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Best Practice use of Wearable Accelerometers in Gait Biomechanics

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Abstract

Advances in wearable accelerometers allow collection of gait biomechanics in natural, non-lab, settings. However, there are currently no standards for using wearable sensors for gait applications. The purpose of this study was to provide evidence-based guidelines for best practice use of wearable accelerometers for studies of gait biomechanics. Literature was reviewed to evaluate and establish procedures for selecting, calibrating, and processing wearable accelerometer data for gait applications. Commercially available accelerometer-based activity monitors were used to test signal time synchronization, peak acceleration magnitude and timing (for accelerometers placed at different body locations during different gait conditions), and the effect device placement has on regression model estimates of vertical ground reaction force (GRFvert) that are based on hip acceleration data. Based on the evidence in the literature and from these tests, we recommend wearable accelerometers be (1) calibrated by the end-user to ensure accuracy and proper range, (2) manually time synched if using multiple accelerometers, (3) placed carefully and securely to the anatomical site of interest, and (4) located at the same anatomical site that was used to develop an acceleration-dependent model if the goal is to use that model to estimate a particular quantity (e.g. GRFvert).

Keywords: Accelerometers; Best Practices; Gait; Wearables

Introduction

Recent advances in wearable technology provide new opportunities to collect biomechanical data in real time and in natural, non-lab, settings. Wearable devices used to assess human movement typically include one or more tri-axial accelerometers that are placed non-obtrusively on different anatomical locations of a person's body. Accelerations are recorded while the person performs their daily activities in natural settings [1-4]. Specific to gait analysis applications, acceleration data have been combined with anthropometric data to estimate various gait kinematic and kinetic quantities (e.g. ground reaction forces) [5]. However, the effect of variations in Wearable Accelerometer (WA) placement on acceleration magnitude and timing, and the subsequent kinematic and kinetic quantities estimated from these accelerations, are currently unknown. The Institute of Electrical and Electronics Engineers (IEEE) established performance standards for use of WAs for biomechanical analysis [6], but there are currently no standards for best practice use of wearable devices for gait applications. With use of WAs on the rise [7], it is important to establish performance standards and best practice guidelines for utilizing this technology and reporting outcomes.

The goals of this study were to (1) evaluate and establish procedures for selecting, calibrating, and testing WAs in preparation for gait applications; (2) quantify differences in acceleration magnitude and timing between WAs placed near the same pelvic anatomical landmark, and placed at different leg anatomical landmarks; (3) evaluate the effect of WA location on acceleration-based regression models of gait metrics; and (4) based on evidence from 1-3, provide best practice recommendations for WA use in gait biomechanics applications. Best practice considerations are presented in the order in which they occur in a gait application – device selection, calibration, placement on the body, and data collection/processing.

Methods

Data were collected using a single type of commercially available WA (Actigraph GT9X) sampling at 100 Hz and from a single subject (the senior author) walking and running with multiple GT9Xs placed on different locations of the body. Use of a common WA and testing of a single subject were deemed sufficient to inform best practice recommendations for WA use in gait applications.

Literature Review

A literature review was conducted to determine (1) the accelerometer range required for WAs placed at various anatomical locations during gait applications, (2) methods to test WA accuracy, and (3) calibration protocols to establish WA orientation relative to anatomical orientation. Databases included PubMed and ScienceDirect, and keywords used were acceleration, gait, accelerometer, wearable, walking/running, and specific locations (e.g. iliac crest, tibia, etc.).

Testing for Accuracy and Time Synchronicity

A series of WA drop tests were performed to determine (1) the time synchronicity of multiple WAs that were initiated at the same time, and (2) the utility of evaluating WA accuracy using a simple drop test. Three sensors were simultaneously initiated using a docking station provided by the manufacturer that reported the same time stamp for each sensor. Sensors were attached to a plastic bushing located on a steel column with the same axis for each WA located vertically (Figure 1A). For each axis orientation (x, y, z), the WAs were allowed to free fall for approximately 2 m before impacting a foam pad. The acceleration peaks that occurred when the WAs hit the foam pad (5 trials in each orthogonal axis) were used to evaluate the time synchronization of the WAs. Analysis of variance and individual paired t-tests were used to test for significant differences in time at impact of WAs. The average of the acceleration during free fall, which should be 0, was used to determine if a simple drop test could be used to evaluate the accuracy of the WA.

