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Wearable bioimpedance technology demonstrates closer agreement with laboratory-based total body water estimates than standing devices in adults with Down syndrome

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Article

Keywords: Intellectual disabilities, total body water, bioimpedance, body composition

Posted Date: April 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9382551/v1

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Additional Declarations: There is **NO** conflict of interest to disclose.

Abstract

Background

Wearable bioimpedance technology offers a potentially accessible method for assessing total body water (TBW), yet its agreement with laboratory-based approaches in adults with Down syndrome remains unclear. The purpose of this study was to evaluate whether a wearable bioimpedance device demonstrates agreement with laboratory-based bioelectrical impedance spectroscopy (BIS) estimates of TBW comparable to standing bioimpedance devices in adults with Down syndrome.

Methods

Sixteen adults with Down syndrome (age: 28.3 ± 9.2 year; height: 150.9 ± 7.8 cm; body mass: 77.4 ± 20.3 kg) completed TBW assessment using BIS (reference), a wearable bioimpedance device (BIA_W), and two standing multi-frequency bioimpedance analyzers (BIA_{ST1}, BIA_{ST2}).

Results

Repeated measures ANOVA revealed significant differences among devices ($F(3,42) = 17.52$, $p < 0.001$). Both standing devices produced lower TBW values compared with BIS ($p < 0.001$; $d = 1.32$ and 1.00), whereas BIA_W did not differ from BIS ($p = 0.106$; $d = 0.45$). All devices demonstrated strong correlations with BIS ($r = 0.92–0.93$). Bland–Altman analyses showed systematic underestimation for standing devices (− 3.12 ± 4.65 L and − 2.36 ± 4.64 L), while the wearable exhibited the smallest bias (− 1.07 ± 4.64 L). Standard error of estimate values were similar across devices (2.34–2.45 L).

Conclusion

These findings indicate that wearable bioimpedance technology demonstrated closer agreement with laboratory-based TBW estimates than standing devices.

INTRODUCTION

Down syndrome is the most common chromosomal condition associated with intellectual disability and is accompanied by a range of physiological and health-related disparities [1,2]. Adults with Down syndrome demonstrate increased prevalence of obesity, altered body composition profiles, and elevated risk for cardiometabolic conditions compared with the general population [3–5]. As life expectancy continues to increase in this population, there is growing clinical interest in accessible methods for monitoring physiological health markers that may support assessment, intervention, and long-term health management [6,7].

Total body water (TBW) represents a clinically meaningful component of body composition, and its assessment may be particularly relevant among adults with Down syndrome. For example, TBW reflects the internal fluid environment, and it supports metabolic processes, cellular function, and tissue integrity [8]. TBW is also closely linked to fat-free mass and may provide indirect insight into muscle quantity and overall physiological status [8,9]. Additionally, hydration status and body water distribution can influence physical function, cardiometabolic health, and interpretation of body composition outcomes [10–12]. These attributes highlight the importance of accurate TBW assessment when evaluating health and functional capacity in this population, particularly given this special populations' reduced muscle mass and altered body composition profiles that have previously been observed [13].

Despite its clinical relevance, direct measurement of TBW using reference techniques such as isotope dilution is costly, time-intensive, and rarely feasible outside specialized research environments. Consequently, bioelectrical impedance–based methods have emerged as practical alternatives for estimating TBW in research and clinical settings [12]. Among these approaches, bioelectrical impedance spectroscopy (BIS) is often considered an advanced technique because it measures tissue impedance across a broad range of frequencies and estimates TBW using biophysical modeling [14]. These characteristics position BIS as an accepted reference method for estimating TBW when direct dilution techniques are not feasible [15].

In addition to BIS, more accessible bioelectrical impedance analysis (BIA) technologies, including standing octopolar multi-frequency analyzers and consumer wearable devices, are increasingly used in clinical and applied environments. However, these devices typically rely on proprietary prediction equations and simplified measurement assumptions, which may introduce systematic differences in TBW estimation compared with BIS-derived values [12,15–17]. These concerns may be amplified in adults with Down syndrome, as most prediction equations are developed using general population samples that may not fully account for population-specific anthropometric and physiological characteristics [18–20]. Furthermore, the rapid growth of consumer wearable technologies has created new opportunities for accessible, user-friendly physiological monitoring methods [21]. However, limited information exists regarding whether wearable-derived TBW estimates demonstrate agreement with BIS comparable to that observed with conventional standing BIA devices in adults with Down syndrome. Therefore, the purpose of this study was to evaluate whether a wearable bioimpedance device demonstrates agreement with laboratory-based BIS estimates of TBW comparable to standing bioimpedance devices in adults with Down syndrome.

