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Research Article

Conceptual Architecture of a Multi-Sensor Real-Time Monitoring System for Biomechanical Analysis of Intramuscular Injections

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Abstract

This article presents the conceptual architecture of a multi-sensor, real-time monitoring system designed for the biomechanical assessment of the intramuscular (IM) injection technique. The proposed system utilizes an inertial measurement unit (IMU) to determine the needle's orientation in conjunction with a Time-of-Flight (ToF) distance sensor to estimate linear displacement. Sensor data are acquired by a central microcontroller and analyzed using geometric, filtering, and adaptive processing models. Letting θ denote the angle between the needle axis and the skin surface, the needle's penetration component perpendicular to the skin surface is defined as follows: $d = L \sin(\theta)$, where L represents the measured linear displacement of the needle. The calculated perpendicular penetration depth is interpreted relative to the effective tissue thickness. In this case, the penetration depth is indicated relative to the effective tissue thickness, which represents the distance from the skin surface to the beginning of the muscle layer. The proposed architecture comprises four functional layers: data acquisition, data processing and modeling, biomechanical analysis, and integrated assessment. The system is designed to quantitatively evaluate the needle insertion direction, penetration depth, trajectory stability, and temporal and velocity characteristics, as well as—when an additional spatial reference system is employed—anatomical topographic deviations. The research is conceptual in nature, and determining the system's actual measurement accuracy, reliability, and educational effectiveness requires the development of a physical prototype, calibration, and experimental validation.

Keywords: multi-sensor system; sensor fusion; real-time monitoring; biomechanical analysis; penetration model; intramuscular injection; objective skill assessment

1. Introduction

Intramuscular (IM) injection is a widely used procedure. Performing the procedure safely and effectively depends on the correct selection of the injection site, the length of the needle, the accuracy of the insertion angle, individual anatomical characteristics, and adherence to aseptic principles [1], [2], [3], [4],[5],[6].

Existing scientific literature highlights the importance of considering the injection site, needle length, subcutaneous tissue thickness, and the patient's anthropometric characteristics for the safe administration of intramuscular injections [3]. In particular, increased subcutaneous tissue thickness can prevent a standard-length needle from reaching the muscle layer, potentially resulting in the unintended deposition of the injection into the subcutaneous tissue [7].

In practical training, the assessment of injection technique is often based on observer feedback, checklists, and general performance indicators. While simulation-based medical training enables the repeated practice and structured assessment of a procedure in a safe environment, the real-time, quantitative monitoring of specific biomechanical parameters requires additional engineering solutions [8], [9], [10]. Objective assessment of technical skills demonstrates that reliability can be enhanced by evaluating measurable indicators during the performance of procedures, rather than relying solely on subjective observation [11]. In this context, the development of biomedical measurement systems capable of quantitatively recording the spatial and temporal parameters of needle manipulation is considered a promising engineering approach for the objective assessment of procedural skills.

Inertial sensors are widely used to assess motion and orientation. Combining data from gyroscopes, accelerometers, and—when necessary—magnetometers through sensor fusion enables the calculation of spatial orientation [12], [13]. Evaluating orientation data alongside parameters such as linear displacement, stability, penetration depth, and timing in penetration-based procedures—such as needle insertion—offers a promising approach for establishing objective training metrics. Measuring user movement and needle-tissue interaction within haptic and computer-aided needle insertion simulators demonstrates the technical potential of this field [14], [15]. Integrating IMUs and distance sensors into a unified measurement system can provide the technical foundation for the synchronous recording and subsequent digital processing of various biomechanical indicators of the procedure.

The aim of this study is to formulate the conceptual architecture, data flow, preliminary mathematical evaluation model, and future experimental validation framework for a multi-sensor biomedical measurement system—based on an IMU, a ToF distance sensor, and a microcontroller—designed to monitor the biomechanical indicators of IM injection technique in real time. The proposed system is intended for the quantitative assessment of the needle's spatial orientation, linear displacement, penetration depth, and movement stability, as well as the procedure's temporal parameters. The present work does not provide experimental results and should be regarded as an engineering framework for future stages of prototyping, calibration, and experimental validation.

