Research Square

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CT-derived surgical corridor anatomy predicts console time beyond body mass index in single-port hairline robotic thyroidectomy

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Abstract

Body mass index (BMI) and other anthropometric measures are widely used as surrogates for operative difficulty in robotic thyroidectomy, yet they may poorly represent the three-dimensional anatomy of the surgical corridor. We investigated whether computed tomography (CT)-derived characteristics of the surgical corridor predict console time in single-port hairline approach thyroidectomy (SPHAT), independently of BMI. We analyzed 125 consecutive robotic thyroid lobectomies with ipsilateral central neck dissection performed by a single surgeon operating within a confirmed expert phase, defined by the absence of a temporal trend in operative time. Corridor length, geodesic tortuosity, and peritrajectory fat heterogeneity were quantified from preoperative CT. Associations with console time were assessed using Spearman correlation and sequential multivariable linear regression. Console time correlated with corridor length ($\rho = 0.210$, $p = 0.019$), geodesic tortuosity ($\rho = 0.190$, $p = 0.033$), and peritrajectory fat heterogeneity ($\rho = 0.319$, $p < 0.001$), but not with BMI ($\rho = 0.160$, $p = 0.075$). On multivariable analysis, geodesic tortuosity and peritrajectory fat heterogeneity were independent predictors of console time (Model A $R^2=0.138$). Peritrajectory fat heterogeneity remained significant across all model specifications ($\beta = 2.22–2.43$ min per standard deviation, all $p \leq 0.002$). Adding BMI did not improve model fit ($R^2=0.144$), and BMI was non-significant after adjustment ($p = 0.395$). Objectively quantified anatomy of the surgical corridor—particularly peritrajectory fat heterogeneity—provides an independent signal of operative difficulty in SPHAT that is not captured by BMI. Because both metrics are derivable from routine preoperative CT, corridor characterization may serve as an objective adjunct for assessing operative complexity and refining preoperative planning.

Introduction

Robotic thyroidectomy now encompasses several remote-access approaches, each defining a distinct working space with its own anatomical constraints and technical demands [1]. Among these, the retroauricular single-port hairline approach thyroidectomy (SPHAT) reaches the thyroid bed through a narrow, curvilinear pathway that follows the convexity of the lateral neck [2]. Unlike axillary or transoral routes, which permit relatively straight-line access, this non-linear trajectory forces instruments to negotiate the curvature of the neck before reaching the target, amplifying the mechanical disadvantage of the robotic arms and heightening the sensitivity of operative performance to individual patient anatomy [3].

Learning-curve analyses in robotic thyroidectomy have focused almost exclusively on cumulative surgeon case volume, yet operative time does not converge to a uniform baseline even after technical proficiency is achieved [4, 5]. We hypothesized that this residual, post-plateau variability is driven less by surgeon-level factors than by patient-level anatomical characteristics intrinsic to the approach. Such determinants are unlikely to be captured by static anthropometric indices such as body mass index (BMI), which reflect neither the three-dimensional geometry of the cervical working space nor the spatial organization of soft tissue along the operative corridor [4].

We therefore quantified the geometry of the surgical corridor—its length and curvature—together with the spatial distribution of peritrajectory fat from preoperative computed tomography (CT), and tested whether these image-derived metrics predict console time independently of BMI and demographic variables. To isolate patient anatomy from residual surgeon effects, we restricted the analysis to a single surgeon operating beyond established learning-curve thresholds [6, 7] and confirmed the absence of a temporal trend in operative time across the series.