MATERIALS AND METHODS

Study Design

A cross-sectional repeated-measures design was used in which each participant completed TBW assessments using one BIS device and three BIA technologies. All measurements were completed

during a single testing session under standardized conditions to minimize biological variability between assessments. Hydration status was verified prior to testing to reduce the influence of acute fluid shifts on impedance-derived estimates.

Participants

Sixteen adults with Down syndrome (age: 28.3 ± 9.2 year; height: 150.9 ± 7.8 cm; body mass: 77.4 ± 20.3 kg) volunteered to participate in this study. Participants were recruited through local community and clinical programs serving individuals with Down syndrome. Inclusion criteria required a confirmed diagnosis of Down syndrome and the ability to stand independently for body composition assessment procedures. Individuals with implanted electronic medical devices, acute illness, or other contraindications to bioelectrical impedance testing were excluded. All participants and their legal guardians provided informed consent prior to participation. The study was approved by the institutional review board in accordance with ethical standards for human research.

Participants were instructed to refrain from structured exercise for at least 24 hours prior to testing and to avoid food intake for at least 3 hours before their scheduled assessment. In addition, participants were encouraged to consume approximately 16–20 oz of water before arriving at the laboratory to help standardize hydration status.

Procedures

Height was measured using a free standing stadiometer and weight was measured with a calibrated digital scale. Hydration status was assessed using urine specific gravity (USG) using a handheld refractometer (Atago SUR-NE, Atago Corp Ltd., Tokyo, Japan). Adequate hydration was verified by all participants providing a USG value ≤ 1.029 (ref.11). Following the assessments of height, weight, and USG, TBW measurements were performed in a standardized order beginning with BIS, followed by the wearable BIA device, and then the two the standing BIA devices.

A hand-to-foot BIS device (SFB7, ImpediMed Limited, Queensland, Australia), served as the laboratory-grade reference method for TBW. Prior to electrode placement, skin sites were cleaned with alcohol pads. In accordance with manufacturer specifications, participants were positioned supine with the arms abducted approximately 30° from the torso and the legs separated to avoid limb contact. Disposable electrodes were placed on the right hand and right foot using a standard tetrapolar configuration. All BIS measurements were obtained following a standardized resting period to ensure stabilization of body fluids prior to assessment, and TBW estimates were generated using the manufacturer's software.

TBW was estimated using a consumer wearable device (Galaxy Watch7; Samsung Electronics Co., Ltd., Suwon, South Korea) (BIA_W). Prior to measurement, the wrist on which the watch was worn and the fingertips of the opposite hand used to contact the device electrodes were cleaned using a spun-laced

non-woven wipe moistened with a mild saline-based solution to improve skin contact and electrical conductivity. The device was then worn on the wrist according to manufacturer instructions, with the watch secured to ensure consistent skin contact throughout testing. Participant demographic information required by the device (e.g., age, sex, height, and body mass) was entered prior to measurement. During assessment, participants remained standing and still while the measurement was initiated through the device interface. Participants were instructed to place the fingers of the hand opposite the watch onto the designated contact points on the device as directed by the manufacturer to complete the bioelectrical impedance measurement. Total body water estimates were obtained directly from the device-generated output.

Two standing octopolar multi-frequency BIA devices were also used to estimate TBW: the InBody 970 (InBody Co., Ltd., Seoul, South Korea) (BIA_{ST1}) and the SECA mBCA 514/515 (SECA GmbH & Co. KG, Hamburg, Germany) (BIA_{ST2}). Prior to measurement, the required demographic information (sex, age, and height) was entered into each device according to manufacturer guidelines. Participants then stood barefoot on the platform electrodes while grasping both the hand electrodes with the palms, fingers, and thumbs maintaining full contact throughout the assessment. Body composition analysis was initiated while participants remained standing upright and as motionless as possible until completion of the scan. TBW estimates were obtained directly from each device's proprietary software output. An approximate 5-minute transition period was allowed between measurement procedures.

Statistical Analyses

Descriptive statistics (mean ± standard deviation) were calculated for TBW estimates from each device. Differences between devices were evaluated using repeated-measures analysis of variance (ANOVA), followed by pairwise comparisons to identify specific differences between methods. Pearson correlation coefficients (r) and standard error of the estimate (SEE) were calculated for each field-based BIA device relative to BIS to quantify the typical prediction error associated with TBW estimates. Agreement between BIS and each field-based device was assessed using Bland–Altman analyses, with constant error (CE) and 1.96 SD of the differences calculated as each BIA device minus BIS values. Statistical significance was set at $p < 0.05$. All analyses were performed using SPSS statistical software (version 29; IBM Corp., Armonk, NY, USA).