2. Related Research and Problem Statement

International guidelines on injection safety establish a clinical-methodological framework for the proper selection of the injection site, adherence to aseptic practices, and the assurance of safety during the procedure [1], [2]. Furthermore, the scientific literature contains reviews and clinical recommendations that systematize various aspects of intramuscular (IM) injection techniques [3], [4], [5], [6]. These studies emphasize the importance of injection site selection, needle length, the patient's anatomical characteristics, and the injection technique itself.

However, the primary objective of these sources is not the real-time, sensor-based biomechanical monitoring of the injection procedure. Consequently, recording the needle's spatial orientation, linear displacement, movement stability, and procedural timing parameters within a unified biomedical measurement system remains a distinct engineering challenge.

Simulation technologies are widely used in medical education to create controlled and safe environments, facilitate repeated practice of procedures, and enable the structured assessment of skills [8], [9], [10]. Objective technical skill assessment systems demonstrate that it is possible to evaluate the performance of training participants using standardized criteria. Research on haptic technologies and needle-insertion simulation highlights the importance—for training systems—of measuring needle movement, user manipulations, and performance parameters during the procedure [14], [15].

The simultaneous recording and integration of various biomechanical parameters into a unified assessment model require the implementation of additional sensor and data-processing solutions.

Inertial measurement units and MARG sensor systems are widely used to determine motion and spatial orientation. For orientation calculation, quaternion-based extended Kalman filters and other sensor fusion methods enable the combination of data from accelerometers, gyroscopes, and—where necessary—magnetometers [12], [13].

In existing studies, the relationship p between tissue thickness and needle length is of particular importance. Increased subcutaneous tissue thickness can result in the needle failing to reach the muscle layer [7], [16], [17]. [18], [19], [20], [21]. Various imaging and anatomical studies of the gluteal and deltoid regions demonstrate the necessity of considering individual anatomical variability when selecting needle length [7], [16], [17], [18], [19], [20], [21].

In this context, the research gap is defined as follows: there is a need for a multisensor biomedical assessment architecture for IM injection training that integrates needle insertion angle, linear displacement, penetration depth, movement stability, and procedural timing metrics into a unified data stream; supports real-time monitoring; and allows for subsequent experimental validation.

3. Conceptual Methodology of the Research

The research is based on a conceptual engineering design approach. Key biomechanical variables targeted for assessment have been identified, and a functional data flow—following the sequence of sensing, processing, analysis, and output—has been established. To combine individual measurement metrics into a unified assessment indicator, a conceptual performance score model based on normalization and weighted integration has been proposed.

The primary input variables for the conceptual model include the needle's spatial orientation, linear displacement, penetration depth, movement stability, and temporal motion characteristics. These parameters are intended to be calculated using data obtained from IMU and ToF sensors.

To ensure measurement reliability, the following procedures must be carried out during the prototyping and experimental validation stages: sensor calibration, selection of sampling frequency, inter-sensor time synchronization, determination of filtering and sensor fusion parameters, and comparison of results with reference measurement methods.

Integrating a measurement or tracking mechanism into the system—one that establishes an additional spatial reference point—is required to assess the needle's deviation from the anatomical target. Therefore, in the current conceptual model, deviation from the anatomical target is treated not as a primary parameter measured directly, but as an additional assessment indicator envisaged for a future stage of the system's development.

Table 1. Functional comparison of the proposed conceptual system with existing approaches.