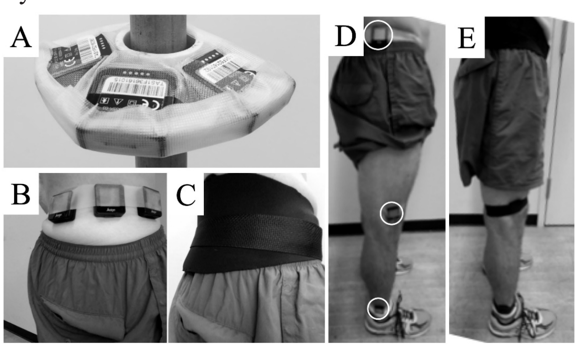

Figure 1: Wearable accelerometer (WA) placement during the various testing. Three WAs were mounted to a plastic bushing that freely slid on a steel column (**A**). The same axis for each WA was located vertically. This setup was used to test WA time synchronization and evaluate the efficacy of using such a test to quantify accelerometer accuracy. Three WAs were placed at different anatomical locations around the right hip (**B**) and then secured in place using a large elastic strap (**C**). Data from these accelerometers were used to determine the effect placement errors could have on acceleration magnitude and timing during gait. WAs were placed along the lateral aspect of the right hip, knee, and ankle (**D**) and then secured in place using elastic bands (**E**). Data from these accelerometers were used to determine the effect WA location can have on acceleration magnitude and timing during gait.

Testing The Effect of Sensor Placement On Acceleration Signals During Gait

A series of gait trials were performed to quantify the difference in impact peak acceleration magnitude and timing between WAs placed (1) in slightly different locations around the hip – a common site for WA placement, and (2) at different locations along the leg. Four walking and four running trials were performed with three Actigraph GT9X WAs first placed 8-12 cm apart below the right iliac crest, with one lateral, one anterior, and one posterior (Figure 1B), and secured with a large elastic waistband (Figure 1C); and then placed just below the right iliac crest, on the lateral femoral condyle, and on the lateral malleolus (Figure 1D), and secured with elastic straps (Figure 1E). The subject walked or jogged across a level floor for approximately ten steps for each condition, with only the middle six steps included in the analysis. All testing was performed during a single data acquisition session. The resultant vector magnitude of the tri-axial accelerations and the time of peak acceleration magnitude were determined. WA signals were temporally aligned based on the drop test results. The data were analyzed to determine differences in acceleration magnitude and timing between WA location and gait type. Significant differences were determined using an analysis of variance and a Tukey honest significance test with significance set at $p < 0.05$.

Testing The Effect of WA Placement On Regression Model Estimates of Vertical Ground Reaction Force

The peak accelerations obtained from WAs secured at slightly different locations near the right iliac crest, at the lateral femoral condyle, and at the right lateral malleolus were used as input to a generalized regression model developed to estimate vertical ground reaction force (GRFvert), based on accelerations of the right iliac crest [5]. These values were compared to assess the effect WA placement can have on GRFvert estimates.

Results

A review of 20 articles measuring accelerations at different anatomical locations indicated that ankle and hip accelerations can exceed ±8 g and ±4 g respectively in walking and ±16 g and ±6 g in running (Table 1). Tibial accelerations and foot accelerations can exceed ±25 g and ±28 g respectively in running.

Location	Walking	Running	References
Lower Back/Sacrum	±2	±12	17-20
Lateral Iliac Crest	±4	±6	5, 21, 22
Lateral Knee	±3		16, 23
Lateral Ankle	±8	±16	24-26
Tibia	±4	±25	17, 27-33
Foot	±5	±28	34

Table 1: Acceleration Ranges by Anatomical Location and Gait Type, range (g).