Materials and Methods

Patients

We analyzed a consecutive series of 125 patients who underwent robotic thyroid lobectomy with ipsilateral central neck dissection via SPHAT between January 1, and December 31, 2024. All procedures were performed by a single experienced surgeon (M.W.H.) who had completed more than 200 SPHAT procedures prior to the study period. Data extracted from institutional medical records included patient height, body weight, BMI, side of resection, and perioperative outcomes including complications. Operative time was recorded in three discrete phases: (1) the docking phase, encompassing loupe-assisted hairline flap elevation through robot docking, (2) the console phase, representing robot-assisted thyroidectomy at the surgical console following docking, and (3) total operative time, defined as the interval from skin incision to wound closure, was recorded as the sum of these two phases. The study protocol was reviewed and approved by the institutional review board of the Ulsan University Hospital (IRB No. UUH2026-02-017) and conducted in accordance with the Declaration of Helsinki; the requirement for informed consent was waived because of the retrospective design.

Quantification of Trajectory Geometry and Adjacent Fat

Preoperative CT images were exported for three-dimensional surface reconstruction to quantify two distinct anatomical domains hypothesized to influence operative difficulty: the geometric complexity of the surgical trajectory, and the body composition of the surrounding soft tissue — specifically, the relative contributions of subcutaneous fat and underlying musculature along the operative corridor.

A three-dimensional body surface model was reconstructed from CT images and represented as a triangular mesh $\mathcal{M}_{body}$ (Fig. 1). The surgical trajectory was defined as the surface-constrained shortest path between the mastoid tip and the thyroid isthmus, computed on the reconstructed surface using geodesic distance estimation based on the heat method [8]. Corridor length was defined as the absolute geodesic distance along this path. Tortuosity was defined as the ratio of the geodesic distance to the straight-line Euclidean distance between the endpoints:

$$\tau\left(p,q\right)=\frac{d_{\mathcal{M}}(p,q)}{\left\|\,p-q\right\|_{\,2}},$$

where $d_{\mathcal{M}}(p, q)$ denotes the geodesic distance on the mesh and $\| p - q \|_2$ represents the Euclidean distance in three-dimensional space. A tortuosity value greater than 1.0 indicates that the surface path is longer than the straight-line distance, reflecting the curvature of the lateral neck.

To quantify adipose tissue surrounding the surgical trajectory, subcutaneous fat regions were segmented from CT images using intensity-based thresholding and retained in voxel space. A tubular neighborhood with radius of 30 voxels was generated around the computed trajectory to capture the immediate peritrajectory soft tissue environment. Within this neighborhood, the distribution of fat voxel volumes was characterized by its standard deviation, quantifying the spatial heterogeneity of fat deposition along the trajectory — that is, the degree to which adipose tissue is focally concentrated rather than uniformly distributed.

Statistical Analysis

Continuous variables are presented as median with interquartile range (IQR) or mean ± standard deviation (SD), as appropriate; categorical variables as frequencies with percentages. Non-normality of operative time variables was confirmed by the Shapiro-Wilk test; Spearman rank correlation was therefore used throughout. Candidate predictors examined against console time included corridor length, tortuosity, peritrajectory fat heterogeneity, BMI, age, sex, and tumor size.

To assess whether CT-derived corridor variables predict console time independently of conventional anthropometric and demographic surrogates, a sequential multivariable linear regression strategy was employed. All continuous predictors were standardized (z-score) prior to entry to facilitate comparison of effect sizes. Four models were specified: Model A included CT-derived variables only (geodesic tortuosity and peritrajectory fat heterogeneity); Model B added BMI to Model A; Model C added sex to Model A; and Model D included CT-derived variables, BMI, and sex simultaneously. This sequential approach was designed to isolate the independent contribution of CT-derived anatomy from that of conventional clinical variables, and to examine whether demographic factors (sex, BMI) account for or are accounted for by corridor geometry.

All statistical analyses were performed using R (version 4.5.1; R Foundation for Statistical Computing, Vienna, Austria). A two-sided P value of less than 0.05 was considered statistically significant.

Results

Patient Characteristics

The cohort comprised 125 patients with a median age of 43.0 years (IQR 36.0–54.0); 103 (82.4%) were female. Median BMI was 23.3 kg/m² (IQR 21.2–26.4) and median tumor size was 0.9 cm (IQR 0.6–1.5). Median total operative time, console time, and docking time were 55.0 min (IQR 50.0–65.0), 28.0 min (IQR 24.0–35.0), and 29.0 min (IQR 24.0–33.0), respectively. CT-derived corridor characteristics are presented in Table 1.

