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RoboGait Studio: Multi-Sensor Gait Analysis and Synchronization

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Resumen

RoboGait Studio es una plataforma software diseñada para el análisis sincronizado de la marcha mediante múltiples sensores y la comparación entre sistemas. La herramienta integra la gestión de participantes y ensayos, visualización de señales, sincronización temporal, normalización de ciclos de marcha y análisis comparativo dentro de un flujo de trabajo unificado. La alineación temporal se realiza utilizando trayectorias de distancia entre tobillos obtenidas de registros adquiridos de forma independiente, evitando la necesidad de sincronización a nivel hardware. El marco fue evaluado utilizando datos pareados procedentes de un sistema RGB-D montado sobre un robot móvil y un sistema de captura de movimiento VICON. Los resultados demostraron una sincronización precisa y una buena concordancia entre sistemas para parámetros espacio-temporales y cinemáticos representativos. La plataforma proporciona una base flexible para futuras aplicaciones de análisis de la marcha en línea y en tiempo real.

Palabras clave: Robots móviles, Visión por computador, Sistemas biomédicos, Análisis del movimiento, Fusión de sensores, Procesamiento de datos

RoboGait Studio: Análisis y Sincronización Multisensor de Marcha

Abstract

RoboGait Studio is a software framework designed for synchronized multi-sensor gait analysis and cross-system comparison. The platform integrates participant and trial management, signal visualization, temporal synchronization, gait-cycle normalization, and comparative analysis within a unified workflow. Temporal alignment is achieved using ankle-distance trajectories extracted from independently acquired gait recordings, avoiding hardware-level synchronization requirements. The framework was evaluated using paired gait data collected from a mobile robot-assisted RGB-D acquisition system and a VICON motion-capture system. Experimental results demonstrated accurate synchronization and good agreement between systems for representative spatiotemporal and kinematic gait parameters. The proposed framework facilitates consistent comparison of gait data acquired from heterogeneous sensing modalities and provides a flexible foundation for future online and real-time gait-analysis applications.

Keywords: Mobile robots, Computer vision, Biomedical systems, Motion analysis, Sensor fusion, Data processing

1. Introduction

Human gait analysis plays a fundamental role in rehabilitation engineering, clinical biomechanics, sports science, and neurological assessment because gait patterns provide important information about motor control, balance, mobility impairments, and functional recovery (Han et al., 2025; Vun et al., 2024). Quantitative gait assessment is widely used in the evaluation of neurological disorders, musculoskeletal diseases, post-stroke rehabilitation, Parkinson's disease, multiple

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sclerosis, and age-related mobility impairments (Muro-de-la Herran et al., 2014; Clark et al., 2021). Accurate gait analysis enables clinicians and researchers to objectively evaluate locomotor performance, monitor rehabilitation progress, and support personalized therapeutic interventions.

Among existing motion-analysis technologies, marker-based optical motion-capture systems such as VICON are commonly regarded as the gold standard due to their high spatial accuracy and reliable kinematic measurements (VICON Motion Systems Ltd., 2024; Smirnova et al., 2022). However, traditional marker-based systems typically require expensive infrastructures, specialized operators, reflective marker placement, calibration procedures, and dedicated acquisition environments, limiting their portability and accessibility in clinical and robotic applications (Lagomarsino et al., 2024; Barzyk et al., 2024). Recent advances in computer vision and RGB-D sensing technologies have accelerated the development of markerless gait-analysis approaches (Han et al., 2025; Vun et al., 2024). RGB-D cameras enable depth-based human pose estimation and skeletal tracking without requiring reflective markers or wearable instrumentation (Yeung et al., 2021; Balta et al., 2024). Compared with conventional laboratory-based systems, these technologies provide portable, low-cost, and non-invasive alternatives for gait assessment (Mentiplay et al., 2021; Clark et al., 2021).

