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## Brief Report

# IMU Calibration for Post-Stroke Movement Assessment: Does Calibration Quality Depend on Motor Impairment Severity?

Anna Wargel<sup>a,\*</sup>, Andreas Mayr<sup>b</sup>, Steven van Andel<sup>c</sup>, Elke Pucks-Faes<sup>b</sup>, Peter Federolf<sup>a</sup>

<sup>a</sup> Department of Sport Science, University of Innsbruck, Innsbruck, Austria

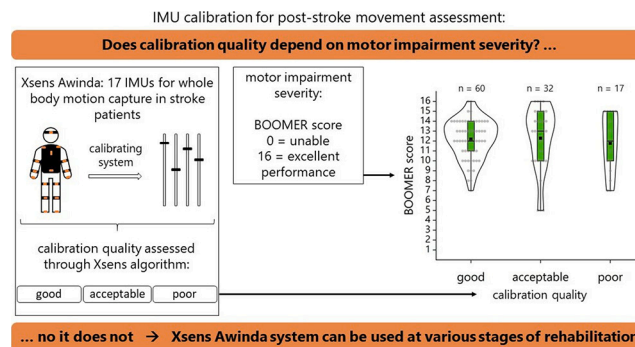
<sup>b</sup> Österreichisches Landeskrankenhaus Hochzirl – Natters, Standort Hochzirl, Austria

<sup>c</sup> IJsselheem Foundation, Kampen, the Netherlands

## HIGHLIGHTS

- Evaluation of IMU calibration quality in stroke patients with motor impairments.
- Calibration quality of Xsens Awinda was independent of stroke-related motor impairment.
- Consequently, Xsens Awinda system can be used at various stages of rehabilitation.
- Current calibration procedures may limit usability for patients with severe impairments.

## GRAPHICAL ABSTRACT



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## ABSTRACT

**Background:** Inertial motion capture systems like Xsens Awinda are increasingly used for assessing movement in clinical populations. However, it remains unclear how stroke-related motor impairments affect the quality of motion capture calibration, which is critical for obtaining reliable data.

**Research question:** Does motor impairment severity in stroke patients influence calibration quality when using the Xsens Awinda system?

**Methods:** Forty-eight individuals with a primary stroke (median age 66 years; 21 female; FAC  $\geq 3$ ) performed a total of 117 motion capture assessments using the Xsens Awinda system. Calibration quality was rated using Xsens' internal quality metrics. Kruskal-Wallis tests were conducted to compare functional motor abilities, assessed using the BOOMER test and 10-meter walk time, across calibration quality levels.

**Results:** Of the 109 valid trials, 55% achieved *good*, 29% *acceptable*, and 16% *poor* calibration quality. Neither the BOOMER scores nor the 10-meter walk time was significantly associated with calibration quality levels.

**Significance:** These findings suggest that the Xsens Awinda system can be used across a range of motor impairment levels without introducing bias due to changes in calibration quality. Nonetheless, calibration may be challenging for severely affected individuals, a limitation that warrants further practical refinement of current procedures.

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\* Corresponding author.

E-mail address: [anna.wargel@uibk.ac.at](mailto:anna.wargel@uibk.ac.at) (A. Wargel).

## 1. Introduction

Assessing movement patterns in clinical populations is essential for tailoring and improving individual rehabilitation strategies [1]. This is particularly important in neurological conditions, where motor impairments can significantly affect independence and quality of life [2].

Although optical motion capture (OMC) remains the gold standard in lab-based movement analysis [1,3], observational methods and standardized subjective assessments are still predominantly used for quantifying movement quality in a clinical context [4,5], since OMC is expensive, time-consuming, and space-intensive. Compared to OMC, inertial measurement unit (IMU) systems are easier to implement, less resource-intensive, and offer greater flexibility across diverse environments, making them a practical alternative for movement analysis [6–11].