Table 1
Patient and Operative Characteristics.

Variable	Value
Patient demographics	
Age, years, median [IQR]	43.0 [36.0–54.0]
Female sex, n (%)	103 (82.4)
Height, m, mean ± SD	1.63 ± 0.08
Weight, kg, median [IQR]	62.0 [54.0–69.0]
BMI, kg/m², median [IQR]	23.3 [21.2–26.4]
Right-sided approach, n (%)	75 (60.0)
Tumor size, cm, median [IQR]	0.9 [0.6–1.5]
Operative time	
Total operative time, min, median [IQR]	55.0 [50.0–65.0]
Docking time, min, median [IQR]	29.0 [24.0–33.0]
Console time, min, median [IQR]	28.0 [24.0–35.0]
CT-derived corridor variables	
Corridor length, voxel units, mean ± SD	432.5 ± 35.1
Geodesic tortuosity, mean ± SD	1.147 ± 0.033
Peritrajectory fat heterogeneity, voxel³, mean ± SD	10,347 ± 3,345
Data are presented as median [interquartile range], mean ± standard deviation, or number (%), as appropriate.	
Normality assessed by Shapiro-Wilk test; non-normally distributed variables presented as median [IQR].	
BMI, body mass index; IQR, interquartile range	

Confirmation of a Plateaued Expert Operative Phase

Operative time components showed no significant temporal trend across the case series (Fig. 2): total operative time ($\rho = -0.033$, $p = 0.711$), console time ($\rho = +0.078$, $p = 0.390$), and docking time ($\rho = -0.140$, $p = 0.117$). These findings confirmed that the cohort was operating within a stable expert phase in which ongoing skill acquisition no longer reduced operative time, establishing patient anatomy as the primary source of residual variability.

CT-Derived Anatomical Predictors of Console Time

On univariate analysis, all three CT-derived variables were significantly associated with console time: corridor length (ρ = +0.210, p = 0.019), tortuosity (ρ = +0.190, p = 0.033), and peritrajectory fat heterogeneity (ρ = +0.319, p < 0.001). In contrast, BMI was not significantly associated with console time (ρ = +0.160, p = 0.075), despite moderate correlations with corridor length (ρ = +0.460, p < 0.001), tortuosity (ρ = +0.509, p < 0.001), and peritrajectory fat heterogeneity (ρ = +0.297, p = 0.001) (Fig. 3).

On multivariable regression (Table 2) using CT-derived variables only (Model A), both tortuosity (β = +1.83 min per SD, 95% confidence interval (CI) [+ 0.37, + 3.28], p = 0.014) and peritrajectory fat heterogeneity (β = +2.39 min per SD, 95% CI [+ 0.94, + 3.84], p = 0.001) were independent predictors of console time (R^2 = 0.138). Corridor length and tortuosity were collinear (ρ = +0.381, p < 0.001); when all three CT variables were entered simultaneously, tortuosity retained significance while corridor length did not, and peritrajectory fat heterogeneity remained significant throughout. Tortuosity was therefore selected as the representative corridor geometry variable for all subsequent models.

Table 2
Multivariable Linear Regression: Predictors of Console Time (N = 125)

Covariates	**Model A**	**Model B**	**Model C**	**Model D**
	Anatomic variables	**+ BMI**	**+ Sex**	**+ All**
Peritrajectory fat heterogeneity	+ 2.39 **	+ 2.22 **	+ 2.43 **	+ 2.43 **
Geodesic tortuosity	+ 1.83 *	+ 1.48	+ 1.56	+ 1.56
BMI	-	+ 0.74	-	−0.07
Sex (male)	-	-	+ 5.24 *	+ 5.24 *
R^2	0.138	0.144	0.190	0.190
Values are β coefficients (min per 1 SD). ** p < 0.01; * p < 0.05; unmarked = not significant.				
Model A: CT-derived anatomic variables only. Model B: Model A + BMI. Model C: Model A + sex. Model D: Model A + BMI + sex.				
1 SD: geodesic tortuosity = 0.03; peritrajectory fat heterogeneity = 3,345 voxel³.				