Despite these advances, integrating data from heterogeneous sensing systems remains a major challenge in comparative gait analysis and robot-assisted motion assessment. Differences in sampling frequencies, acquisition delays, signal noise, and independent recording procedures complicate direct comparisons between RGB-D-based robotic systems and professional motion-capture systems (Smirnova et al., 2022; Barzyk et al., 2024). In addition, many existing studies mainly focus on sensor-specific acquisition pipelines, while comparatively limited attention has been devoted to unified frameworks integrating synchronization, visualization, gait-cycle normalization, and comparative multi-sensor analysis within a single workflow-oriented environment.

To address these limitations, this paper presents RoboGait Studio, a unified workflow-oriented framework for synchronized multi-sensor robot-assisted gait analysis and comparative experimental evaluation. The proposed framework combines robot-based RGB-D gait-acquisition systems and reference motion-capture systems within a unified analysis environment, using VICON in this work as a representative reference system for experimental validation.

In the experimental configuration considered in this work, gait data were acquired using a mobile robotic platform equipped with RGB-D sensors. The robot autonomously moved in front of the participant during walking trials using a ROS2-based human-following navigation system while maintaining a predefined observation distance for continuous gait acquisition.

The main contributions of this work can be summarized as follows:

- Development of RoboGait Studio, a unified workflow-oriented framework for synchronized multi-sensor robot-assisted gait analysis and comparative experimental evaluation.
- A temporal synchronization methodology based on ankle-distance trajectories, automatic gait-event peak matching, and temporal alignment for heterogeneous gait-acquisition systems.
- An interpolation-based gait-cycle normalization pipeline enabling consistent cross-system comparison of spatiotemporal and kinematic gait parameters across different sensing modalities.
- Experimental validation using synchronized robot-assisted RGB-D gait recordings and a VICON reference motion-capture system across multiple walking trials, including quantitative synchronization evaluation and comparative gait analysis.

2. System and Methods

2.1. Multi-sensor gait acquisition setup

The proposed framework combines a robot-assisted RGB-D gait-acquisition system with reference motion-capture data for multi-sensor gait analysis and cross-system validation. In this work, a VICON optical motion-capture system was used as a representative reference system for experimental validation. The overall workflow of the proposed framework is illustrated in Fig. 1.

The robot-assisted acquisition system was implemented on a differential-drive mobile robotic platform equipped with RGB-D sensors and running ROS2 Humble. ROS2 Humble was used for sensor integration, navigation, human-following control, and data acquisition.

During gait-acquisition experiments, the robotic platform autonomously moved in front of the participant using a ROS2-based human-following navigation system. The robot continuously adjusted its position and heading to maintain a predefined observation distance throughout the walking trial while acquiring RGB-D data for gait analysis. This capability enabled continuous gait monitoring over extended walking trajectories while preserving a consistent sensor viewpoint relative to the participant.

Although the proposed framework is designed to support different RGB-D gait-acquisition systems, the experimental validation reported in this paper was conducted using an Azure Kinect camera mounted on the robotic platform. Depth-based body-tracking tools were used to estimate lower-limb joint trajectories from the RGB-D sequences.

For the validation reported in this paper, reflective markers were attached according to standard lower-limb biomechanical protocols, allowing the VICON system to provide reference joint trajectories and spatiotemporal gait parameters for cross-system comparison. The robot-based RGB-D data and VICON data were acquired and stored independently before being imported into RoboGait Studio for offline synchronization and comparative analysis.

