Geometry-Dependent Tracking Accuracy of an Optical Surface Imaging System for SGRT Using Symmetric Phantoms

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Abstract

The accuracy of surface-guided radiation therapy (SGRT) depends on reliable optical surface tracking, which varies with surface geometry. This study evaluates a widely-used commercial SGRT system by measuring its tracking performance on three symmetric phantoms representing common treatment sites.

Innovation/Impact

1) Novel geometry-specific evaluation framework: This work establishes a new validation paradigm for optical surface tracking by systematically assessing performance across three distinct, clinically relevant geometries, flat, spherical, and cylindrical, rather than relying on conventional single-phantom testing. This approach directly links system performance to anatomical shape, providing a more realistic and site-specific accuracy profile; **2) Quantification of error-displacement relationships:** The analysis documents and quantifies a previously underexplored phenomenon: tracking errors may scale with the magnitude of patient shift. This finding offers potential predictive insight into clinical scenarios involving larger setup corrections, moving beyond the typical characterization of system performance at minimal displacements; **3) Anatomy-aware commissioning and tolerance development:** Results support the development of treatment-site-specific commissioning protocols and action thresholds. For instance, surface-guided alignment may be sufficient for spherical surfaces (e.g., breast), whereas flat surfaces (e.g., abdomen) may necessitate combined modality verification, advancing practice toward individualized quality assurance; **4) Evidence-based risk mitigation strategy:** The study identifies distinct failure modes per geometry, such as elevated RTN (Rotation) errors for flat/spherical surfaces and poor ROLL tracking for cylindrical surfaces. These insights enable clinics to implement focused safety protocols, like prioritizing radiographic confirmation for high-risk geometries to enhance patient safety and streamline clinical workflow through risk-adapted practices.

Figure 1. Spherical phantom (left) and cylindrical phantom (right) setups for breast and limb surface simulation. A red glossy spherical phantom (12-cm diameter) was positioned with its center of rotation aligned to the machine isocenter. Due to the phantom's isotropic symmetry, rotational tracking was evaluated only for the RTN (yaw) axis, as performance in PITCH and ROLL was assumed equivalent under rotational invariance.

Methods and Materials

- Three phantoms were tested: a flat board (simulating abdomen), a spherical phantom (simulating breast), and a cylindrical phantom (simulating limb).
- Each underwent controlled displacements (±1–100 mm translations, ±0.5–3° rotations) on a 6-degree-of-freedom couch (6 DOF) (PerfectPitch™) as the reference.
- Absolute errors between system measurements and couch-encoder values were calculated.
- Statistical analysis included mean absolute error (MAE), median, interquartile range (IQR), Pearson correlation, linear regression, and Wilcoxon signed-rank tests.

