# Inter-Device Reliability of Tri-Axial Accelerometers for Identifying Steps and Quantifying External Load while Walking in Field-Based Environments

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**Abstract:** The monitoring of accelerometry derived load has received increased attention in recent years. However, the ability of such measures to quantify training load during field-based activities is not well established. Thus, the current study aimed to assess the inter-device reliability of tri-axial accelerometers to identify step counts and quantify external load while walking a range of distances. **Method**: Thirty physically active college students (height = 176.8 ± 6.1 cm, weight = 82.3 ± 12.8 kg) volunteered to participate in this study. Acceleration data was collected via two tri-axial accelerometers (Device A and B) sampling at 100 Hz, mounted closely together at the xiphoid process. Each participant walked a different known distance ranging from 12.57 to 376.99 m around a circle. Device A and Device B were used to assess the inter-device reliability of the accelerometry based metrics; step counts, Impulse Load (IL), and Magnitude g (MAG). **Results**: The two instruments reliably detected steps and quantified the external load during all trials. Good inter-device reliability was found with a coefficient of variation (CV) <5% for step counts, IL, and MAG during all courses. **Conclusion**: This research indicates that tri-axial accelerometers can be used to identify steps and quantify external load when movement is completed at a range of distances.

**Keywords**: wearable technology, physical activity, sport performance, external load, monitoring, sensors

**دراسة ثبات أجهزة قياس التسارع ثلاثية المحاور لتحديد عدد الخطوات وقياس الحمل التدريبي الخارجي أثناء المشي: دراسة ميدانية**

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**الملخص العربي**: حظيت مراقبة الاحمال التدريبية عن طريق استخدام أجهزة قياس التسارع باهتمام متزايد في السنوات الأخيرة، إلا أن قدرة مثل هذه الأجهزة على تحديد حجم الأحمال التدريبة خلال ممارسة الأنشطة البدنية المختلفة لم يتم دراستها بشكل كافي. لذلك هدفت هذه الدراسة إلى تقييم ثبات أجهزة قياس التسارع ثلاثية المحاور لتحديد عدد الخطوات وقياس الحمل التدريبي الخارجي أثناء المشي لمسافات مختلفة. **الطريقة**: تطوع عدد ثلاثون طالباً جامعياً ممارسين للأنشطة البدنية (الطول = ١٧٦,٨ ± ٦,١ سم، الوزن = ٨٢,٣ ± ١٢,٨ كجم) للمشاركة في هذه الدراسة. تم جمع البيانات المتعلقة بالخطوات والحمل التدريبي الخارجي عن طريق استخدام جهازين لقياس التسارع ثلاثية المحاور (الجهاز أ والجهاز ب)، بمعدل جمع بيانات للجهازين يساوي ١٠٠ هرتز في الثانية. تم تركيب الجهازين بشكل محكم بجانبي بعض على منطقة عظم القص. تم إعداد ميداني دائري في ملعب خارجي، وتم الطلب من كل مشارك أن يمشي مسافة مختلفة عن المشاركين الآخرين حيث تراوحت المسافات المقطوعة من قبل جميع المشاركين من ١٢,٥٧ إلى ٣٧٦,٩٩ متراً. تم استخدام الجهاز أ والجهاز ب لتقييم الثبات بين الأجهزة للمتغيرات والمقاييس التالية: عدد الخطوات، الحمل التدريبي الخارجي ايبولس لود (Impulse Load)، والحمل التدريبي الخارجي ماقناتود جي (Magnitude g). **النتائج**: قاما الجهازان بتحديد الخطوات والحمل التدريبي بشكل موثوق وثابت خلال جميع التجارب. تم تحقيق درجة ثبات ممتازة بين الأجهزة حيث أن درجة معامل التباين (coefficient of variation) كانت $< 5\%$ لمتغير عدد الخطوات، ومتغيرات الحمل التدريبي الخارجي خلال جميع المسافات المقطوعة. **الاستنتاج**: يشير هذا البحث إلى أنه يمكن استخدام مقاييس التسارع ثلاثية المحاور لتحديد الخطوات وقياس الحمل التدريبي الخارجي خلال الحركة والمشي لمسافات مختلفة.