One example of an IMU-based motion capture system is the Xsens Awinda system (Xsens Technologies; Enschede, the Netherlands). Xsens has been validated in healthy populations, showing good agreement with OMC, especially in sagittal joint angles with root mean square error values around 5° [12–14]. Meralau et al. demonstrated its validity for spatiotemporal parameters in clinical settings [15], and specifically in stroke patients, Unger et al. confirmed its validity for upper-limb kinematics [16]. Xsens has been applied, for example, for longitudinal monitoring of upper-limb use in stroke survivors [10] or in case studies assessing gait and posture for rehabilitation planning in orthopedic and neurological patients [17,18].

Accuracy and precision of Xsens data largely depend on the calibration conducted before taking any measurements with the system. Therefore, the Xsens system includes an internal algorithm that estimates calibration quality using the categories *good*, *acceptable*, and *poor*. A previous study with stroke patients recommended the dynamic calibration procedure for Xsens measurements [19], where the patient executes specific poses and movements. However, depending on how severely stroke affects a patient's motor abilities, such calibration steps may be difficult to achieve, may be achievable only with external support, or may not be possible. Hence, it seems a plausible assumption that the calibration quality may depend on the patient's motor impairment severity.

The current short communication explores the relationship between calibration quality as quantified by the Xsens algorithm and the motor impairment severity suffered by the stroke patients. We hypothesized that more severe motor impairment would be associated with a poorer calibration quality.

## 2. Methods

### 2.1. Participants

The study was conducted at the Neurology Department of the hospital Hochzirl-Natters (Austria), Hochzirl site. Patients with a primary stroke were included once they were able to walk at least 10 meters without physical assistance. A Functional Ambulation Categories (FAC) score [20] of  $\geq 3$  (walking with supervision, no physical contact) was required for inclusion. Exclusion criteria were additional neurological conditions affecting balance (e.g., Parkinson's disease), orthopedic impairments restricting standing or walking, cognitive or communication deficits interfering with task understanding (e.g., global aphasia), cardiovascular conditions preventing a 10-meter walk, and acute illness. The study was approved by the Ethics Committee of the Medical University of Innsbruck, and all participants gave written informed consent.

### 2.2. Measurement protocol

The current retrospective observational study utilizes data from a three-visit longitudinal study originally designed to monitor rehabilitation progression in stroke patients. Measurements were taken at three rehabilitation stages: T1 (admission, 51 participants), T2 (discharge, 39 participants), and T3 (three months post-discharge, 27 participants). The reduction in sample size over time was due to patient dropouts and logistical constraints. At each visit, patients' functional mobility was assessed using the Balance Outcome Measure for Elder Rehabilitation (BOOMER) test [21,22] and by a 10-meter walk test [23,24]. The BOOMER score ranged from 0 (unable to perform) to 16 (excellent performance) [21,25]. In the 10-meter walk test, time to completion (10mWT) was used as dependent variable. To minimize potential bias, all measurements were performed by trained experimenters who were unaware that calibration quality would be evaluated.