WAs can be calibrated and accuracy evaluated using a centrifuge system. Coolbaugh and Hawkins created such a system using a variable speed motor (0-140 rpm) and a 122 cm long beam attached at a center point [8]. They tested two ActiGraph GT3X+ WAs simultaneously and determined (1) calibration factors to convert accelerometer outputs to WA enclosure accelerations, and (2) the accuracy of these WAs. They found the average calibration factors for WAs differed by up to 6% compared to data sheet specifications for the accelerometer used in the WA device. This was attributed to slight variations in alignment of the accelerometer within the WA enclosure. These results highlight the importance of checking the calibration of these devices. They also found the accuracy across their specified range of ±6 g varied between 0.2 % and 4.7 % in each axis [8].

Because gravity affects acceleration values and WA axes may not align with anatomical segment orientations, it can be important in some applications to establish a calibration procedure to convert WA accelerations into a body segment reference frame [9-10]. Picerno, et al. introduced an anatomical calibration technique for WAs based on the direct measure of anatomical axes using anatomical landmarks [11]. Fabre, et al. defined anatomical frames such that anatomical knee joint angles equaled zero during standing posture [12]. Cutti, et al. proposed an Outwalk technique that requires precise monitoring to compute and measure WA orientation with the body oriented in a predefined posture [13]. Palermo, et al. proposed a calibration consisting of measuring the vertical axis acceleration in two static postures that requires precise configuration of segments [14]. Nazarahari, et al. presented a calibration procedure that independently calibrates WAs attached to the pelvis, thigh, shank, and foot through measurements in quiet standing and ten consecutive functional hip movements [15].

There was a significant difference between the time of impact peak between WAs for all drop trials performed in our testing ($p < 0.001$) with temporal differences up to 1.06 s (Figure 2). The vector magnitude accelerations during freefall were accurate within 0.17 g (17 %) [16-18].