When BMI was added to the CT-only model (Model B), it was non-significant (β = +0.74, p = 0.395) and neither CT predictor was meaningfully attenuated, demonstrating that BMI does not capture the anatomical information conveyed by corridor geometry or fat distribution. Docking time showed no significant association with any predictor throughout (all p > 0.05), confirming that the identified effects were specific to the console phase.

Relationship Between CT Variables and Demographic Factors

When sex was incorporated into the model (Model C), tortuosity lost independent significance (β = +1.56, p = 0.059) while peritrajectory fat heterogeneity remained robustly significant (β = +2.43, p = 0.002) and sex itself was significant (β = +5.24, 95% CI [+ 1.26, + 9.22], p = 0.010). The further addition of BMI (Model D) did not alter these patterns (R^2 = 0.190), and BMI remained non-significant (β = −0.07, p = 0.934) (Table 2).

Male patients (n = 22) had significantly longer corridors (475.6 [458.2–490.8] vs. 422.8 [409.9–440.5] voxel units, p < 0.001) and taller stature (1.75 [1.69–1.78] vs. 1.60 [1.57–1.65] m, p < 0.001), and longer console time (35.0 [26.0–43.0] vs. 27.0 [24.0–32.5] min, p = 0.028). Neither tortuosity (p = 0.104) nor peritrajectory fat heterogeneity (p = 0.894) differed significantly by sex (Fig. 4). These findings indicate that corridor length — not tortuosity or fat heterogeneity directly — underlies the sex difference in operative time. The loss of tortuosity's significance upon sex adjustment in multivariable modeling is therefore attributable to its collinearity with corridor length rather than a direct sex effect, while peritrajectory fat heterogeneity represents a sex-independent anatomical determinant of operative difficulty (Table 2).

Discussion

Objective quantification of operative difficulty remains a persistent challenge in surgery. Although surgeons readily recognize a technically demanding case, this difficulty is hard to express through reproducible parameters. Demographic and anthropometric variables—sex, BMI, and body habitus—have therefore served as convenient surrogates for technical difficulty [9, 10]. Such measures, however, inevitably reduce a highly individual three-dimensional operative environment to a single number and may incompletely reflect the true determinants of operative performance [11, 12].

Advances in surgical data science and medical image analysis now allow this environment to be characterized directly rather than through indirect surrogates [13, 14]. Anatomical features that were previously assessed only qualitatively can be measured objectively from routinely acquired imaging and incorporated into models of operative complexity, offering a path toward individualized preoperative planning and risk stratification [15, 16].

Within a confirmed expert operative phase, console-time variability in SPHAT was explained in part by patient-specific corridor anatomy that BMI did not capture. Geodesic tortuosity and peritrajectory fat heterogeneity were independent predictors of console time, and peritrajectory fat heterogeneity retained significance across every model specification regardless of demographic adjustment, establishing it as the most robust anatomical predictor in this cohort [17–19]. Although the CT-derived model accounted for a modest share of total variance (R^2=0.138), operative time is inherently multifactorial; the salient point is not the absolute variance explained but that objectively measurable corridor anatomy contributes an independent, reproducible signal that conventional anthropometry misses.

The predictive value of geodesic tortuosity is mechanistically plausible. A more tortuous corridor requires instruments to traverse greater angular deviation from a straight path, compounding leverage

loss and restricting the effective range of motion at the operative field. Tortuosity correlated with BMI, indicating that body habitus influences corridor curvature, but BMI alone did not capture this geometric consequence. When sex entered the model, tortuosity lost independent significance—not through any direct anatomical link with sex, but because male patients have substantially longer corridors and tortuosity is collinear with corridor length, so that sex absorbs this composite geometric information.