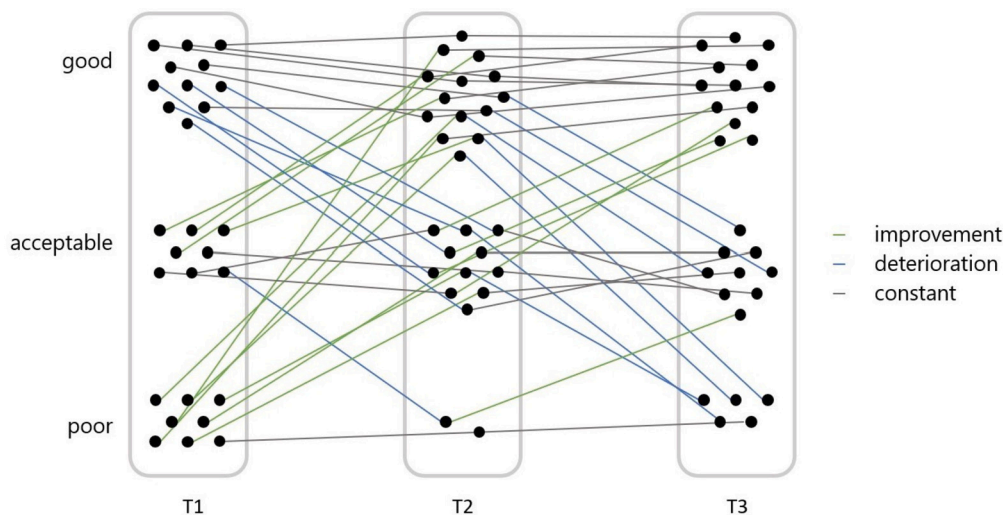
### 2.3. Instrumentation

Full-body kinematic data were recorded at 60 Hz using the Xsens Awinda (Movella Technologies, Enschede, the Netherlands) system with 17 wireless inertial sensors attached to the recommended anatomical segments: head, shoulders, sternum, upper arms, wrists, hands, pelvis/sacrum, upper and lower legs, and feet. Sensors were worn using a full-body strap set, including a shirt. Each session began with a dynamic calibration (N-pose and movement), rated by the Xsens software, Xsens MVN Analyze (version 2021.2), as *good*, *acceptable*, or *poor*. Experimenters were instructed to repeat the calibration until a *good* rating was achieved whenever possible. However, in cases where participants fatigued quickly, an *acceptable* or *poor* calibration was accepted to prevent excessive strain. Because all participants had motor impairments, some were unable to independently maintain the required N-pose or generate sufficient movement during the walking phase of the calibration. In such cases, minimal assistance was provided by the assessors to help patients assuming the correct posture or simulate arm swing during walking, ensuring the best possible calibration within their physical limitations. After data collection, the data was manually quality screened by assessing plausibility of the Xsens avatar movements. Eight trials with flawed calibration (3, 4, and 1 with *good*, *acceptable*, and *poor* calibration quality, respectively) had to be excluded.

