range of accelerations experienced during an activity. Bouten et al[4] recommended that since most activity monitors used for activity assessment are placed on the waist, an amplitude range of −6 to +6g would be sufficient. These recommendations were based primarily on laboratory studies using skin-mounted accelerometers not suitable for multiple day-long collections in the free-living environment. Consistent with these recommendations, commercial activity monitors primarily capture movements up to ±6g, and collect at a frequency of 100 to 128 Hz (Table 1). However, there are no clear guidelines on acceleration requirements for acquiring activity monitoring data on the thighs and ankles, in addition to the waist, over a range of intensity levels.

The purpose of this study was to define the acceleration range at the waist and lower extremities for a range of gait velocities. The results of this study provided the activity monitoring research community with reference data upon which the choice of the necessary accelerometer g-range could be chosen based on the specifics of the field-based activities to be studied. Further, this reference data provided specific quantification of the data that was likely to be gained or lost by using a particular g-range accelerometer.

## Methods

The study protocol was approved by the Mayo Clinic Institutional Review Board. Written informed consent was obtained from all research participants prior to initiating data collection procedures.

Custom built accelerometry-based activity monitors developed at Mayo Clinic (Figure 1A) were utilized for all data collections. Each self-contained sensor contained a tri-axial MEMS accelerometer (analog, ±16g, Analog Devices, Boston, MA, USA), microcontroller (12 bit ADC, Texas Instruments, Dallas, TX, USA), power source (Tadiran battery, semiconductor voltage regulator), and onboard data storage (NAND flash memory, 4 Gbit memory chip, Micron, Boise, ID, USA). The battery life capacity for each device exceeded ten continuous days with a sampling frequency of 100 Hz. Accuracy of the devices was determined to be within ±0.09g.

Waist and lower extremity activity monitoring data were collected in the laboratory setting. Activity monitors were worn on the waist, right thigh, and bilaterally on the ankles using body fixation methods appropriate for field testing. The waist monitor was worn on a belt clip attached to the waistline of the subjects' clothing (shorts/pants), and the thigh and ankle

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monitors were worn inside a pocket attached to a Velcro strap placed on the lateral aspect of the distal thigh and distal tibia, respectively.

A gait velocity protocol was performed. Data were collected from 11 healthy participants (8 F, Age: 33.4±10.5 yrs.; BMI: 23.6±2.7 kg·m$^{-2}$). Participants were instructed to ambulate from one side of the lab to the other during seven to ten trials at self-selected slow, normal, and fast gait velocities that included a range from very slow walking (0.4 m/s) through running (4.8 m/s). Gait velocities were calculated using timings recorded with photocells positioned at the ends of the 8.5m walkway. After each trial, subjects were instructed to go "slower" or "faster" to ensure we collected the range of gait velocities. The total length of the room was approximately 24m which allowed sufficient space for acceleration and deceleration before and after each trial.

All subsequent filtering and analysis methods were applied uniformly to the signal of all data sets and did not vary between body segments nor motor tasks. An anti-aliasing single-pole RC low-pass filter with an upper 3 dB cutoff frequency set to 50 Hz and a rolloff of 10 dB/decade was implemented at the output of the accelerometer and before the input to the analog-to-digital converter (ADC). The ADC was set to a sampling rate of 100 samples/second with 12 bits/sample. The digital, tri-axial raw signal was reported in the x, y, and z axes (Figure 1B). 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 (Figure 1B). Proper alignment of the activity monitor was visually confirmed by study investigators.

All post processing and analysis of raw accelerometer data were performed using MATLAB (Version 7.11.0, Mathworks, Natick, MA, USA). The frequency distributions of acceleration amplitudes using a 1g bin size were determined for each body segment during each trial. Data from all three axes were included, and data were averaged over all trials for all subjects for each body segment. Additionally, the peak acceleration amplitudes were identified from all three axes for each body segment based on the absolute value of the signal amplitudes. The maximum gait velocity under which no peak acceleration exceeded ±6g was also determined for each body segment.

## Results

As the gait velocity increased, more of the acceleration was contained in the higher acceleration bins (Table 2). The majority of the acceleration was between 0g and ±1g for all segments. Below 1 m/s, 100% of the acceleration magnitudes for the waist, thighs, and ankles were contained within ±6g. Above 4 m/s, at least 96% of the signal was contained within ± 6g for the waist, thighs, and ankles.

The greatest peak acceleration amplitude was recorded at the ankle (±16g, Figure 2A), followed by the thigh (13g, Figure 2B), and the waist (7g, Figure 2C). No peak accelerations exceeded ±6g below 1 m/s at the ankle, 1.8 m/s at the thigh, and 4.1 m/s at the waist. Subject-specific data (Table 3) revealed that the trend of high accelerations at the thighs and ankles at faster gait velocities was observed across all subjects.