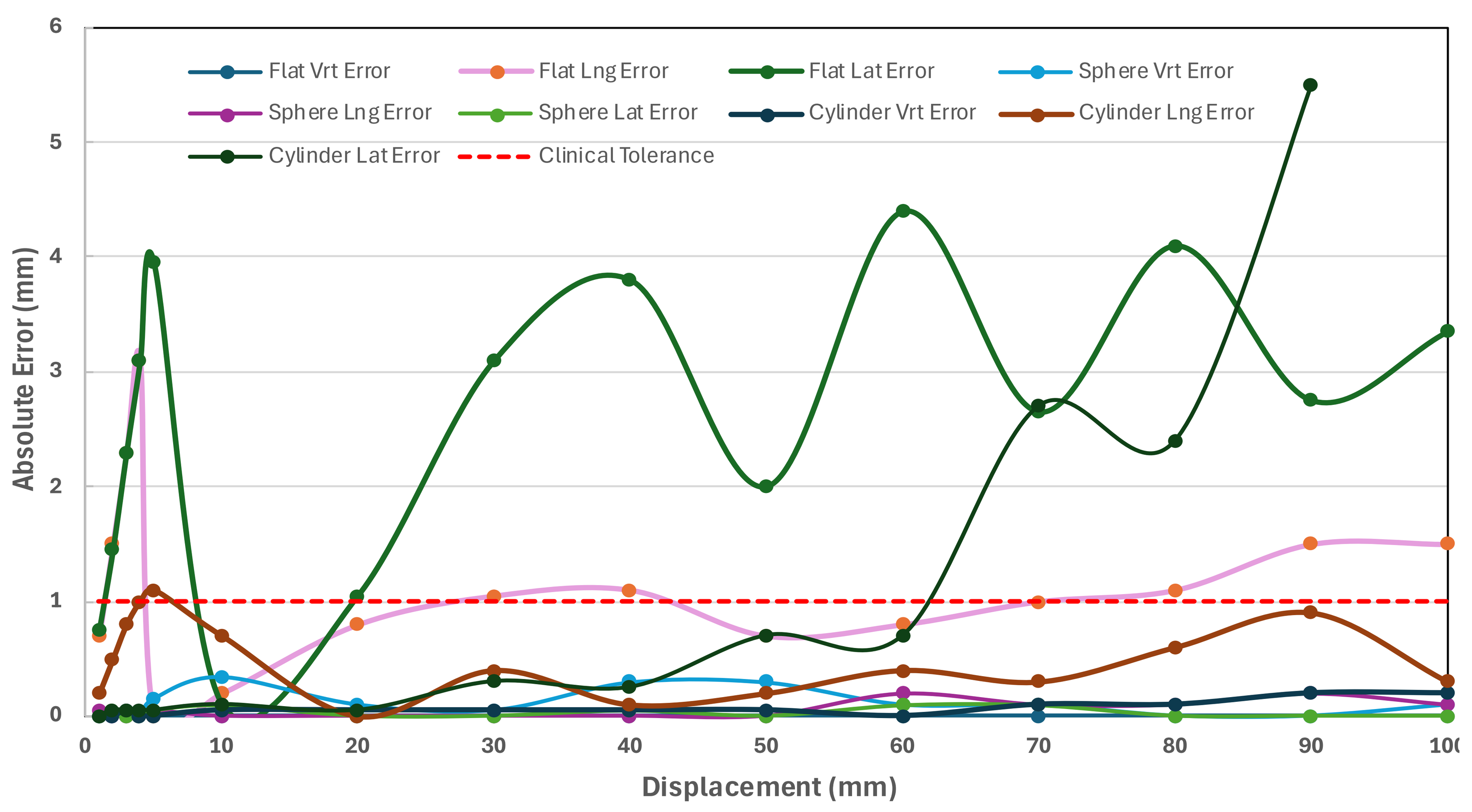

Figure 2. Scatter plots showing relationship between applied displacement and absolute translational error for three phantom geometries. Flat board shows strong positive correlation (r=0.84–0.87) with 95% CIs for mean error: Longitudinal (0.86–1.74 mm), Lateral (2.03–3.57 mm). Spherical phantom demonstrates consistent sub-millimeter accuracy with narrow CIs: Longitudinal (0.04–0.18 mm), Lateral (0.06–0.22 mm). Cylindrical phantom exhibits moderate correlation (r=0.79–0.82) with wider CIs: Longitudinal (2.19–5.95 mm), Lateral (2.56–6.60 mm). Dashed horizontal line indicates clinical tolerance (≤1 mm).