Criterion	Clinical standard approach	Traditional simulation	IMU-based measurement	Proposed system
Objective measurement	Limited	Limited/partial	Yes	Included
Real-time monitoring	Usually no	Platform-dependent	Yes	Included
Penetration/displacement	Clinical recommendation	Platform-dependent	Not directly	ToF-based measurement included
Orientation	Clinical recommendation	Platform-dependent	Yes	IMU-based assessment included
Stability	Not directly measured	Platform-dependent	Calculable	Assessment based on RMS/variation included
Multi-parameter integration	No	Platform-dependent	Usually limited	Composite score model proposed

The comparison presented in Table 1 reflects the intended engineering capabilities of the proposed system rather than its experimentally verified advantages.

4. Conceptual Architecture of the Multi-Sensor Monitoring System

4.1. System architecture

The proposed conceptual system architecture consists of four functional components:

I . Acquisition of raw data regarding the needle's spatial orientation, linear displacement, and temporal movement dynamics from IMU and ToF sensors;

II . Processing, calibration, and filtering of sensor data via a central microcontroller, along with the application of sensor fusion methods where necessary;

III . Calculation of the needle's orientation, linear displacement, penetration depth, movement stability, and temporal parameters based on the processed data. Assessment of positional deviation is possible only if an additional anatomical reference or tracking mechanism is integrated into the system;

IV Normalization of individual biomechanical parameters and their aggregation into a unified conceptual performance score based on a weighted integration model. The weights and decision boundaries of the scoring model are conceptual in nature at this stage, and their validity must be determined during the subsequent experimental validation phase.

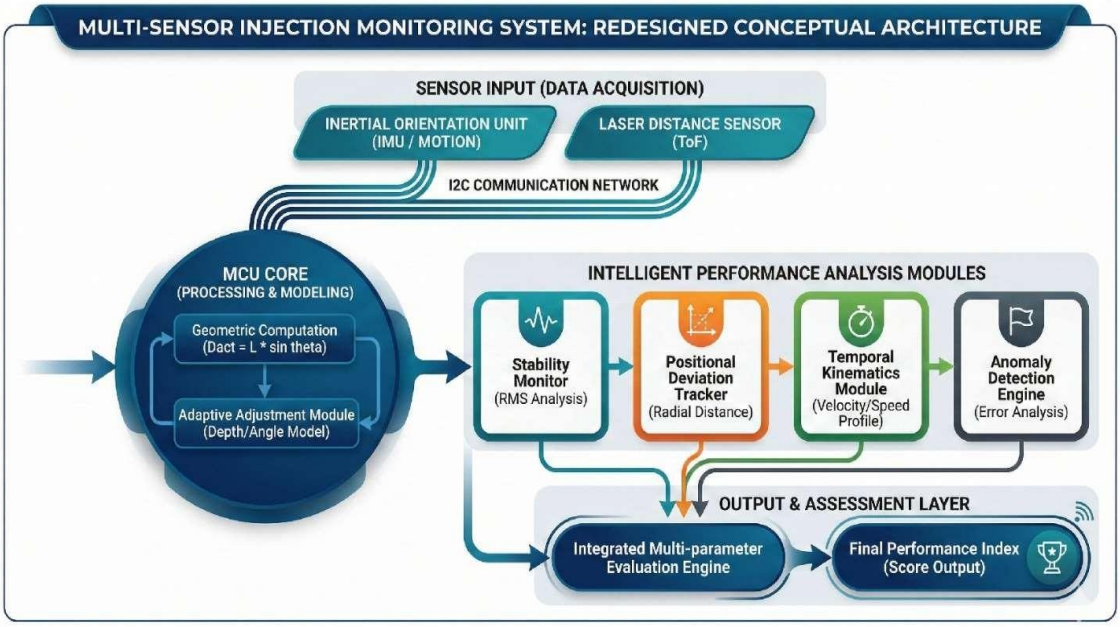


Figure 1. Conceptual diagram of a multi-sensor system for IM injection monitoring architecture and data flow.