**الكلمات المفتاحية**: التكنولوجيا القابلة للارتداء، النشاط البدني، الأداء الرياضي

## Introduction

Accelerometers have become a commonly used tool in tracking physical activity and monitoring training load [1–3]. A tri-axial accelerometer is an accelerometer that measures movement in three dimensions: vertical, horizontal, and lateral. This type of accelerometer is often used to quantify events such as steps, jumps, kicks and throws [4–7]. Accelerometers are also used to quantify training load in sports [8]. Moreover, accelerometers have been compared to different training load metrics such as heart rate-based training impulse [9] oxygen ($O^2$) consumption [10], total distance [11], Global Navigation Satellite System metrics (GNSS) [12], and session rating of perceived exertion (sRPE) [13]. However, the validity and reliability of tri-axial accelerometers in identifying events and quantifying external load have been a topic of debate in recent years.

Step count identification is a common method used to assess physical activity [14] Accelerometer-based event identification and human motion assessment use different event-specific algorithms and acceleration thresholds [15–17]. Moreover, a variety of algorithms have been used and validated to identify steps in field and laboratory environments [7,16,18,19] Recently, Bursais et al. [18] has found that a tri-axial accelerometer is a valid instrument to detect steps when movement is completed at different speeds on a field-based 20m straight-line course (positive predictive value (PPV) of 96.98-99.41% and an agreement of 93.08-96.29%). Although the unit was precise in detecting steps, the course used in the study required only a short bout of exercise.

Reliability is a key consideration for devices used to monitor physical activity is reliability. Several studies have investigated the reliability of tri-axial accelerometers in detecting steps and quantifying external load [18,20,21]. A recent study by Armitage et al. [20] has reported excellent inter-unit reliability of step counting (intra-class coefficient (ICC) = 0.96) and (95% confidence interval (CI) = 0.90-0.99) during various running-based team sports when devices located on the right shank. However, placing devices on a shank might not be applicable in some sports.

Assessing the inter-device reliability of accelerometry-derived external loads has been attracting considerable interest in the literature [10,18,21,22]. Gomez et al. [22] reported excellent inter-device reliability (CV = 2.96%) of eight devices mounted at four anatomical locations during a Sport-Specific Aerobic Field Test (SAFT90). Additionally, two accelerometers reliably quantified external load (CV 1.9%) during Australian football matches when devices were mounted at the upper back [21]. Several recent studies indicate the potential utility of accelerometers in evaluating external load. However, further research is needed to assess the applicability of accelerometry data for detecting specific events (such as steps) and quantifying training load while performing various activities. Therefore, the purpose of this study was to assess the inter-device reliability of tri-axial accelerometers to identify steps and quantify external load while walking a range of distances.

## Methods

### Experimental Approach for the Problem

A circle was designed on a grass field. Table 1 details the dimensions of the circle, and Figure 1 illustrates the course design. A measuring tape was used to measure the diameter of the circle and subsequently used to calculate the circumference. Flags marked the circle to guide the walking path for subjects. Flags were designed with a height of approximately 5cm to minimize any hindrance to walking. A circular structure was employed to limit the influence of initiating movement and braking that is naturally associated with changes in direction. For more information about the study design read [11]. The total distance was the only variable considered in the study to assess training loads.

**Table .1 Dimensions of the Circle.**

| | Circle |
|---|---|
| **Diameter** | 8m |
| **Circumference** | 25.13m |
| **Distance** | Half-lap = 12.56m<br>One-lap = 25.13 |

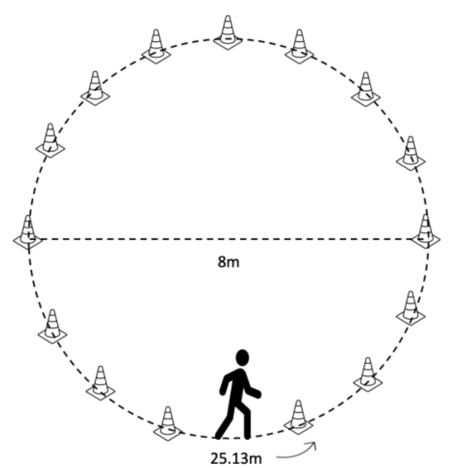


**Figure (1). Illustration of the Experiment**

### Subjects

Thirty college students (height = 176.8 ± 6.1 cm, weight = 82.3 ± 12.8 kg, age = 26.8 ± 3.1) who engaged in organized physical activity/exercise for a minimum of three days per week volunteered to participate in this study. This study was approved by East Tennessee State University's Institutional Review Board, and participants provided written consent for their involvement.