RESULTS

Mean ± SD values for total body water (TBW) obtained from each device are presented in Table 1. Repeated measures ANOVA revealed significant differences in TBW estimates among devices ($F(3,42) = 17.52$, $p < 0.001$). Pairwise comparisons demonstrated that both standing BIA devices produced significantly lower TBW values compared with BIS (BIA_{ST1}: $p < 0.001$; BIA_{ST2}: $p < 0.001$), whereas TBW estimates obtained from BIA_W were not significantly different from BIS ($p = 0.106$). Strong positive correlations were observed between BIS-derived TBW and all field-based devices ($r = 0.92–0.93$, all $p <$

0.05). SEE values were similar across devices, ranging from 2.34 to 2.45 L, indicating comparable individual-level variability relative to BIS.

Table 1. Comparison of TBW (L) from the criterion BIS and the three BIA devices.

					Limits of Agreement			
Value	Mean ± SD	p	r	SEE	CE ± 1.96 SD	Upper	Lower	Trend
BIS	36.86 ± 6.10							
BIA_W	35.79 ± 6.37	0.106	0.93*	2.34	-1.07 ± 4.64	3.57	-5.71	0.11
BIA_{ST1}	33.74 ± 5.62	<0.001	0.92*	2.45	-3.12 ± 4.65	1.53	-7.77	-0.21
BIA_{ST2}	34.53 ± 6.32	<0.001	0.93*	2.44	-2.36 ± 4.64	2.28	-7.00	0.01

BIS = Bioelectrical impedance spectroscopy, BIA_W = bioelectrical impedance analysis wearable device, BIA_{ST1} = bioelectrical impedance analysis standing device 1, BIA_{ST2} = bioelectrical impedance analysis standing device 2, SD = standard deviation, SEE = standard error of estimate, CE = constant error/mean bias, *Indicates statistical significance ($p < 0.05$).

Limits of agreement analyses using Bland–Altman methodology are summarized in Table 1 and illustrated in Figs. 1–3. CE (± 1.96 SD) values demonstrated systematic underestimation of TBW relative to BIS for both standing devices (BIA_{ST1}: −3.12 ± 4.65 L; BIA_{ST2}: −2.36 ± 4.64 L). In contrast, the BIA_W demonstrated the smallest bias relative to BIS (-1.07 ± 4.64 L), indicating closer group-level agreement. Trend values were small and non-significant for all comparisons, indicating minimal evidence of proportional bias across the range of TBW values.

DISCUSSION

The purpose of this study was to evaluate whether a wearable bioimpedance device demonstrates agreement with laboratory-based BIS estimates of TBW comparable to standing bioimpedance devices in adults with Down syndrome. The BIS device was selected as the reference method in the study due to previous research demonstrating valid TBW estimates compared to isotope dilution techniques [17,22]. The primary finding of this study was that the mean TBW comparisons to BIS differed across the three BIA devices despite there being similar strong associations. Both standing octopolar multi-frequency BIA systems demonstrated systematic underestimation relative to BIS, whereas the wearable device exhibited the smallest mean bias and was not significantly different from BIS at the group level. Collectively, these findings highlight the importance of evaluating bias and limits of agreement, rather than correlation alone, when interpreting TBW estimates across bioimpedance technologies in adults with Down syndrome where device-specific differences may influence clinical interpretation.

A key finding of the present study was that the BIA_W demonstrated the smallest mean bias relative to BIS. This was noteworthy given that the BIA_W is a consumer-oriented wearable device rather than a

laboratory-based assessment tool. The reduced mean bias observed for the BIA_W compared to the standing units likely reflects differences in proprietary prediction algorithms and how TBW is estimated from impedance-derived signals [14,16]. In addition, the bioelectrical current pathway used by the wearable device is primarily confined to the upper body. This characteristic is similar to earlier hand-to-hand bioimpedance models, which have historically demonstrated limitations for estimating body fat due to incomplete assessment of regional adipose tissue distribution [23,24]. However, TBW estimation may be less sensitive to this limitation because electrical current preferentially travels through hydrated fat-free tissues, which are more uniformly distributed than adipose tissue [8,12,25,26]. Thus, although regional current pathways can influence fat estimation, their impact on TBW determination may be comparatively smaller [8], potentially contributing to the closer agreement observed between the wearable device and BIS in the present study. This also raises the possibility that wearable-derived TBW estimates could serve as a user-friendly input for emerging clinical and field-based multi-compartment body composition models [27], although this application requires direct validation. Nevertheless, these findings suggest that consumer-grade technologies may, in some contexts, produce TBW estimates that align closely with laboratory-based reference methods [21,28].