4.1.1. Inertial measurement unit

The Inertial measurement unit is designed to evaluate the spatial orientation and movement dynamics of the needle. A three-axis gyroscope measures the needle's angular velocity along three coordinate axes, while a three-axis accelerometer measures the linear acceleration and specific force components. The joint processing of these data forms the basis for the assessment of needle motion characteristics and spatial orientation.

Accelerometer and gyroscope data are supposed to be combined through sensor fusion methods for a more stable and reliable assessment of orientation [12], [13]. Integration of magnetometer data, if necessary, can allow orientation estimation to be provided with additional information. The choice of specific IMU module, such as MPU6050 or BNO055, is not finalized at the current conceptual stage.

Sensor selection should be determined during the prototyping phase, taking into account measurement range, sampling frequency, measurement accuracy, calibration requirements, data interface, computing resource requirements, and the possibility of mechanical integration with the needle.

4.1.2. ToF displacement sensor and hardware interface

In the conceptual prototype, the application of the VL53L1X type Time-of-Flight distance sensor is considered for the evaluation of the linear displacement of the needle. The sensor supports the I²C digital communication interface and is designed by the manufacturer to perform measurements at different distance ranges [22].

It is methodologically incorrect to consider the measurement accuracy of the sensor as a constant value for all working conditions. Distance measurement error may depend on factors such as optical properties of the target surface, measurement distance, sensor configuration, measurement time, and ambient lighting [22].

Therefore, the actual measurement error, repeatability, and measurement stability of the VL53L1X sensor in the intended working distance range in the injection simulator should be determined experimentally during the prototyping stage. To assess the reliability of the sensor readings, the obtained distance should be compared with a suitable reference measurement system, and a calibration procedure should be performed.

The use of a microcontroller included in the STM32 family can be considered as the central data collection and processing unit of the system. Data acquisition from IMU and ToF sensors can be arranged through the I²C interface, depending on the technical capabilities of the sensors. SPI and other compatible digital communication interfaces can be used when high-speed data exchange, logging, and integration of additional peripherals are required. The selection of a specific microcontroller model is not finalized at the current conceptual stage.

Computational performance, sampling frequency, memory capacity, peripheral interfaces, power consumption, and data transfer rate should be taken into account during MCU selection [23].

4.2. Adaptive penetration model

Let the measured linear displacement of the needle be L, and the angle formed by the needle axis with the skin surface be denoted by θ. In this case, the displacement of the needle in the direction normal to the skin surface:

$$d = L \sin(\theta)$$

expressed in

the form Here:

d — needle insertion depth calculated perpendicular to the skin surface;

L — length of needle displacement beneath the skin; θ — angle between the needle's central axis and the skin surface.

The choice of angle and the direction of orientation are predetermined in the software, during calibration,

and in experimental protocols, and must be kept constant (Figure 2).

Studies have shown that the thickness of the skin and subcutaneous tissue influences the needle's

penetration into the muscle layer [7], [16], [17], [18], [19], [20], [21], [24]. Let skin thickness be denoted by

h_s, and subcutaneous tissue

thickness by $h_s c$. In the simplified model, the thickness of the tissue from the skin surface to the surface of

the muscle layer is calculated as follows:

$h_t = h_s + h_s c$ can be expressed a (Figure 2).

In this case, the initial geometric estimate:

$d \leq h_t$ — that the geometric limit to reach the muscle layer is not met, and when $d > h_t$ — it may indicate that the geometric limit has been exceeded to reach the muscle layer.

This approach is consistent with the relationship between subcutaneous tissue thickness and actual muscle reach reported in the literature [7], [16], [17], [18], [19], [20], [21].

However, this classification does not prove that the needle tip is in a safe and optimal position within the muscle. The model only evaluates whether the penetration component calculated in the direction normal to the skin surface exceeds a predefined tissue thickness threshold. The proposed threshold model is a conceptual mathematical approach for the preliminary quantitative estimation of the penetration index in the injection simulator.