2.2. Gait signal processing workflow

RoboGait Studio provides a unified MATLAB-based framework for multi-sensor gait processing, synchronization, normalization, and comparative analysis. Although VICON

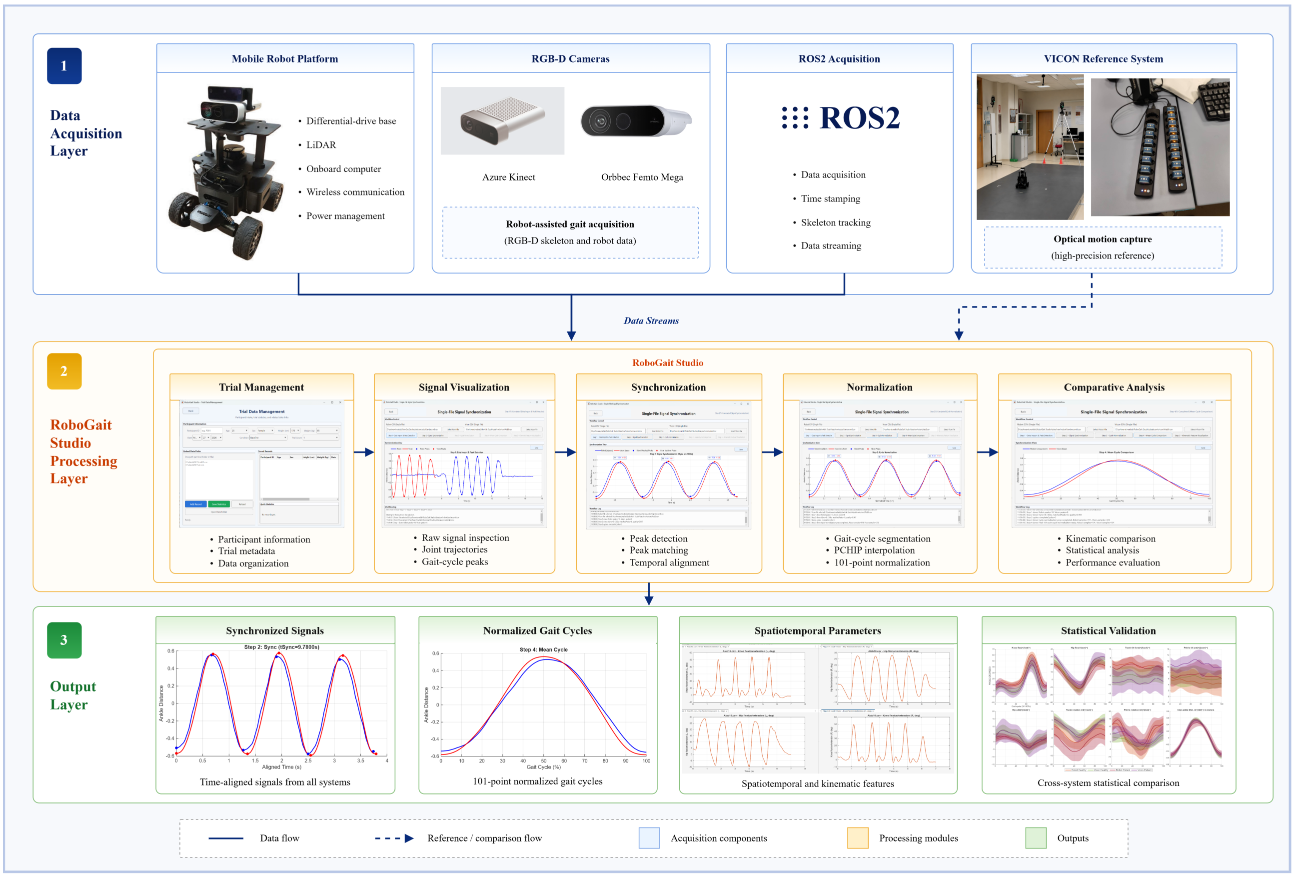

Figure 1: Overview of the RoboGait Studio framework for multi-sensor gait analysis and cross-system comparison.

data were used as the reference dataset in the present validation, the processing workflow was designed to accommodate heterogeneous gait signals acquired from different sensing systems.

Raw trajectories acquired from the robot-assisted system and the reference motion-capture system were inspected prior to synchronization to identify noisy or incomplete recordings. The processing workflow supports the visualization of joint-angle trajectories, ankle-distance signals, gait-event peaks, synchronized temporal windows, and normalized gait cycles.