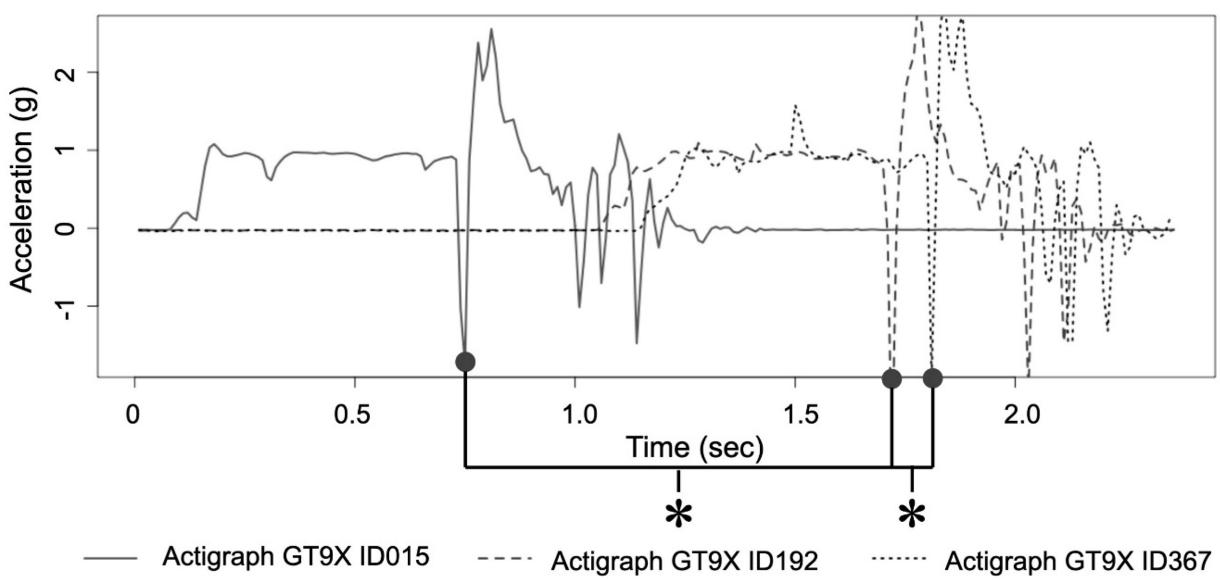

Figure 2: Drop test acceleration plot over time for an example trial in the y-axis. Circles represent the time identified as impact peaks and used to determine time synchronization. There was a significant difference between the time of impact peak between WAs in all trials ($p < 0.001$), noted as * in figures.

There were no significant differences among acceleration ($p > 0.38$) or time values ($p > 0.97$) of WAs located anterior, posterior, and just below the right iliac crest in both gait types (Figure 3).

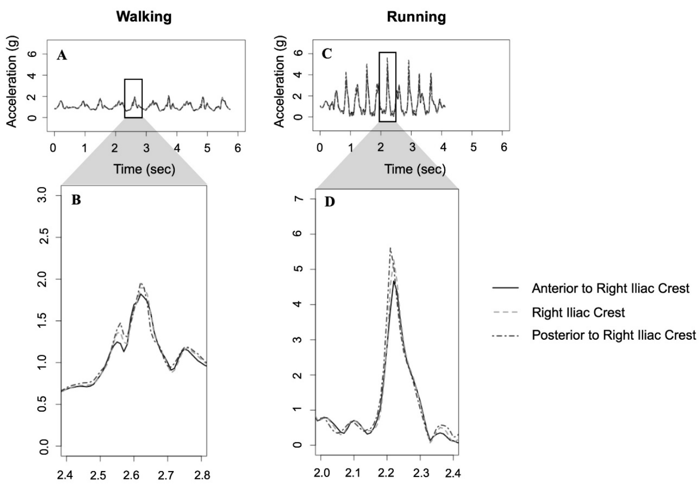

Figure 3: Walking (**A**) and running (**C**) vector magnitude acceleration with respect to time for WAs located on the right iliac crest, slightly anterior, and slightly posterior to the right iliac crest. (**B**) and (**D**) are increased resolution images of the peaks indicated in the rectangle in (**A**) and (**C**) respectively. WA signals were temporally aligned based on the drop test results.

There were significant differences among peak acceleration values and time of peak acceleration ($p < 0.001$) among WAs placed along the lateral right leg at the iliac crest, femoral condyle, and malleolus in both gait types (Figure 4).

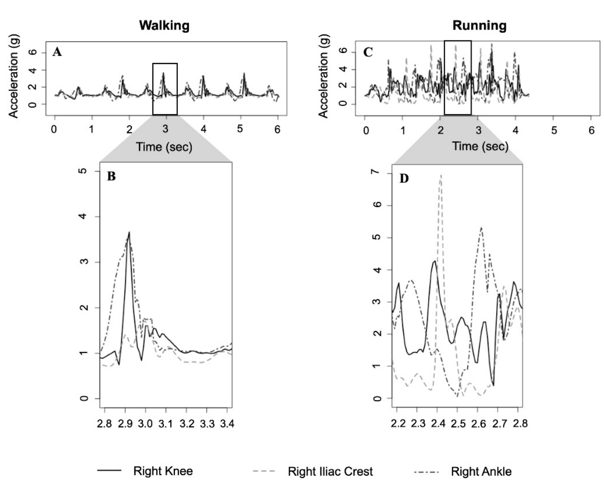

Figure 4: Walking (**A**) and running (**B**) vector magnitude acceleration with respect to time for WAs located on the right knee, hip, and ankle. (**C**) and (**D**) are increased resolution images of the peaks indicated in the rectangle in (**A**) and (**B**) respectively. Temporal values have been manually calibrated after vertical drop testing. WA signals were temporally aligned based on the drop test results.