In real-world application, skin and subcutaneous tissue thickness, tissue deformation, actual needle trajectory, muscle thickness, patient gender, body mass, body mass index, and individual anatomical variability should be taken into account [7], [16], [17], [18], [19], [20], [21]. The effective tissue thickness must be determined using a reliable external reference measurement method, and the proposed model must be experimentally validated by comparing it with reference measurements during the prototyping stage.

The geometry of the needle's insertion relative to the skin surface is shown in Figure 2. Here, L represents the measured linear displacement of the needle, θ the angle between the needle axis and the skin surface, d the component of the needle's displacement perpendicular to the skin surface, h_s is the skin thickness, h_sc is the subcutaneous muscle thickness, and h_t is the thickness of the properly transmitted tissue.

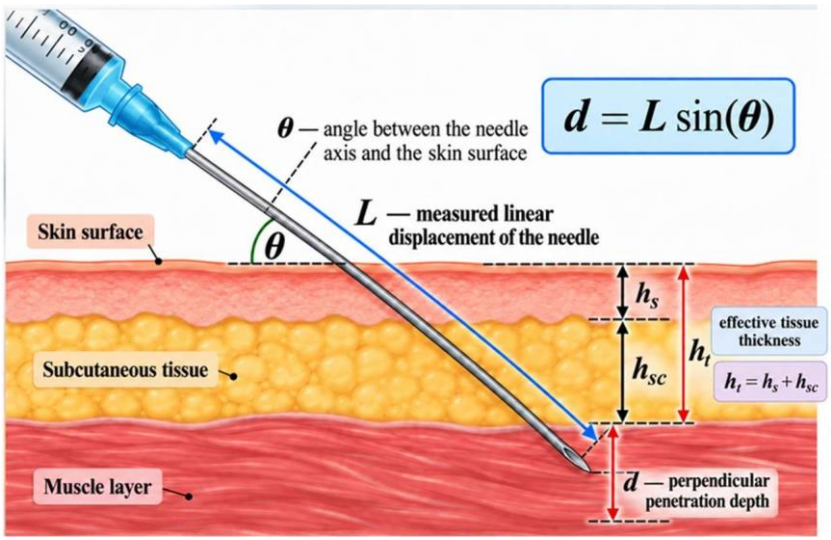


Figure 2. Needle insertion geometry, tissue thickness, and calculation of penetration depth perpendicular to the skin surface.

4.3. Anatomical-topographic and stability modules

The anatomo-topographic module is designed to quantitatively assess the position and deviation of the needle insertion point relative to a pre-defined target zone on the simulator. For this purpose, the radial distance of the insertion point from the target zone's reference point, or the positional difference within a two-dimensional or three-dimensional coordinate system, can be calculated.

Operation of the module requires the pre-definition and calibration of a local coordinate system, reference points, and target zone boundaries on the simulator. If the coordinates of the entry point are denoted as (x_i, y_i) and the coordinates of the target zone's reference point as (x_t, y_t), the expressions for calculating radial deviation in two-dimensional (1) and three-dimensional (2) coordinate systems are:

$$r = \sqrt{[(x_i - x_t)^2 + (y_i - y_t)^2]} \quad (1)$$

$$r = \sqrt{[(x_i - x_t)^2 + (y_i - y_t)^2 + (z_i - z_t)^2]} \quad (2)$$

Calculating this metric requires integrating an additional position-tracking or reference mechanism into the system to determine the coordinates of the entry point. An IMU and a one-dimensional ToF distance sensor alone are insufficient to fully determine these coordinates.

The stability module involves assessing the variation of the needle's selected orientation or position parameter relative to its average value over a specific time window. However, the specific orientation or position parameter, time window, and threshold values that provide the most informative data for assessing procedural stability must be determined during the experimental validation phase.

4.4. Time-dependent velocity module

The duration of needle insertion and withdrawal phases, the variation of linear displacement over time, movement speed, and velocity profile variability can be evaluated as additional biomechanical indicators characterizing the dynamic properties of the procedure. The obtained velocity profile can be used to characterize the duration of insertion and withdrawal phases, average and maximum speeds, and the temporal variability of movement speed.