The proposed pipeline integrates temporal synchronization, gait-cycle normalization, and cross-system comparison procedures within a single processing framework. This design reduces manual processing effort and improves consistency across comparative gait-analysis experiments.

In addition, the framework supports batch processing of synchronized gait trials and unified visualization of representative kinematic trajectories across different sensing modalities. The workflow-oriented architecture enables reproducible experimental processing while reducing the need for manual signal alignment and repeated preprocessing operations.

2.3. *Temporal synchronization*

Temporal synchronization between heterogeneous sensing systems represents a major challenge in comparative gait analysis because differences in sampling frequency, acquisition delay, and recording procedures may introduce temporal misalignment between systems (Smirnova et al., 2022; Lagomarsino et al., 2024).

The proposed synchronization strategy estimates temporal offsets using ankle-distance trajectories extracted from both systems. The ankle-distance signal exhibits quasi-periodic behavior during walking and provides a robust representation for gait-event detection. Positive and negative gait-related peaks were automatically detected and matched to identify corresponding gait events between robot-acquired signals and reference motion-capture signals.

Robot-acquired ankle-distance trajectories were low-pass filtered at 4 Hz prior to peak detection in order to reduce high-frequency fluctuations and depth-estimation noise. The filtering process was implemented using the MATLAB `lowpass` function with a stopband attenuation of 60 dB and a steepness parameter of 0.85. The sampling frequency was automatically estimated from the acquisition timestamps. In contrast, VICON ankle-distance trajectories were directly used for synchronization without additional smoothing.

Positive and negative gait-related peaks were automatically detected using the MATLAB `findpeaks` function with a minimum peak distance of 5 samples and a minimum prominence threshold corresponding to 5% of the signal amplitude range. Peaks with amplitudes below predefined relative thresholds were discarded in order to improve robustness against local signal noise and irregular gait transitions.

To improve synchronization robustness, matched gait-event peaks were paired according to their temporal proximity after adaptive peak detection. The synchronization offset was estimated using the median temporal difference across all matched peak pairs rather than relying on a single gait event.

The temporal offset between both systems was estimated as:

$$\Delta t = \text{median}\left(t_{p,k}^{robot} - t_{p,k}^{ref}\right) \quad (1)$$

where $t_{p,k}^{robot}$ and $t_{p,k}^{ref}$ denote the timestamps of matched gait-event peaks detected in the robot-assisted and reference motion-capture signals, respectively.

The reference signal was used as the temporal basis, while the robot-acquired signals were shifted according to the estimated synchronization offset Δt. After temporal alignment, only the overlapping gait segments simultaneously recorded by both sensing systems were retained for comparative analysis. Segments outside the common synchronized temporal window were discarded to ensure that both systems contributed data from the same gait events and walking periods. No interpolation or replacement was performed for discarded segments.

The synchronization pipeline includes signal filtering, gait-peak detection, peak matching, temporal alignment, and synchronized-window trimming. Considering both positive and negative peaks improves synchronization robustness under varying gait amplitudes and walking conditions.

Synchronization quality was quantitatively evaluated using peak timing error, cross-correlation lag, and Pearson correlation coefficients between synchronized ankle-distance trajectories.

After synchronization, synchronized gait segments shared by both sensing systems were independently normalized. This strategy reduces the influence of incomplete gait cycles near signal boundaries and improves consistency during cross-system gait comparison.

2.4. Gait-cycle normalization and comparative analysis

Following synchronization, gait cycles were segmented and temporally normalized to enable comparisons between trials with different durations and walking speeds. Consecutive gait-event peaks detected from the ankle-distance trajectories were used to define individual gait cycles within the synchronized temporal window.