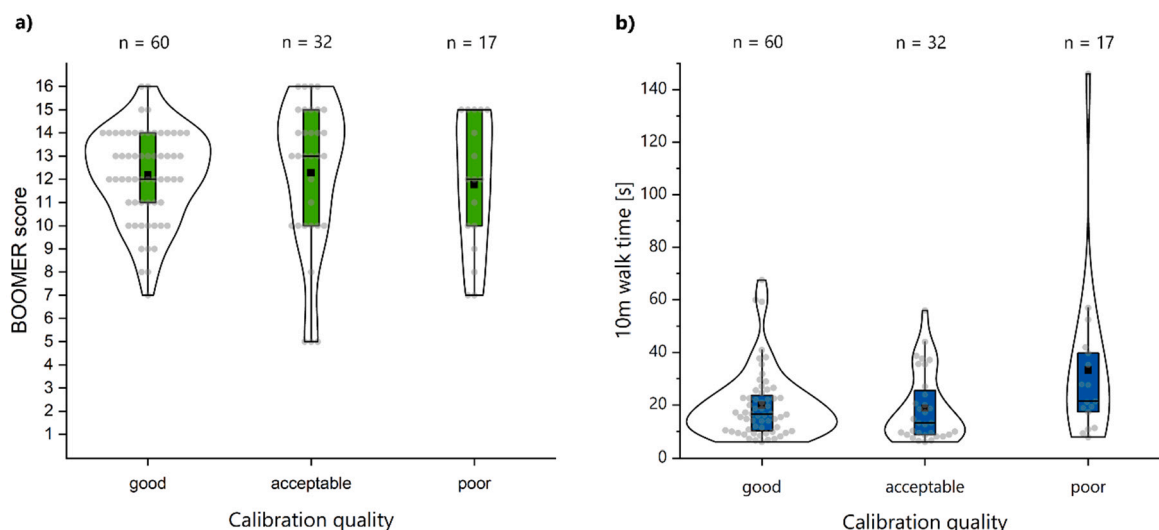
### 2.4. Statistical analysis

Statistical analyses were performed in jamovi 2.3.28 [26] and in IBM SPSS Statistics (Statistical Package for the Social Sciences, version 26; IBM Corp., Armonk, NY, USA). The significance level was set at  $\alpha = 0.05$ , and p-values  $< 0.10$  were considered as evidence of a potential trend. All data are presented as median and interquartile range (IQR). As the variables were ordinal or not normally distributed, non-parametric tests were applied. Furthermore, since calibration quality varied substantially from trial to trial, even within the same participant (Fig. 1), and given that calibration quality had only three levels, data points were treated as independent samples. This way, all available data from participants who did not complete all three measurement points could still be included. A low Kendall's coefficient of concordance ( $W = 0.04$ ,  $p = 0.336$ ) and a non-significant Friedman test ( $\chi^2(2) = 2.18$ ,  $p = 0.336$ ), based on the 27 participants with complete data, provided statistical support for the assumption of independence.

Thus, the Kruskal-Wallis test was used to assess differences in functional mobility (BOOMER score) and walking ability (10mWT) across calibration quality levels. Epsilon squared ( $\epsilon^2$ ), which ranges from 0 (no relationship) to 1 (perfect relationship) [27] was reported as effect size.



**Fig. 1.** Changes in calibration quality over time for the 27 patients who completed all three measurement time points at T1, T2, and T3. Each line represents a patient's calibration quality trajectory across three time points. Grey indicates unchanged, green improved, and blue deteriorated calibration quality.



**Fig. 2.** Visualization of the distribution of the a) BOOMER score and b) time to complete the 10-meter walk test for the three calibration qualities.

**Table 1**

Patient's baseline (T1) characteristics, n = 48.

	Median	IQR
Sex		
Female	21	
Male	27	
Affected side		
Right	26	
Left	18	
Both	4	
Age	66	55.3-72.3
Time post-stroke at T1 (days)	51.5	32-91
Functional performance		
BOOMER		
10-meter walk time [s]	19.9	11.4-35.5
10-meter walk speed [m/s]	0.51	0.28-0.88

### 3. Results

A total of 48 stroke patients participated in the study. The patient's baseline characteristics are presented in Table 1. They provided a total of 117 calibrations, of which 109 valid calibrations were included in the analysis after quality screening.

Of the 109 calibrations, 60 (55%) achieved *good*, 32 (29%) *acceptable*, and 17 (16%) *poor* calibration quality (Fig. 2). The Kruskal-Wallis test indicated no significant differences in functional mobility (BOOMER score:  $\chi^2(2) = 1.22$ ,  $p = 0.544$ ,  $\epsilon^2 = 0.011$ ) across calibration quality levels (Fig. 2a). There was a statistical trend (10mWT:  $\chi^2(2) = 5.77$ ,  $p = 0.056$ ,  $\epsilon^2 = 0.054$ ) suggesting that poorer walking ability may be related to reduced calibration quality (Fig. 2b), however, this potential effect did not reach the level of statistical significance. Furthermore, the latter result was influenced by a single strong outlier in the 10mWT data (Fig. 2b), whose removal from the calculations produced a clear non-significant outcome ( $\chi^2(2) = 4.47$ ,  $p = 0.107$ ,  $\epsilon^2 = 0.042$ ).

### 4. Discussion

The hypothesis that more severe motor impairment would be associated with poorer calibration quality was not supported in this study. Evidently, when experimenters try their best to achieve high-quality calibration, good calibration quality can be obtained even in severely impaired patients. Conversely, poor calibration quality can occur even in trials with relatively well-performing participants. Furthermore, despite its apparent plausibility, even the

ability to walk was not associated with good calibration outcomes in our data.

Optimistically interpreted, our findings suggest that calibration quality is independent of motor impairment severity in stroke patients using the Xsens Awinda system. This, in turn, suggests that this system can be reliably used to monitor the rehabilitation progress without introducing bias from improved calibration quality as patients regain motor function.