The clinical and educational significance of the optimal target velocity range and the threshold values adopted for velocity profile assessment must be substantiated based on future experimental data.

4.5.Integrated assessment mechanism

To combine biomechanical indicators—which possess diverse physical units and measurement ranges—into a unified assessment score, the process involves first normalizing each parameter to a dimensionless 0–1 interval. Comparing the results obtained by combining biomechanical parameters into an integrated performance score with expert assessments and structured technical skill assessment methods can be used for construct validation [11].

5. Experimental Validation Plan

In the subsequent development phase of the proposed system, a physical prototype must be constructed, and the metrological characteristics of the sensor measurements must be experimentally determined. To validate linear displacement and angular measurements, pre-determined geometric positions, precision calibration devices, or suitable reference measurement systems may be employed.

Metrics such as mean error (bias), mean absolute error (MAE), root mean square error (RMSE), and Bland-Altman analysis can be used to evaluate the measurement between the sensor and the skin [25], [26]. Appropriate reliability indicators should be used to assess the reliability of repeated measurements, depending on the study design. Cronbach’s alpha, an indicator of internal consistency, should be applied only in cases where multiple items or indicators are theoretically and methodologically justified as components of the same latent construct.

Methodological approaches from existing haptic and computer-assisted needle insertion systems may be utilized when evaluating needle insertion and needle-tissue interaction under simulation conditions [14], [15]. The current work covers the conceptual engineering design phase, and no experimental studies involving human participants have been conducted. Therefore, the presented approaches should not be interpreted as results validating the system's clinical efficacy, diagnostic value, or actual measurement accuracy.

6. Limitations

The primary limitation of the study is that it is confined to the conceptual engineering design phase. Although the selection of sensor technologies and system architecture is justified based on existing technical specifications and intended measurement requirements, the current stage has not involved measurements on a physical prototype, experimental sample testing, comparative testing against a reference measurement system, or statistical validation.

Another significant limitation is that the conversion of the distance measured by the ToF sensor into the needle's actual axial displacement depends on the mechanical placement of the sensor and the geometry of the reference surface.

Finally, the target values for the proposed normalization functions, the acceptable deviation limits, and the weighting coefficients for the integrated performance score have not been experimentally determined at this stage. The scientific justification of these parameters and the constructive validation of the scoring model should be the subject of future prototyping and experimental research.

7. Conclusion

This study presents the conceptual architecture of a multi-sensor system designed for the multi-parameter biomechanical assessment and real-time monitoring of the intramuscular injection technique. The significant impact of the needle actually reaching the muscle layer has been extensively demonstrated in previous studies [7], [16], [17], [18], [19], [20], [21], [24]. Therefore, explicitly accounting for effective tissue thickness in the proposed penetration model is considered a key component of the biomechanical assessment. The proposed approach involves normalizing sensor and biomechanical indicators— which possess different physical units—and combining them into a conceptually integrated performance score.

A validation framework has been established to evaluate the system's measurement reliability; this framework encompasses sensor calibration, comparison with reference measurement systems, calculation of error metrics, and statistical assessment of intermethod agreement [25], [26]. The primary scientific outcome of this work is not a finished clinical device, an experimentally verified measurement system, or a validated performance metric, but rather a multi-sensor system model that can be physically realized and experimentally tested in subsequent stages.

Therefore, at this stage, no definitive conclusions are drawn regarding the system's measurement accuracy, reliability, or advantages in a training context. The next research phase envisages the development of a physical prototype, the calibration of IMU and ToF sensors, the comparison of linear displacement and orientation measurements against reference systems, the quantitative assessment of measurement errors and repeatability, and the analysis of inter-sensor time synchronization and system latency.

Author Contributions

All authors reviewed, edited, and approved the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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