Each gait cycle was independently resampled to 101 temporal samples using piecewise cubic Hermite interpolation (PCHIP). This interpolation strategy preserves local signal characteristics while reducing overshoot artifacts commonly associated with higher-order interpolation methods. PCHIP interpolation is particularly suitable for gait-cycle normalization because it preserves the local shape and temporal continuity of biomechanical time-series data (Fritsch and Carlson, 1980; Winter, 2009).

The normalized gait-cycle representation was defined as:

$$x_n(i) = x(t_i), \quad i = 1, 2, \ldots, 101 \quad (2)$$

where $x_n(i)$ represents the normalized gait signal and t_i corresponds to the interpolated temporal samples uniformly distributed across the gait cycle. The 101-point representation corresponds to the normalized gait-cycle interval from 0% to 100% of the gait cycle.

Temporal normalization reduces inter-cycle variability caused by differences in gait-cycle duration and walking speed, thereby enabling direct cross-system comparison across trials and participants.

After normalization, gait trajectories from both sensing systems were independently averaged across synchronized gait cycles to obtain representative mean gait patterns. Representative spatiotemporal and kinematic gait parameters, including cadence, step time, stride time, walking speed, and lower-limb range of motion, were subsequently computed for comparative analysis between the robot-assisted RGB-D system and the VICON reference system.

The proposed normalization and comparative-analysis workflow enables consistent cross-system gait evaluation while reducing the influence of temporal variability and incomplete gait cycles near signal boundaries.

3. Experimental Results and Discussion

3.1. Experimental setup

Preliminary experiments were conducted to evaluate the feasibility of the proposed RoboGait Studio framework for synchronized multi-sensor gait analysis and cross-system comparison.

Gait recordings were acquired from 10 healthy participants during multiple walking trials using the robot-assisted RGB-D system and the VICON reference motion-capture system. A total of 47 paired gait recordings were initially collected. After data-quality inspection and synchronization validation, 34 paired trials were retained for subsequent comparative analysis, while recordings affected by incomplete trajectories, excessive noise, or synchronization failure were excluded.Consequently, 13 of the 47 initially acquired paired recordings (27.7%) were discarded. Excluded recordings were not replaced and were removed from subsequent processing and analysis. Only synchronized temporal windows simultaneously available in both sensing systems were retained for gait-cycle normalization and comparative evaluation.

All experiments were conducted under indoor laboratory conditions. Gait data were independently recorded using the robot-assisted RGB-D system and a VICON optical motion-capture system during walking trials, and subsequently imported into RoboGait Studio for offline synchronization, gait-cycle normalization, and comparative analysis.

The robot-assisted system acquired lower-limb kinematic trajectories using RGB-D cameras mounted on the mobile robotic platform, while the VICON system provided reference gait trajectories and representative spatiotemporal gait parameters for validation. The synchronized datasets were processed using the proposed workflow, including gait-event peak detection, temporal synchronization, gait-cycle segmentation, normalization, and comparative gait analysis.

Fig. 2 illustrates the experimental configuration adopted for synchronized gait acquisition using the robot-assisted RGB-D platform and the VICON reference motion-capture system.