## Discussion

This study reported on acceleration amplitudes of the waist, thighs, and ankles experienced during a range of gait velocities encompassing slow walking to running (0.4 m/s to 4.8 m/s). The overwhelming majority of the acceleration amplitudes for the waist, thighs, and ankles were within the standard commercial g-range of ±6g (Table 1). However, peak acceleration amplitudes exceeding the limits of many commercially available activity monitors were observed at the waist, thighs, and ankles. The highest peaks were observed at the ankles (Figure 2) as expected. Peak values at the thighs and ankles went beyond the recommended ±12g range reported by Bouten et al [4], and peak accelerations even went beyond ±6g at the waist when the gait velocity exceeded 4m/s . While 99.8% of the acceleration range measured at the waist would be captured with a ±6g activity monitor, during running or other high intensity activities, the peak accelerations would be missed. For waist measurement of walking at average gait speeds (1-2m/s) of the general population, a ±2g activity monitor would suffice (Table 2). At the thighs, and more so at the ankles, nearly 50% of the peak accelerations would not be detected when the gait velocity exceeds 2m/s. This would result in an underestimation of the maximum acceleration that an individual underwent during the period of interest. This point is particularly important for high intensity sport and exercise measurements of the lower extremities. The potential problems that arise from missing the full range of accelerations of an activity, including the peak acceleration, include misclassification of the intensity, activity counts, or step counts associated with an activity.

There were limitations to this study. First, a sample size of 11 participants is not sufficient to be generalizable to a population; however, this sample size was sufficient to explicitly demonstrate that lower extremity accelerations will exceed ±6g accelerometer measurement capabilities at higher gait velocities. Second, we did not utilize a treadmill to control the gait velocity for each participant. However, our motivation for performing this study over ground was because treadmill walking/running confines the motion of the body and segment and is not representative of free-living over ground walking/running accelerations. Lastly, multiple subjects had peak accelerations at the ±16g limit of the accelerometer used in the study. The actual peak may be beyond ±16g, but the accuracy of accelerations beyond the specified g-range has not been defined.

Tri-axial accelerometer amplitudes across gait velocities presented in this report may assist users in selecting the most appropriate device for their identified applications or provide operational characteristics needed for designing a custom device. While segmental accelerations at various body locations have been previously described,[4] the results from this study provide novel reference data to allow for proper selection of an accelerometry-based activity monitor, based on g-range, that is specific to the gait velocity likely to occur during the activity. Researchers should be aware that when measuring high intensity gait velocity activities with commercial units that impose a ceiling at ±6g, peak accelerations may not be measured.

## Acknowledgments

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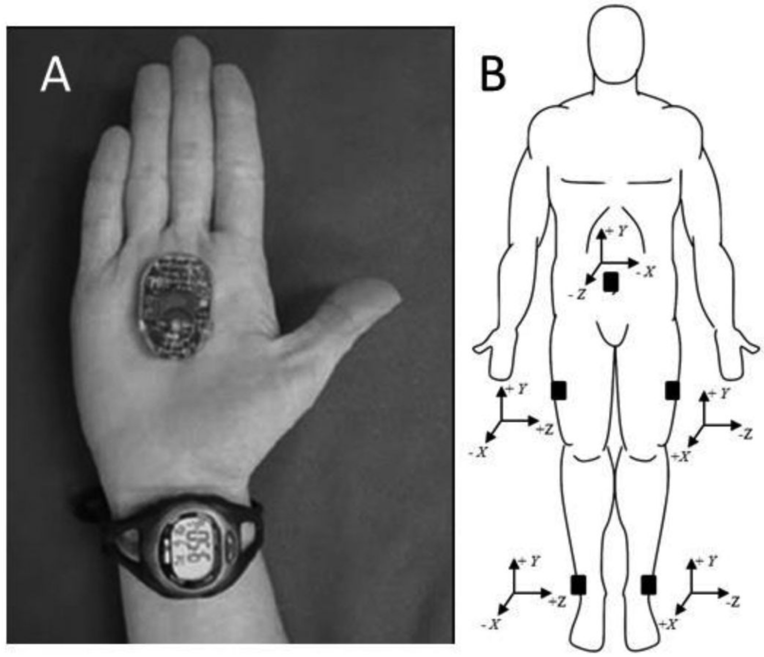


**Figure 1.**
Activity monitor and body segment placement. **A**) Custom tri-axial accelerometer activity monitor utilized for data collections. Activity monitors weigh 22g and have dimensions of 4.7 cm x 2.8 cm x 1.2 cm. **B**) Local coordinate systems of 3-axis accelerometers in the anatomical position for each body segment. In anatomical position, coordinate systems align with the anatomical axes: anterior-posterior, medial-lateral, and superior-inferior.