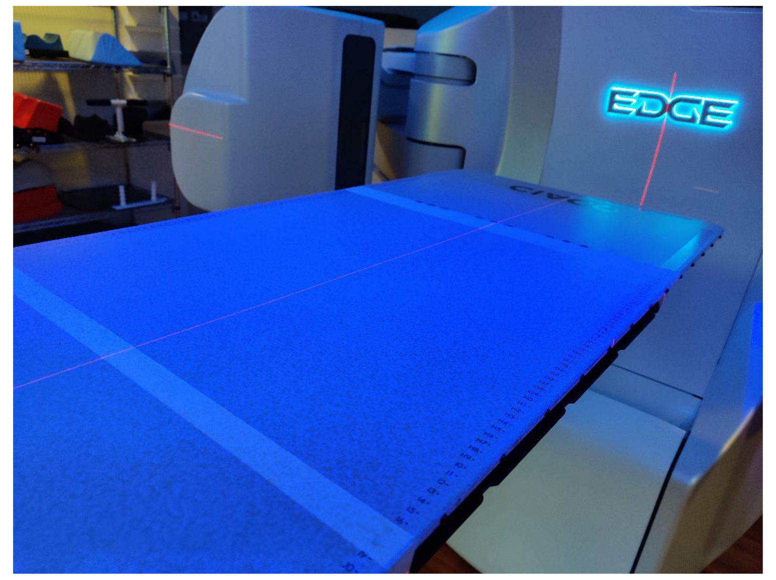

Figure 3. Flat prostate board setup for abdominal surface simulation. The board's smooth, uniform white surface provides an optimal geometry for evaluating large, flat abdominal regions. All measured errors, including translational and rotational deviations, were recorded as positive values to ensure standardized data analysis and facilitate direct comparison across different phantom types.

Results

- Tracking accuracy was strongly geometry-dependent. The spherical phantom achieved sub-millimeter translational accuracy (MAE 0.12 mm; median 0.08 mm, IQR 0.17 mm) with 96% of measurements within the ≤1 mm tolerance. The flat board showed larger translational errors (MAE 1.38 mm; median 0.90 mm, IQR 1.65 mm), with only 47% within tolerance and strong correlation between displacement magnitude and error ($r = 0.84$–0.87, $p < 0.001$). The cylindrical phantom exhibited intermediate translational accuracy (MAE 2.90 mm; median 1.40 mm, IQR 3.85 mm; 61% tolerance compliance) and moderate displacement correlation ($r = 0.79$–0.82). For rotations, the cylindrical phantom showed acceptable PITCH tracking (median 0.20°, IQR 0.30°) but poor ROLL performance (median 1.15°, IQR 1.80°), with most ROLL measurements exceeding ≤0.5°. Flat and spherical phantoms demonstrated high rotational (RTN) errors, with RTN errors (median 1.25°, IQR 1.05°) exceeding the ≤0.5° tolerance in 92% of cases, indicating a fundamental tracking limitation for these geometries.