The systematic underestimation of TBW observed in the standing BIA devices relative to BIS likely reflects differences in underlying prediction models and measurement assumptions rather than random measurement error [12,16]. Standing BIA systems typically estimate TBW using proprietary regression equations derived from general population samples, which may not fully account for variation in body proportions, muscle mass, and hydration characteristics present in adults with Down syndrome [12,16,18,19,29]. In contrast, BIS estimates TBW using multi-frequency impedance modeling, which may reduce dependence on population-specific assumptions[14,30,31]. Collectively, these findings suggest that the standing devices evaluated in the present study may produce consistently lower TBW estimates relative to BIS at the group level, emphasizing the importance of considering device-specific bias when interpreting values across technologies.

Previous investigations comparing conventional BIA methods with BIS or other reference approaches in general adult populations have similarly reported strong correlations accompanied by systematic differences in TBW estimates [22,32,33]. These studies consistently demonstrate that devices can exhibit high linear associations while still producing clinically meaningful bias, largely attributable to differences in prediction equations, frequency ranges, and modeling assumptions [14,31,33,34]. The present findings align with this broader body of literature by demonstrating that strong correlations alone are insufficient to establish interchangeability between impedance technologies [34]. Importantly, the current study extends these observations to adults with Down syndrome, a population in which device comparability for TBW has received limited attention despite known differences in body composition and physiological characteristics [3,18].

Although systematic differences in mean TBW estimates were observed between devices, the limits of agreement were consistent across all methods. Furthermore, the SEE values for each field-based device

in comparison to BIS were approximately 2.34–2.45 L, representing roughly 6.5% of the mean BIS-derived TBW value. These findings suggest that, regardless of device type, a similar magnitude of individual-level error should be expected when estimating TBW in adults with Down syndrome. Consequently, individual TBW estimates should still be interpreted with awareness of inherent measurement variability when used in clinical or applied settings [16].

From a clinical perspective, these findings indicate that TBW estimates derived from different bioelectrical impedance technologies may not be directly interchangeable in adults with Down syndrome due to device-specific systematic differences. While the wearable device demonstrated closer group-level agreement with BIS, the standing octopolar BIA systems consistently produced lower TBW estimates. This indicates that absolute values may vary depending on the technology used even under standardized conditions. This consideration is particularly relevant in populations with altered body composition characteristics, where prediction equations developed from general population samples may introduce additional bias [16,20,35–37]. Consequentially, these findings emphasize the importance of considering device-specific characteristics when evaluating TBW and support the use of consistent measurement methods within clinical or applied settings involving adults with Down syndrome.

Several limitations should be acknowledged when interpreting the findings of this study. First, the sample size was modest and limited to adults with Down syndrome, which may restrict generalizability to other populations. However, this reflects the practical challenges associated with recruiting and testing individuals within this clinical group. Therefore, the findings provide important preliminary data in an understudied population. Second, BIS was used as the reference method rather than isotope dilution techniques, which are considered criterion measures for TBW assessment[8]. Nevertheless, BIS is widely accepted as a valid laboratory-based reference approach when dilution methods are not feasible [15–17]. Third, device-specific prediction algorithms are proprietary and not accessible for analysis. This limits the ability to determine the exact sources of systematic differences observed between methods. Finally, the cross-sectional design evaluated agreement during a single testing session. Therefore, the responsiveness to changes in TBW over time between the devices cannot be determined. Future research should examine these relationships in larger samples and explore whether similar patterns of agreement are observed across different clinical populations and testing conditions.

Conclusion

In adults with Down syndrome, TBW estimates from three different BIA technologies differed when compared to BIS despite strong associations between methods. Standing multi-frequency BIA devices demonstrated systematic underestimation relative to BIS, whereas the wearable device exhibited the smallest mean bias and showed no significant group-level difference from the reference method. Importantly, individual-level variability was similar across all devices, indicating that differences between technologies were primarily driven by systematic bias rather than measurement precision. Collectively, the findings suggest that TBW estimates from a wearable bioimpedance analyzer provided better agreement with laboratory-grade BIS technology compared to two standing BIA devices.