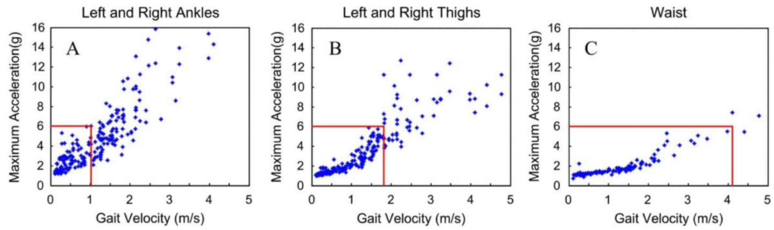


**Figure 2.**
Maximum acceleration amplitudes for all subjects over the range of gait velocities for the (A) left ankle, (B) left thigh, and (C) waist. Each data point represents a single trial from a single subject. The horizontal red line corresponds to the ±6g amplitude cut-off as is common in commercial activity monitors and the vertical red line corresponds to the maximum gait velocity for which no recorded peak acceleration values exceeded ±6g.

## Table 1

Accelerometer range and available sampling frequencies for commercially available activity monitors

| | Accelerometer Range | Sampling Frequency |
|---|---|---|
| Actigraph wGT3X+ | ±6g | 30 to100 Hz |
| APDM Opal (IMU) | ±2g to ±6g | 20 to 128 Hz |
| McRoberts Dynaport | ±2g to ±6g | 100 Hz |
| MiniSun IDEEA | ±6g | 100 Hz |
| ActiPal | ±2g | 100 Hz |
| Actical | ±2g | 32 Hz |
| GENEActiv | ±8g | 10 to 100Hz |

## Table 2

Average acceleration frequency distribution for each segment measured over all trials across the range of gait velocities.

| Accelerometer Amplitude (g) | 0-1 | 1 to 2 | 2 to 3 | 3 to 4 | 4 to 5 | 5 to 6 | 6 to 7 | 7 to 8 | 8 to 9 | 9 to 10 | 10 to 11 | 11 to 12 | 12 to 13 | 13 to 14 | 14 to 15 | 15 to 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **<1m/s** | | | | | | | | | | | | | | | | |
| Waist (% Activity) | 62.36 | 37.64 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Thigh (% Activity) | 62.51 | 37.4 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ankle( % Activity) | 64.08 | 34.81 | 1.05 | 0.04 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **>=1m/s and <2m/s** | | | | | | | | | | | | | | | | |
| Waist (% Activity) | 60.15 | 39.06 | 0.79 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Thigh (% Activity) | 52.22 | 43.9 | 3.19 | 0.54 | 0.12 | 0.02 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ankle( % Activity) | 52.8 | 36.35 | 8.39 | 1.85 | 0.44 | 0.12 | 0.03 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **>=2m/s and <3m/s** | | | | | | | | | | | | | | | | |
| Waist (% Activity) | 61.22 | 34.78 | 3.48 | 0.39 | 0.1 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Thigh (% Activity) | 47.72 | 41.07 | 7.81 | 2.29 | 0.68 | 0.25 | 0.11 | 0.05 | 0.01 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ankle( % Activity) | 45.27 | 39.01 | 9.66 | 3.49 | 1.43 | 0.61 | 0.26 | 0.07 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0 | 0 | 0 |
| **>=3m/s and <4m/s** | | | | | | | | | | | | | | | | |
| Waist (% Activity) | 59.69 | 35.15 | 4.01 | 0.86 | 0.22 | 0.05 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Thigh (% Activity) | 46.9 | 37.85 | 9.04 | 3.58 | 1.5 | 0.69 | 0.27 | 0.1 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 | 0 | 0 | 0 |
| Ankle( % Activity) | 43.09 | 36.95 | 10.06 | 4.95 | 2.29 | 1.22 | 0.58 | 0.37 | 0.19 | 0.12 | 0.09 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 |
| **>=4m/s** | | | | | | | | | | | | | | | | |
| Waist (% Activity) | 56.2 | 36.11 | 4.63 | 1.69 | 0.58 | 0.55 | 0.18 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Thigh (% Activity) | 40.36 | 37.78 | 10.44 | 5.21 | 3.31 | 1.9 | 0.54 | 0.26 | 0.1 | 0.06 | 0.03 | 0.01 | 0 | 0 | 0 | 0 |
| Ankle( % Activity) | 36.02 | 34.77 | 12.78 | 7.32 | 3.48 | 2.1 | 1.43 | 0.77 | 0.52 | 0.38 | 0.18 | 0.04 | 0.06 | 0.02 | 0.03 | 0.02 |