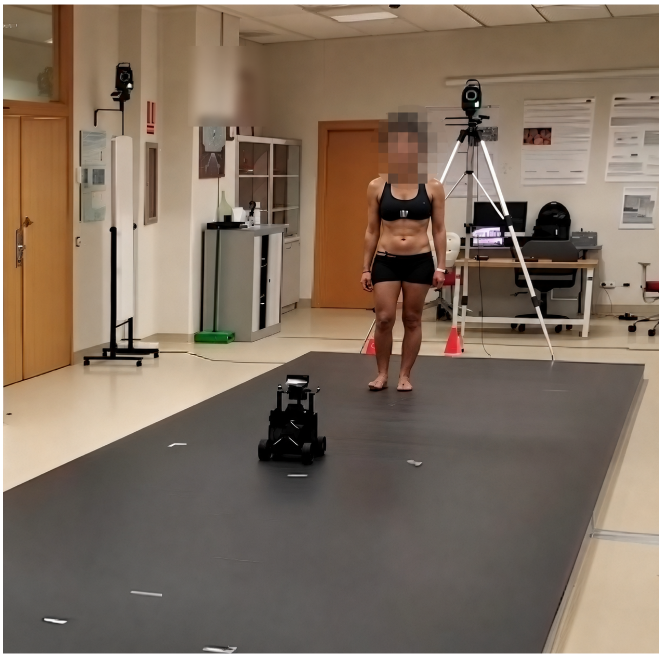

Figure 2: Experimental setup used for gait acquisition with the robot-assisted RGB-D system and the VICON reference motion-capture system.

3.2. Synchronization and gait-cycle normalization results

Fig. 3 presents representative synchronization and normalization results obtained using the proposed RoboGait Studio framework. Fig. 3(a) shows the raw ankle-distance trajectories acquired from the robot-assisted RGB-D system and the VICON reference system before synchronization. Fig. 3(b) illustrates the automatically detected gait-event peaks and temporal alignment between both systems after synchronization. Fig. 3(c) presents the normalized gait cycles obtained after temporal interpolation to 101 samples. Fig. 3(d) shows the averaged normalized gait trajectories used for cross-system comparative analysis.

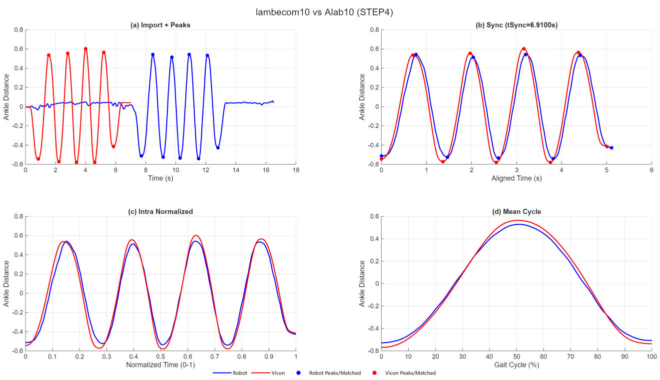

Figure 3: Representative synchronization and normalization results obtained using the proposed RoboGait Studio framework. (a) Raw ankle-distance trajectories before synchronization. (b) Peak matching and temporal alignment between both sensing systems. (c) Normalized gait cycles after temporal interpolation. (d) Averaged normalized gait trajectories used for cross-system comparison.

Before synchronization, the robot-acquired and VICON ankle-distance trajectories exhibited clear temporal offsets caused by differences in acquisition timing and recording duration. After automatic peak detection and temporal alignment, synchronized gait trajectories with consistent temporal behavior were obtained. Following synchronization, gait cycles were segmented and normalized to 101 temporal samples using PCHIP interpolation.

As shown in Fig. 3, the proposed synchronization strategy successfully aligned heterogeneous gait signals despite differences in sampling frequency and acquisition timing. Minor residual phase shifts and local amplitude differences remained, particularly near gait-transition regions, which may be associated with depth-estimation uncertainty and differences between markerless RGB-D skeletal reconstruction and marker-based optical motion capture.

3.3. Quantitative synchronization evaluation

To further evaluate synchronization quality, representative temporal-alignment metrics were computed before and after synchronization using matched ankle-distance trajectories extracted from both sensing systems. Table 1 summarizes the synchronization-performance indicators obtained across the synchronized walking trials.

Table 1: Representative synchronization performance before and after temporal alignment (mean ± standard deviation).

Metric	Before Sync	After Sync
Peak timing error (ms)	476.75 ± 111.90	44.17 ± 13.23
Cross-correlation lag (s)	1.090 ± 0.665	0.022 ± 0.022
Pearson correlation	0.325 ± 0.131	0.987 ± 0.008

The quantitative results show that the proposed synchronization strategy substantially reduced temporal misalignment between the robot-assisted RGB-D system and the VICON reference system. The peak timing error decreased from 476.75 ± 111.90 ms before synchronization to 44.17 ± 13.23 ms after synchronization. Similarly, the cross-correlation lag decreased from 1.090 ± 0.665 s to 0.022 ± 0.022 s, while the Pearson correlation increased from 0.325 ± 0.131 to 0.987 ± 0.008 after temporal alignment.