Declarations

Ethical Approval

Authors must provide a statement regarding ethical approval (see information on Human Experiments in the Editorial Policy section for further details). If ethical approval was not required, authors must provide an explanation of why it was not needed.

Competing Interests:

Authors must declare whether or not there are any competing financial interests in relation to the work described. This information must be included at this stage and will be published as part of the paper. Please see the Competing Interests section under Editorial Policies for detailed information.

Funding:

The funding section is mandatory. Authors must declare sources of study funding including sponsorship (e.g. university, charity, commercial organization) and sources of material (e.g. novel drugs) not available commercially. If no financial assistance was received in support of the study, please include a statement to this fact here.

Author Contributions:

This section is mandatory. The individual contributions of authors to the manuscript should be specified in this section (for example JS designed experiments and helped write the manuscript; NAL contributed to data extraction and provided feedback on the report. Guidance and criteria for authorship can be found in the section on Authorship on the Editorial Policies page.

Acknowledgements:

These should be brief, and should include sources of technical assistance, critical advice or other assistance, which contributed to the final manuscript.

Data Availability Statement:

Data are available from the corresponding author on reasonable request.

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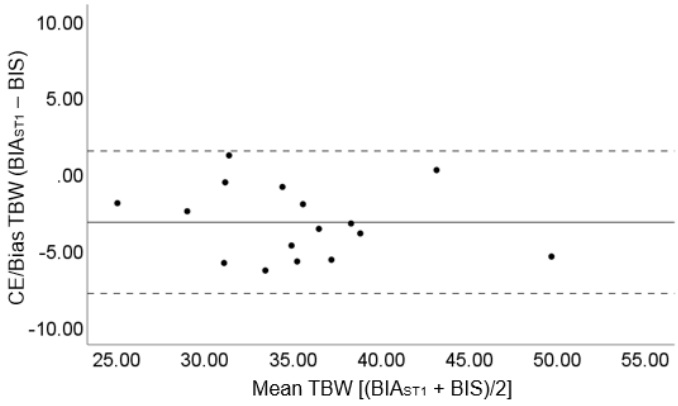
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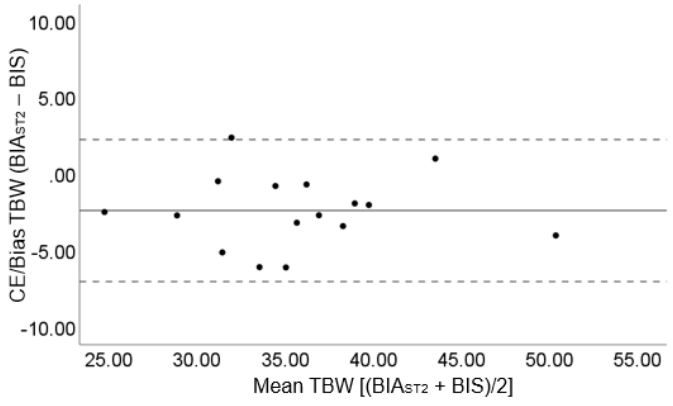
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Figures





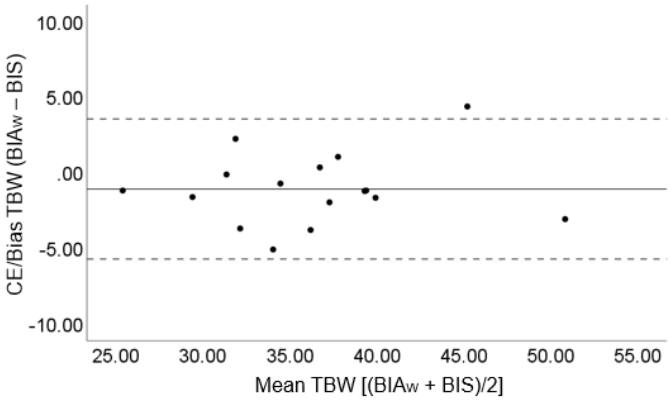


Figure 1

Bland-Altman plot comparing total body water (TBW) estimates from the standing bioelectrical impedance devices 1 (BIA_{ST1}) and 2 (BIA_{ST2}), and the wearable bioimpedance analyzer (BIA_{W}) against the reference method of bioimpedance spectroscopy (BIS). The middle solid line in each graph represents the constant error (CE) values of each BIA device. The 2 outside dashed lines indicate the upper and lower limits of agreement.