### Table 3

Overall peak acceleration (ace) and average peak accelerations for each axis for each subject across all trials

| Subject | Segment | Peak Acc (±g) | Average Peak Acc X (±g) | mean ± sd | Average Peak Acc Y (±g) | mean ± sd | Average Peak Acc Z (±g) | mean ± sd |
|---|---|---|---|---|---|---|---|---|
| **1** | *Waist* | 2.3 | 0.4 | 0.2 | 1.4 | 0.4 | 1.1 | 0.7 |
| | *Thigh* | 4.1 | 1.6 | 0.8 | 2.1 | 1.2 | 1.4 | 0.8 |
| | *Ankle* | 9.8 | 2.1 | 1.3 | 3.0 | 1.9 | 3.6 | 2.8 |
| **2** | *Waist* | 4.5 | 0.3 | 0.6 | 1.8 | 1.2 | 0.9 | 0.8 |
| | *Thigh* | 8.8 | 1.9 | 1.1 | 3.3 | 2.7 | 1.9 | 2.0 |
| | *Ankle* | 11.0 | 3.7 | 2.0 | 3.9 | 3.5 | 2.8 | 2.7 |
| **3** | *Waist* | 7.4 | 0.8 | 0.9 | 2.3 | 2.0 | 1.0 | 1.2 |
| | *Thigh* | 8.8 | 2.6 | 2.3 | 2.9 | 2.0 | 1.9 | 1.8 |
| | *Ankle* | 16.0 | 4.4 | 3.0 | 5.6 | 7.0 | 4.0 | 3.9 |
| **4** | *Waist* | 4.7 | 0.4 | 0.6 | 2.1 | 1.3 | 0.9 | 1.2 |
| | *Thigh* | 12.4 | 2.6 | 2.3 | 4.4 | 3.4 | 2.9 | 2.1 |
| | *Ankle* | 16.0 | 5.5 | 4.3 | 3.5 | 2.8 | 3.3 | 3.1 |
| **5** | *Waist* | 2.2 | 0.6 | 0.3 | 1.5 | 0.5 | 1.1 | 0.6 |
| | *Thigh* | 4.8 | 1.0 | 0.7 | 2.5 | 1.6 | 1.9 | 1.6 |
| | *Ankle* | 8.3 | 4.9 | 2.2 | 2.8 | 1.7 | 2.5 | 1.5 |
| **6** | *Waist* | 2.4 | 0.3 | 0.2 | 1.4 | 0.7 | 0.7 | 0.5 |
| | *Thigh* | 6.8 | 1.3 | 1.2 | 2.4 | 2.0 | 1.7 | 1.4 |
| | *Ankle* | 7.2 | 2.6 | 1.9 | 2.4 | 1.2 | 3.1 | 2.0 |
| **7** | *Waist* | 4.5 | 0.6 | 0.4 | 1.8 | 1.2 | 1.0 | 0.8 |
| | *Thigh* | 9.2 | 3.2 | 1.9 | 2.9 | 2.0 | 3.6 | 3.0 |
| | *Ankle* | 16.0 | 4.1 | 1.9 | 4.6 | 5.4 | 2.5 | 1.7 |
| **8** | *Waist* | 7.1 | 0.6 | 0.7 | 2.2 | 1.8 | 1.6 | 2.1 |
| | *Thigh* | 11.2 | 2.9 | 3.2 | 3.1 | 3.2 | 3.2 | 3.8 |
| | *Ankle* | 16.0 | 4.1 | 3.7 | 5.5 | 6.2 | 5.7 | 7.3 |
| **9** | *Waist* | 5.5 | 0.7 | 0.8 | 2.5 | 1.8 | 1.9 | 1.6 |
| | *Thigh* | 9.3 | 3.8 | 3.1 | 3.8 | 2.5 | 2.0 | 1.8 |
| | *Ankle* | 16.0 | 6.1 | 4.8 | 5.0 | 4.4 | 3.5 | 3.4 |
| 10 | *Waist* | 2.1 | 0.5 | 0.2 | 1.3 | 0.4 | 0.9 | 0.5 |
| | *Thigh* | 5.1 | 1.6 | 0.7 | 1.6 | 1.1 | 1.5 | 1.4 |
| | *Ankle* | 6.2 | 2.7 | 1.9 | 2.0 | 1.0 | 1.3 | 0.7 |
| 11 | *Waist* | 3.6 | 0.4 | 0.4 | 1.6 | 1.0 | 1.4 | 0.8 |
| | *Thigh* | 12.7 | 5.2 | 4.0 | 3.9 | 3.5 | 3.4 | 1.7 |

| Subject | Segment | Peak Acc (±g) | Average Peak Acc X (±g) | mean ± sd | Average Peak Acc Y (±g) | mean ± sd | Average Peak Acc Z (±g) | mean ± sd |
|---|---|---|---|---|---|---|---|---|
| | *Ankle* | 9.7 | 3.8 | 2.5 | 3.1 | 2.1 | 3.3 | 2.0 |