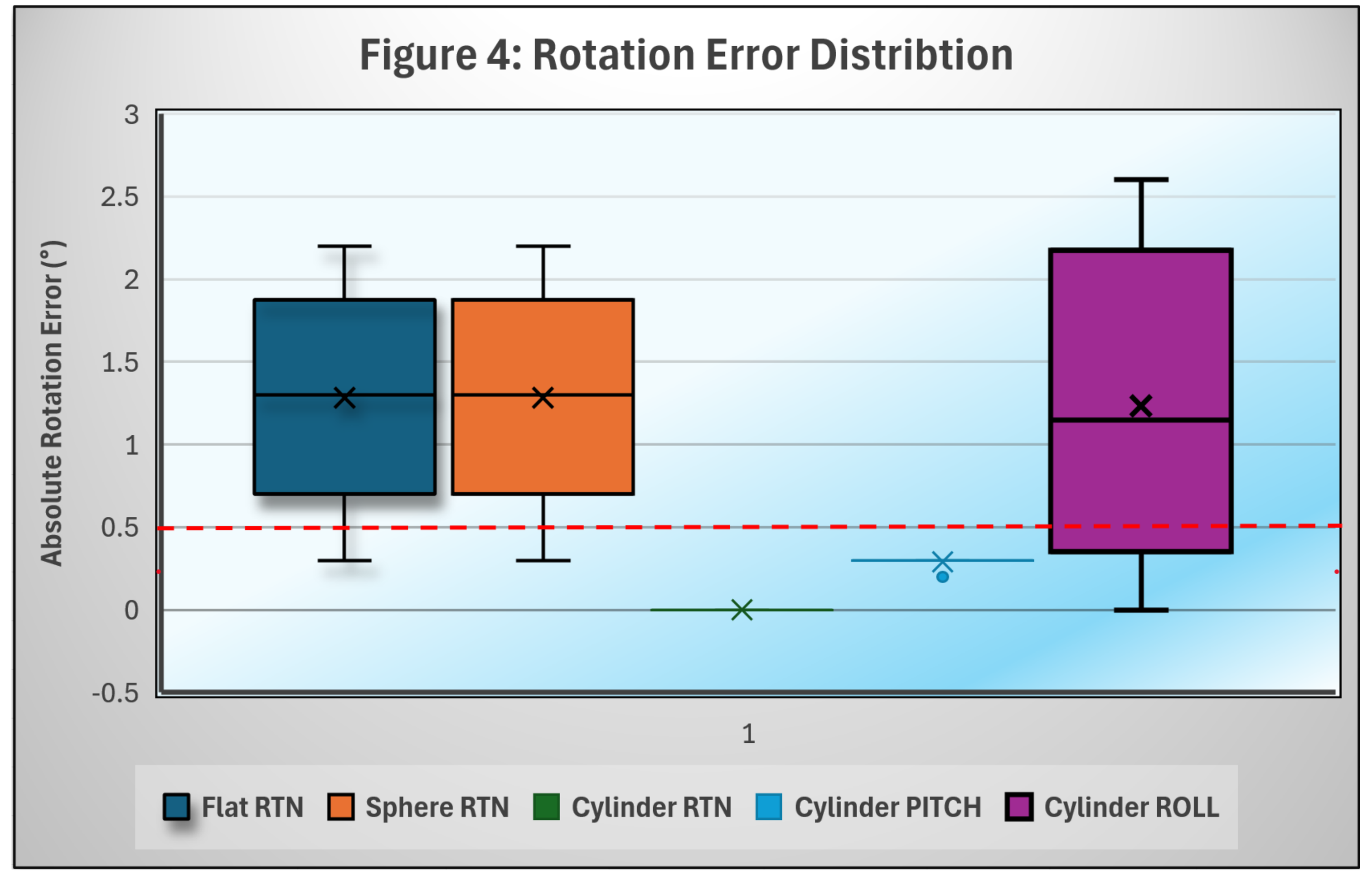

Figure 4. Distribution of absolute rotational errors for each phantom and rotational degree of freedom. Boxes represent interquartile range (IQR, 25th–75th percentile), central line indicates median, cross depicts mean, whiskers show 1.5×IQR, and points denote outliers. The red dashed line marks clinical tolerance (≤0.5°). Cylindrical phantom demonstrates acceptable RTN (median = 0.10°, IQR = 0.15°) and PITCH (median = 0.20°, IQR = 0.30°) performance but poor ROLL tracking (median = 1.15°, IQR = 1.80°). Flat and spherical phantoms show consistently high RTN errors (median = 1.25–1.30°, IQR = 1.00–1.05°) exceeding tolerance limits.

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Conclusions

- The tested SGRT system performed well for translational tracking of spherical breast surfaces but showed unacceptable RTN errors for both spherical and flat surfaces. Cylindrical surfaces showed intermediate translational accuracy, acceptable PITCH tracking, and poor ROLL performance. These geometry-specific limitations necessitate tailored commissioning protocols. Clinical implementation should adopt geometry-specific tolerances, including supplemental verification, especially for ROLL corrections on cylindrical surfaces and RTN corrections on spherical and flat surfaces.