### Procedures

Prior to beginning the course, subjects were informed of the number of laps they were to complete around the circle; participants also performed a familiarization trial prior to completing their trials. Following familiarization, each participant walked a different known distance around the circle. Thirty distances ranged from 12.57 to 376.99 m completed by thirty participants. Table 2 details the number of laps and total distance each participant completed. Participants were directed to walk at their normal speed and keep the flags between their feet during the walk to ensure the course was completed accurately, and a research assistant was counting the laps loudly during the trials. Each Participant also wore two triaxial accelerometer (Device A & B). Devices A and B were used to assess the inter-device reliability of the Bioharness™ during the course design.

**Table (2). Number of Laps and Distance Traveled around the Circle.**

| Participants | Number of Laps | Known Distance/m |
|---|---|---|
| **1** | 0.5 | 12.57 |
| **2** | 1 | 25.13 |
| **3** | 1.5 | 37.70 |
| **4** | 2 | 50.27 |
| **5** | 2.5 | 62.83 |
| **6** | 3 | 75.40 |
| **7** | 3.5 | 87.96 |
| **8** | 4 | 100.53 |
| **9** | 4.5 | 113.10 |
| **10** | 5 | 125.66 |
| **11** | 5.5 | 138.23 |
| **12** | 6 | 150.80 |
| **13** | 6.5 | 163.36 |
| **14** | 7 | 175.93 |
| **15** | 7.5 | 188.50 |
| **16** | 8 | 201.06 |
| **17** | 8.5 | 213.63 |
| **18** | 9 | 226.19 |
| **19** | 9.5 | 238.76 |
| **20** | 10 | 251.33 |
| **21** | 10.5 | 263.89 |
| **22** | 11 | 276.46 |
| **23** | 11.5 | 289.03 |
| **24** | 12 | 301.59 |
| **25** | 12.5 | 314.16 |
| **26** | 13 | 326.73 |
| **27** | 13.5 | 339.29 |
| **28** | 14 | 351.86 |
| **29** | 14.5 | 364.42 |
| **30** | 15 | 376.99 |

## Instrumentation

Acceleration data was collected via two tri-axial accelerometer sampling at 100 Hz (ZephyrTM BioHarness v3, Zephyr Technology Corp., Annapolis, MD, USA). The two accelerometers were placed at the level of the xiphoid process, along the midsternal line. Accelerometry derived metrics; Step counts, Impulse Load (IL) and Magnitude g (MAG) were assessed in this study. IL an accumulative measure of mechanical load expressed in arbitrary units, while MAG is the square root of the sum of squared accelerations expressed as gravitational equivalents (1g = 9.81m/s2). The formula for each accelerometry based metric is described in Table 3. It is worth noting that IL aims to include only accelerations from locomotor events such as walking, running, jumping, and impacts, but as a proprietary metric, the methods utilized to determine accelerations from these events are not public. To facilitate data analysis, participants were asked to tap the accelerometer four times at the beginning and end of each trial.

**Table (3). Formula for Accelerometry Based Metrics Impulse Load and Magnitude g.**

| Metric | Definition and formula* |
|---|---|
| **Magnitude g** | $MAG = \sum_{s=1}^{n} \sqrt{x_s^2 + y_s^2 + z_s^2}$ |
| **Impulse Load**** | $IL = \sum_{s=1}^{n} \frac{\sqrt{x_s^2 + y_s^2 + z_s^2}}{9.8067}$ |

* In the formulas above, x = forward and backward acceleration, y = lateral acceleration and z = vertical acceleration.