3.4. Comparative gait-analysis results

Table 2 summarizes representative gait parameters extracted from synchronized and normalized gait cycles across all paired trials.

Table 2: Comparison of representative gait parameters between the robot-assisted RGB-D system and the VICON reference system.

Parameter	Unit	Robot	VICON
Cadence	steps/min	95.76 ± 1.83	95.57 ± 0.57
Step time	s	0.627 ± 0.012	0.628 ± 0.004
Stride time	s	1.243 ± 0.011	1.248 ± 0.005
Walking speed	m/s	0.845 ± 0.015	0.902 ± 0.010
Knee ROM	deg	56.53 ± 2.96	54.72 ± 3.07
Hip ROM	deg	33.67 ± 0.56	35.04 ± 0.68

The results indicate that temporal gait parameters extracted from the robot-assisted RGB-D system were highly consistent with those obtained from VICON. Cadence, step time, and stride time exhibited only minor inter-system differences, suggesting stable temporal alignment after synchronization and gait-cycle normalization.

Small discrepancies in walking speed and lower-limb range of motion may be related to depth-estimation uncertainty, markerless skeletal reconstruction errors, and differences between RGB-D-based pose estimation and marker-based optical motion capture.

3.5. Discussion

The proposed synchronization and normalization pipeline enabled stable temporal alignment between independently acquired gait recordings without requiring hardware-level synchronization. The quantitative results showed substantial reductions in peak timing error and cross-correlation lag after alignment, together with a clear increase in Pearson correlation, indicating that the ankle-distance-based synchronization strategy can effectively align heterogeneous gait signals.

The experimental results also demonstrated good agreement between the RGB-D gait-acquisition system and the VICON reference system across representative temporal and kinematic gait parameters. Minor residual discrepancies, particularly in gait-transition regions and range-of-motion estimation, may be associated with RGB-D depth-estimation uncertainty, viewpoint-dependent occlusions, markerless skeletal reconstruction limitations, and differences between RGB-D-based pose estimation and marker-based optical motion capture.

Although the current implementation operates offline, the proposed framework already automates the main processing stages, including temporal synchronization, gait-cycle segmentation, normalization, and comparative analysis after data import. Consequently, only minimal user intervention is required during the analysis workflow. Future work will focus on integrating these processing modules directly into the ROS2 acquisition pipeline, enabling online data processing and supporting real-time gait-analysis applications during robot-assisted gait assessment.

Nevertheless, the present validation was limited to healthy participants and to a specific experimental configuration involving RGB-D and VICON recordings. Further validation using additional sensing modalities, more diverse participant groups, and different acquisition environments will be necessary to evaluate the generalizability and robustness of the proposed framework for broader gait-analysis applications.

4. Conclusions

This paper presented RoboGait Studio, a unified framework for multi-sensor gait analysis, temporal synchronization, gait-cycle normalization, and cross-system comparison. The proposed framework integrates heterogeneous gait data acquired from robot-based RGB-D systems and reference motion-capture systems within a single workflow-oriented environment, supporting signal visualization, participant and trial management, batch processing, and comparative kinematic analysis.

Experimental results obtained from synchronized RGB-D and VICON gait recordings demonstrated stable temporal alignment and consistent gait-cycle behavior across multiple walking trials. Representative temporal and kinematic gait parameters showed good agreement between both systems, supporting the feasibility of the proposed framework for reliable cross-system gait comparison.

Future work will focus on larger-scale validation, integration of additional sensing modalities, and extension toward real-time gait-analysis applications in rehabilitation and clinical assessment environments.

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