

## Article

# On the Reliability of Wearable Technology: A Tutorial on Measuring Heart Rate and Heart Rate Variability in the Wild

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**Abstract:** Wearable sensors are quickly making their way into psychophysiological research, as they allow collecting data outside of a laboratory and for an extended period of time. The present tutorial considers fidelity of physiological measurement with wearable sensors, focusing on reliability. We elaborate on why ensuring reliability for wearables is important and offer statistical tools for assessing wearable reliability for between participants and within-participant designs. The framework offered here is illustrated using several brands of commercially available heart rate sensors. Measurement reliability varied across sensors and, more importantly, across the situations tested, and was highest during sleep. Our hope is that by systematically quantifying measurement reliability, researchers will be able to make informed choices about specific wearable devices and measurement procedures that meet their research goals.

**Keywords:** wearables; measurement reliability; heart rate; heart rate variability

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## 1. Introduction

A bathroom scale is a reliable measure of one's weight, provided one stands still on the scale for several moments. Yet, one is likely to discard the measurement shown by the scale if one is startled by a spider during these moments. Trying to measure cardiac signals with a wearable sensor is similar to trying to measure one's weight while dancing on the scale. The fidelity of the measurement will depend not only on the sensor's accuracy but also on the environmental conditions under which the measurement was taken.

The recent rapid proliferation of wearable sensing technology has been accompanied by many tests of their validity [1–7], usually by examining the correlation of the wearable's signal with that of trusted laboratory equipment [8]. A lot of effort has been put into developing hardware and processing algorithms to ensure high correspondence with benchmark equipment [9–14]; for latest reviews, see [15,16]. What is usually overlooked in these tests is that most laboratory measurement procedures severely limit participants' bodily movements and cognitive activities [17]. In sharp contrast, wearable devices promise to measure the same physiological signals across a wide variety of environments and bodily states. Yet, without further testing, there is no guarantee that wearables will yield accurate measurements in all contexts.

For example, Empatica's electrodermal activity (EDA) measurement showed high agreement with the EDA measurement taken under laboratory conditions. Yet, in a study that measured EDA with Empatica for 20 hrs per participant in their daily lives, 78% of the measurements were artifacts and no meaningful analysis could be performed with the remaining data [18]. In another study, which aimed to establish the validity of Empatica's HRV measurement against a Holter ECG monitor in 24-hour ambulatory monitoring, the

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## **Table of Contents Technology Tutorial America 20 2637 Wearable Technology Tutorial United**

1. Understanding the eBook Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - The Rise of Digital Reading Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - Advantages of eBooks Over Traditional Books
2. Identifying Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - User-Friendly Interface
4. Exploring eBook Recommendations from Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - Personalized Recommendations
  - Technology Tutorial America 20 2637 Wearable Technology Tutorial United User Reviews and Ratings
  - Technology Tutorial America 20 2637 Wearable Technology Tutorial United and Bestseller Lists
5. Accessing Technology Tutorial America 20 2637 Wearable Technology Tutorial United Free and Paid eBooks
  - Technology Tutorial America 20 2637 Wearable Technology Tutorial United Public Domain eBooks
  - Technology Tutorial America 20 2637 Wearable Technology Tutorial United eBook Subscription Services
  - Technology Tutorial America 20 2637 Wearable Technology Tutorial United Budget-Friendly Options

6. Navigating Technology Tutorial America 20 2637 Wearable Technology Tutorial United eBook Formats
  - ePub, PDF, MOBI, and More
  - Technology Tutorial America 20 2637 Wearable Technology Tutorial United Compatibility with Devices
  - Technology Tutorial America 20 2637 Wearable Technology Tutorial United Enhanced eBook Features
7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - Highlighting and Note-Taking Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - Interactive Elements Technology Tutorial America 20 2637 Wearable Technology Tutorial United
8. Staying Engaged with Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Technology Tutorial America 20 2637 Wearable Technology Tutorial United
9. Balancing eBooks and Physical Books Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Technology Tutorial America 20 2637 Wearable Technology Tutorial United
10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
11. Cultivating a Reading Routine Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - Setting Reading Goals Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - Fact-Checking eBook Content of Technology Tutorial America 20 2637 Wearable Technology Tutorial United
  - Distinguishing Credible Sources
13. Promoting Lifelong Learning
  - Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
14. Embracing eBook Trends

- Integration of Multimedia Elements
- Interactive and Gamified eBooks

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