Regression model estimates of GRFvert based on accelerations recorded from WAs located lateral, anterior, and posterior to the right iliac crest were lower for walking (895 N, 915 N and 897 N, respectively) compared to running (1744 N, 1788 N, 1722 N, respectively). GRFvert estimates based on WAs located anterior and posterior to the iliac crest differed from estimates based on the iliac crest acceleration by less than 3% [19,20].

The predicted GRFvert based on acceleration of the lateral femoral condyle differed from GRFvert based on acceleration of the right iliac crest by -5 ± 28 N in walking and -142 ± 80 N in running. The predicted GRFvert based on acceleration of the right lateral malleolus differed from GRFvert based on acceleration of the right iliac crest by 261 ± 28 N in walking and -274 ± 66 N in running.

Discussion

A review of the literature and specific gait testing were performed to inform best practice recommendations for WA use in gait applications. Selecting a WA with the proper accelerometer range is important and requires prior knowledge of the acceleration magnitudes expected for specific anatomical locations and gait conditions [21]. Different acceleration ranges were identified in the literature and summarized to provide a starting point for selecting an appropriate WA for a specific application (Table 1). Though not noted specifically in the literature, how a WA is secured to the body will affect the acceleration magnitudes. WAs should be secured to the anatomical site as firmly as possible within the tolerance of the individual and so as not to impede normal motion [22-24].

WAs initialized at the same time by a commercial docking station do not necessarily provide accurate time synchronization. Therefore, if time synchronization of multiple WAs being needed for a given application, then the investigator should utilize their own synchronization approach or validate approaches proposed by others. Some investigators have used the timing of peak accelerations during a human jump landing test to synchronize multiple WAs secured to different body locations. We do not recommend this approach since we have found that such tests do not provide accurate time synchronization. Signal synchronization can be achieved by securing all WAs to a rigid wand and tapping that wand to impose an impact pulse easily identified in the WA data. The WA data can then be temporally align using the impact peak in post-processing. We have also observed that sampling rate may vary slightly between WAs and therefore it is advised that an impact test be performed again at the end of testing to check for drift between signals [25-30].

WAs were accurate to within 17 % for a 1 g freefall test and 0.2 % to 4.1 % for centrifuge tests over a ±6 g range. The simple free fall test is not an appropriate test of the accuracy of a WA. It is recommended that a centrifuge test, similar to that described by Coolbaugh and Hawkins, be used to determine the accuracy of WAs over the range of accelerations expected for the desired gait applications [8]. WA reliability should be determined by turning the WA on and off several times and remeasuring the output accelerations relative to the known applied acceleration [31-34].

Though the data collected in this study were from a single subject and single type WA, we believe the results highlight important issues that should be considered in best practice use of WAs. Our subject reported a midfoot strike pattern during walking and a forefoot strike pattern during running. Difference in gait mechanics would result in differences in peak acceleration magnitudes and timing between anatomical locations. However, the best practice guidelines provided here would still apply.

Summary

In summary, our best practice recommendations for using WAs for gait biomechanics applications are:

- Identify the full-scale acceleration range expected (Table 1) and select a WA with the appropriate range.
- Prior to using the WA, evaluate the WA accuracy and reliability using a centrifuge system.
- If accelerations from the WA must be converted into an anatomical reference frame, then perform appropriate calibration tests to allow the appropriate coordinate transformations.
- When using multiple WAs, and if time synchronization is important, then establish a protocol to time synchronize the WA signals during the testing period (e.g. an impact test). Do not rely on manufacturer time synchronizing methods without validating the method.
- When placing WAs around the pelvis, local precision in placement is not necessary since statistically similar resultant acceleration vector magnitude and timing was observed among sites 8-12 cm apart (an error much worse than would be expected during any WA placement in a real application). It is unknown whether such precision is necessary at other anatomical locations.
- When placing WAs along the lower limb, accelerations and temporal values at the hip, knee, and ankle can be expected to differ. Thus, when using accelerations to estimate other important measures (e.g. GRFvert), a model specific to the location of the WA should be used.

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