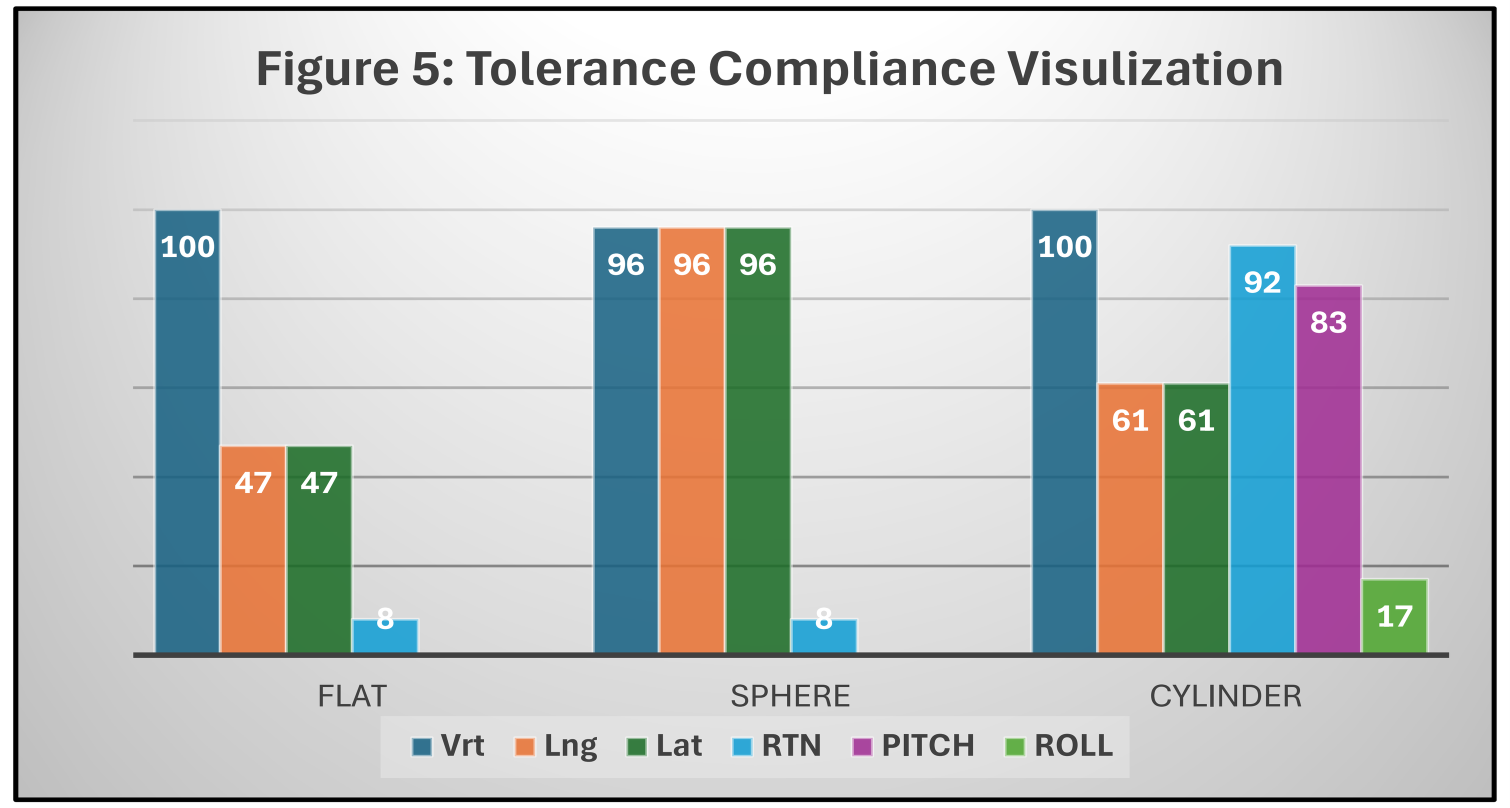

Figure 5. Distribution of absolute rotational errors for each phantom and rotational degree of freedom. Boxes represent interquartile range (IQR, 25th–75th percentile), central line indicates median, cross depicts mean, whiskers show 1.5×IQR, and points denote outliers. The red dashed line marks clinical tolerance (≤0.5°). Cylindrical phantom demonstrates acceptable RTN (median = 0.10°, IQR = 0.15°) and PITCH (median = 0.20°, IQR = 0.30°) performance but poor ROLL tracking (median = 1.15°, IQR = 1.80°). Flat and spherical phantoms show consistently high RTN errors (median = 1.25–1.30°, IQR = 1.00–1.05°) exceeding tolerance limits.

Disclaimer

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