** IL is propriety by the manufacture and is only associated with locomotor events that are detected by Zephyr (e.g., walking, running, bounding, jumping).

## Statistical Analysis

Accelerometry data were downloaded into OmniSense™ Analysis (version 4.1.4; Zephyr Technology Corporation, Annapolis, MD, USA) and exported to Microsoft Excel 2019 (Microsoft Corporation, Redmond, WA, USA) for analysis. Data were expressed as means and standard deviations. Inter-device reliability was assessed by calculating the Coefficient of variation (CV) and 90% Confidence interval (CI) of step counts, IL and MAG for devices A and B. CV has been categorized as good (<5%), moderate (5%–10%), or poor (>10%) for reliability investigations as suggested in sports literatures [12,23–26].

## Results

Thirty participants completed a total of 30 trials, each participant walked a different known distance ranging from 12.57 to 376.99 m. The two Bioharness™ detected steps and quantified the external load during all trials. Table 4 details the number of laps and distance traveled around the Circle, as well as the number of step counts, IL, and MAG for all trials quantified by Device A and Device B. The results, as shown in Table 5, indicate that Bioharness™ reliability quantified step counts and the external load as the CV were below < 5%.

**Table (2). Number of Step Counts, IL, and MAG for all Trials Quantified by Device A and Device B**

| Participants | Number of laps | Known Distances/m | Device A | | | Device B | | |
|---|---|---|---|---|---|---|---|---|
| | | | Steps Count | IL | MAG | Steps Count | IL | MAG |
| 1 | 0.5 | 12.57 | 17 | 29.04 | 25.08 | 19 | 30.97 | 28.43 |
| 2 | 1 | 25.13 | 40 | 103.53 | 57.66 | 39 | 106.97 | 57.5 |
| 3 | 1.5 | 37.70 | 61 | 198.92 | 90.43 | 59 | 190.9 | 89.38 |
| 4 | 2 | 50.27 | 77 | 274.39 | 117.24 | 72 | 293.23 | 109.21 |
| 5 | 2.5 | 62.83 | 79 | 297.61 | 126.21 | 78 | 311.15 | 125.8 |
| 6 | 3 | 75.40 | 102 | 224.65 | 159.53 | 104 | 233.85 | 164.85 |
| 7 | 3.5 | 87.96 | 114 | 374.6 | 185.52 | 114 | 395.39 | 186.58 |
| 8 | 4 | 100.53 | 136 | 390.72 | 213.75 | 136 | 390.15 | 218.13 |
| 9 | 4.5 | 113.10 | 146 | 598.23 | 235.34 | 146 | 597.42 | 240.84 |
| 10 | 5 | 125.66 | 166 | 597.66 | 264.97 | 166 | 612.99 | 270.24 |

| Participants | Number of laps | Known Distances/m | Device A | | | Device B | | |
|---|---|---|---|---|---|---|---|---|
| | | | Steps Count | IL | MAG | Steps Count | IL | MAG |
| 11 | 5.5 | 138.23 | 201 | 439.48 | 311.61 | 200 | 464.01 | 311.55 |
| 12 | 6 | 150.80 | 237 | 471.66 | 350.42 | 237 | 475.5 | 350.5 |
| 13 | 6.5 | 163.36 | 246 | 719.49 | 358.9 | 243 | 687.48 | 363.65 |
| 14 | 7 | 175.93 | 241 | 895.41 | 399.65 | 239 | 885.98 | 411.35 |
| 15 | 7.5 | 188.50 | 285 | 1071.26 | 418.64 | 285 | 1178.79 | 420.69 |
| 16 | 8 | 201.06 | 297 | 999.68 | 437.84 | 295 | 991.84 | 443.29 |
| 17 | 8.5 | 213.63 | 281 | 1154.62 | 420.24 | 281 | 1152.02 | 429.87 |
| 18 | 9 | 226.19 | 313 | 1006.09 | 488.78 | 315 | 1018.15 | 500.96 |
| 19 | 9.5 | 238.76 | 360 | 819.64 | 514.5 | 370 | 882.71 | 539.39 |
| 20 | 10 | 251.33 | 408 | 1238.42 | 669.27 | 407 | 1213.87 | 687.16 |
| 21 | 10.5 | 263.89 | 358 | 1215.66 | 560.68 | 360 | 1207.85 | 578.55 |
| 22 | 11 | 276.46 | 445 | 981.49 | 648.91 | 444 | 1021.97 | 661.02 |
| 23 | 11.5 | 289.03 | 421 | 1073.9 | 641.12 | 421 | 1102.24 | 644.74 |
| 24 | 12 | 301.59 | 424 | 1081.76 | 646.01 | 424 | 1072.71 | 654.97 |
| 25 | 12.5 | 314.16 | 363 | 1460.79 | 631.2 | 362 | 1491.92 | 643.63 |
| 26 | 13 | 326.73 | 415 | 1346.23 | 680.51 | 415 | 1349.15 | 694.01 |
| 27 | 13.5 | 339.29 | 472 | 1223.83 | 709.73 | 472 | 1223.52 | 723.18 |
| 28 | 14 | 351.86 | 457 | 1833.86 | 767.71 | 455 | 1805.92 | 775.67 |
| 29 | 14.5 | 364.42 | 483 | 1631.2 | 796.79 | 484 | 1675.08 | 808.88 |
| 30 | 15 | 376.99 | 630 | 2028.99 | 946.7 | 628 | 1981.61 | 961.29 |

