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Inertial joint angle estimation – How accurate is accurate enough?

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Abstract: This review investigates accuracy requirements for IMU-based joint angle estimation in rehabilitation. While visual gait assessment errors often exceed 20°, manual goniometry achieves a standard error of measurement (SEM) of 1.5°–6°. However, clinical relevance is determined by minimal clinically important changes (MCIC), typically 6° (hip) to 8.5° (knee). Consequently, IMU systems do not need to match goniometer precision. Our analysis concludes that keeping random and systematic errors below these MCIC thresholds is sufficient for clinical utility. Thus, IMUs offer a viable solution for objective long-term monitoring in rehabilitation, bridging the gap between subjective visual estimates and static manual measurements.

I. Introduction

While the ultimate goal of rehabilitation according to the WHO International Classification of Functioning, Disability and Health is to restore activities and participation, the assessment of body functions, specifically joint angles (JA), remains a fundamental prerequisite. Accurate JA monitoring enables the assessment of range of motion (ROM), supports differential diagnostic decisions, identifies functional limitations such as asymmetries, and guides therapeutic interventions. The utilization of wearable technology, i. e. inertial measurement units (IMUs), enabling objective and continuous JA measurement in everyday situations, offers particular added value, as it can positively influence the course of therapy and also enables ergonomic analyses in the workplace environments.

Previous studies show high test-retest reliability of such systems with regard to various gait parameters after strokes [1]. Facilitating clinical application through plug-and-play capabilities is actively researched [2]. However, it is still unclear what accuracy requirements IMU-based systems must meet in order to enable clinically useful JA estimates. This paper summarizes the results of a structured literature review and provides an overview of the accuracy needed for clinical applications.

II. Methods

To clarify the required accuracy, a systematic analysis was conducted of how JA are currently assessed in physiotherapy practice, covering both walking and isolated functional examinations The analysis focused on literature where medical specialists (physiotherapists) estimate JA with methods currently used in clinical practice and was strictly limited to joints of the extremities. The definition of clinically relevant JA accuracy thresholds was based on established literature and quality criteria such as the standard error of measurement (SEM) and minimal clinically important changes (MCIC). Since no truly objective ground truth is available in many clinical settings, the inter-rater reliability of expert measurements is often used as a practical approximation of the SEM. To provide objective measurements and support long-term monitoring in everyday life, an IMU-based system must at least provide a level of precision achieved in current clinical practice. For deterministic IMU estimation methods, SEM corresponds to the standard deviation (SD) compared to a validated ground truth.

III. Results and discussion

Currently, visual estimation (rounded to 5° increments) is considered the practical standard for assessing JA during walking. However, this method has a low interrater reliability [3]. The error varies greatly depending on experience and task, reaching averages between 5° and over 20° when assessing knee or hip angles during walking, for example. Table 1 lists the estimation errors for the JA of the hip, knee and ankle, respectively. The estimation was done by experts with varying experience and compared to the JA obtained from video analysis.

Table 1: Joint angle estimation error from visual inspection by experts during gait according to [3]. NI = Not investigated.

Gait phase \ Joint	Hip	Knee	Ankle
Initial Contact	11°±10°	7°±5°	8°±6°
Loading Response	NI	8°±6°	NI
Terminal Stance Phase	11°±8°	10°±11°	12°±8°
Swing Phase	NI	20°±14°	NI
Pre-Swing	NI	NI	8°±6°

Isolated functional measurements are significantly more precise, but they are more complex and require clinical specialists. The SEM values summarized in Table 2 are taken from studies in which experts examined the use of standard instruments (goniometers and inclinometers) under highly controlled conditions. These tests were performed in standardized, often static poses in order to isolate movement to the target joint. For example, defined positions were adopted for hip rotation (e.g., 90° knee flexion in the supine position) to enable isolated rotation and minimize compensatory pelvic movements. The measurements generally represented the maximum active or passive ROM at static endpoints.

The SEM for these measurements using goniometers and inclinometers typically ranges from approximately 1.5° to 5.9° for the joints of the extremities (see Table 2). It can be seen that the most precise values (SEM often below 3° for flexion/extension) are achieved for joints whose movements can best be approximated as hinge joints, such as the knee and ankle. In contrast, multiaxial joints such as the hip and shoulder exhibit higher and more variable errors depending on the plane of motion and isolation method.

*Table 2: Measurement inaccuracy of joint angle measurement by experts using standard measurement methods in physical therapy, i.e., goniometers and inclinometers. NI stands for not investigated. * Internal and external rotation in the elbow corresponds to pronation/supination.*

Motion / Joint	Flexion/ Extension	Adduction/ Abduction	Internal/ external rotation
Ankle	2.8° [4]	NI	NI
Knee	2.15° [5]	NI	NI
Hip	3.94° [6]	3.8° [7]	2.53° [6]
Elbow	2.6° [8]	NI	3.1° * [9]
Shoulder	4.13° [8]	2.26° [10]	5.1° [7]

Table 2 shows that isolated functional measurements allow for much higher accuracy than visual assessments during walking (see Table 1). Transferring such tests to home environments without professional guidance therefore places high demands on the precision of an automated system. It should be noted that functional tests include both passive and active ROM assessment. Passive ROM cannot be transferred to home environments without clinical supervision, while isolated movements required for active ROM are not always feasible for patients with existing pathologies. This makes it challenging to use IMU-based JA estimation systems for this kind of applications.
However, the required accuracy for IMU-based systems is primarily dictated by clinical relevance, not just technical precision. Although goniometers enable precise JA estimation, such accuracy is often unnecessary, as MCIC values are typically less accurate. Studies report a self-perception threshold of about 8.5° for the knee [11] and 6° for hip [12] flexion/extension, consistent with clinical impressions. Thus, IMU-based estimates do not need to match goniometer precision to provide clinically useful information on motion behavior. Therefore, accuracy requirements must be evaluated depending on the context.

The SEM values in Table 2 reflect random error resulting from the limited reliability of manual methods, yet this represents only a baseline requirement. An automated IMU system must reduce both random and systematic error, meaning that the standard deviation of the estimation error and its mean bias must fall below relevant clinical thresholds (e. g. MCIC). However, estimating isolated joint movements is typically less complex for most algorithms, as the reduced movement variability enables additional assumptions and more stable kinematic constraints.

IV. Conclusions

This paper presents, to the best of the authors' knowledge, the first systematic overview that directly compares the achievable measurement accuracy in clinical practice (SEM) with the required clinical relevance (MCIC) for IMU-based JA estimation. The required accuracy is context-dependent and primarily defined by clinical relevance rather than technical precision. The key finding is that IMU-based JA estimation can provide clinically valuable information even when absolute precision is below that of standard goniometry, as the MCIC often exceeds the technical measurement error (e.g., 6° and 8.5° for knee and hip ROM). The critical requirement is that both random (SD) and systematic (bias) errors remain below these clinically relevant thresholds dependent on the application. When integrated into everyday life, IMU systems offer the potential to enhance objectivity and enable continuous long-term monitoring, thus representing a meaningful complement to traditional visual and manual assessment.

AUTHOR'S STATEMENT

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