On the other hand, the fact that 16% of trials achieved only poor calibration quality, and the fact that an additional eight trials had to be excluded entirely due to corrupted calibration, raises concerns about the appropriateness and robustness of the current calibration procedures. The required N-pose and movement phases are challenging for many stroke patients to perform accurately, which may compromise data quality and limit the usability of the system in clinical populations with significant impairments. As highlighted by Lallès et al., alternative calibration methods that account for restricted movement are required to improve data accuracy and reliability [19]. For example, a recent study by Di Raimondo et al. introduced a new calibration approach for whole-body kinematics using Xsens and an open-source biomechanical modeling program [28]. Although promising, this method may be too demanding for stroke patients with substantial motor impairments given the complexity of the movements required. Similarly, McInnes et al. proposed an alternative calibration method tailored for upper-limb assessments in motor-impaired individuals [29]. While effective, this method is limited to upper-limb analysis, leaving lower-limb and full-body assessments unaddressed. Although these alternative calibration approaches aim to address the limitations for motor-impaired populations, they often require technical expertise and are not practical in routine clinical settings. What's still missing are calibration methods that are both reliable and easy to integrate into busy clinical workflows.

There are a few limitations to consider in the interpretation of these findings. First, some participants required assistance during calibration, particularly in achieving the correct posture for the N-pose. Unfortunately, the frequency of this assistance was not systematically recorded, preventing us from quantifying how often external help was needed. Such assistance may have influenced calibration quality, and tracking its occurrence in future studies could help to refine the calibration procedures and guide protocol adaptations for patients with restricted movement. Second, Xsens system's internal quality metrics might not always align with real-world movement accuracy, particularly in motor-impaired individuals. The fact that even data categorized as *good* in the internal assessment sometimes had to be excluded due to obvious calibration issues corroborates this issue. Third, motor impairment severity was characterized using only two variables, the BOOMER score and 10mWT. While these measures capture key aspects of motor function, they may not fully reflect the range of impairments experienced by stroke patients. Finally, this study used a convenience sample of stroke patients rather than an a priori non-inferiority design. While a non-inferiority trial comparing calibration quality between stroke patients and healthy individuals would provide a more rigorous assessment, it was beyond the scope of this exploratory study. Future research should consider such designs to confirm the present findings.

## 5. Conclusions

This study found no clear association between calibration quality and motor impairment severity in stroke patients. This suggests that the Xsens Awinda system can be used at various stages of rehabilitation, without concerns about introducing bias from improved calibration quality as patients regain motor function.

Our findings also highlight opportunities for improvement: the current calibration procedures are (too) demanding for patients with severe motor impairments. Adapting and simplifying the calibration process to account for patients' limitations may improve data quality and streamline patient handling, thereby enhancing the overall clinical applicability of the Xsens system.

## CRediT authorship contribution statement

**Anna Wargel:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Andreas Mayr:** Writing – review & editing, Methodology, Investigation. **Steven van Andel:** Writing – review & editing, Funding acquisition, Conceptualization. **Elke Pucks-Faes:** Writing – review & editing, Supervision. **Peter Federolf:** Writing – review & editing, Supervision, Conceptualization.

## Author contributions

All authors attest that they meet the current International Committee of Medical Journal Editors (ICMJE) criteria for Authorship.

## Informed consent and patient details

The authors declare that this report does not contain any personal information that could lead to the identification of the patient(s).

The authors declare that they obtained a written informed consent from the patients and/or volunteers included in the article. The authors also confirm that the personal details of the patients and/or volunteers have been removed.

## Human and animal rights

The authors declare that the work described has been carried out in accordance with the Declaration of Helsinki of the World Medical Association revised in 2013 for experiments involving humans as well as in accordance with the EU Directive 2010/63/EU for animal experiments.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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## Declaration of competing interest

The authors declare that they have no known competing financial or personal relationships that could be viewed as influencing the work reported in this paper.

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