IL = Impulse Load; MAG = Magnitude g

**Table 5 The Inter-Device Reliability of Step Counts, IL, and MAG**

| Accelerometry Derived Metrics | Inter-device CV (%) | CV 90% CI |
|---|---|---|
| **Step Counts** | 0.84% | 0.33 – 1.36% |
| **IL** | 2.06% | 1.51 – 2.60% |
| **MAG** | 1.56% | 1.03 - 2.10% |

IL = Impulse Load; CV = Coefficient of variation; CI = Confidence interval

MAG = Magnitude g; CV = Coefficient of variation; CI = Confidence interval

## Discussion

The purpose of this study was to assess the inter-device reliability of tri-axial accelerometer metrics (step count, IL, and MAG) while covering a range of distances. A primary finding is that the Bioharness$^{TM}$ is a reliable instrument used to assess steps when movement is completed at different distances. Additionally, Bioharness$^{TM}$ are highly reliable to assess external load when walking is performed. This may also suggest that accelerometry derived measures might reliably quantify training loads associated with sport-related training and competition.

This investigation revealed promising inter-device reliability (Step counts CV = 0.84%; IL CV = 2.06%; MAG CV = 1.56%) during all trials. There appears to be some agreement in the literature that Bioharness$^{TM}$ is precise and reliable when detecting steps and quantifying external load [18,27]. This also accords with our earlier observations, which showed that two Bioharness$^{TM}$ reliability quantifying external load (IL CV = 1.13-2.67 %; MAG CV = 1.61-2.10%) when sport related activities (walking, jogging, and running) performed on a 20-m straight-line course. Nevertheless, Bioharness$^{TM}$'s ability to detect steps and quantify external load on prolonged sport-related activities needs to be investigated.

In accordance with the present results, previous studies have demonstrated that different accelerometry based metrics might not equally quantify training loads in sport-related activities [11,28]. These results (IL CV = 2.06%; MAG CV = 1.56%) also seem to be consistent with other research which found that the accelerometry based metrics MAG (CV = 1.69%) might reliably better indicate training load while walking compared to IL (CV = 2.67%) [18]. Further research should be undertaken to investigate which accelerometry derived metrics best quantify external load in sports.

Although this study has successfully indicated that the Bioharness$^{TM}$ is a reliable instrument for step detection and assessing external load, this study has several limitations. First, it is noteworthy that while the Bioharness$^{TM}$ devices were positioned in close proximity, they were not placed in identical positions as recommended by the manufacturer, potentially leading to variations in the measurement of movement between the devices. Although any disparities are expected to be minor, they should be acknowledged. Second, the scope of activities performed was limited to walking, excluding other sport related actions such as running, sprinting, change of direction, and jumping. These results therefore need to be interpreted with caution when applying it to individual and team sports.

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Conflict of interest: Authors state no conflict of interest.

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