Peritrajectory fat heterogeneity captures not the quantity of fat along the corridor but the spatial consistency of the tissue traversed during instrument passage. A high value indicates that the corridor alternates between adipose and non-adipose zones, obliging the surgeon to adapt repeatedly to abrupt changes in tissue resistance rather than working within a homogeneous plane. This distinction between tissue composition variability and tissue bulk may explain why BMI fails as a predictor: a patient with uniformly distributed fat may present an easier corridor than one with focally concentrated adipose tissue. That this metric was independent of both BMI and sex supports spatial tissue organization as a distinct dimension of operative difficulty that is invisible to conventional preoperative assessment [20].

Taken together, these findings position demographic variables such as sex and BMI as imperfect proxies for underlying anatomy rather than direct determinants of operative difficulty. Notably, the CT-derived model achieved explanatory power comparable to the fully adjusted demographic model without requiring the patient's sex or body weight. Because both corridor metrics are derived from preoperative CT already obtained in this population, corridor characterization may function not only as a research tool but as a potentially actionable preoperative adjunct.

A practical constraint is that these metrics currently depend on CT-based mesh reconstruction and are not available as bedside measurements. Whether simplified surrogates—such as skin-to-target distance on scout imaging or external neck dimensions—can approximate corridor geometry and fat heterogeneity with sufficient fidelity for routine use warrants dedicated study.

Docking time was associated with no anatomical or demographic predictor throughout the analysis. As this phase reflects flap elevation and robot positioning rather than real-time corridor navigation, its consistent insensitivity to patient anatomy serves as an internal control, indicating that the observed effects are specific to the robot-assisted console phase.

This study has several limitations. It reflects a single surgeon at a single institution, and generalizability to other platforms, approaches, and experience levels requires external validation. The cohort is modest in size, which limits statistical power and precludes more complex modeling; the observed effect sizes (approximately 2 min per standard deviation) are small relative to median console time and should be interpreted as proof of concept rather than as a clinically deployable predictive tool. Peritrajectory fat classification relies on CT intensity thresholding and may be sensitive to scanner calibration. Finally, corridor metrics are expressed in voxel units; conversion to physical dimensions and prospective validation against clinical outcomes beyond operative duration remain necessary before clinical application.

Conclusions

In 125 consecutive SPHAT procedures performed within a confirmed expert operative phase, CT-derived characteristics of the surgical corridor predicted console time independently of BMI, with peritrajectory fat heterogeneity emerging as the most robust anatomical predictor. Although demographic variables partly reflected corridor anatomy, direct quantification of patient-specific anatomy provided more specific insight into operative difficulty. These findings indicate that residual variability in operative performance after the learning curve is driven substantially by anatomy intrinsic to the surgical corridor rather than by gross body habitus, and support image-derived anatomical quantification as an objective framework for assessing operative complexity and informing preoperative planning in SPHAT.

Declarations

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics Approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Institutional Review Board of Ulsan University Hospital (IRB No. UUH2026-02-017).

Consent to Participate

The requirement for informed consent was waived by the Institutional Review Board of Ulsan University Hospital because of the retrospective design of the study.

Consent to Publish

Not applicable. The manuscript contains no identifiable individual patient data or images; the three-dimensional reconstructions in Fig. 1 are de-identified.

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Author Contribution

Ji Won Kim: Data curation, Investigation, Formal analysis, Writing – original draft. Jungirl Seok: Conceptualization, Methodology, Funding acquisition, Supervision, Writing – original draft. Jae Yeong Kim: Formal analysis, Software, Visualization, Writing – review & editing. Dong Hyeong Lee: Methodology, Writing – review & editing. Jae Hyun Kim: Resources, Writing – review & editing. Myung Woul Han: Conceptualization, Funding acquisition, Supervision, Project administration, Writing – review & editing. All authors read and approved the final manuscript.

Data Availability

The patient data are not publicly available because patient consent for the sharing of personal information was not obtained.

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Figures

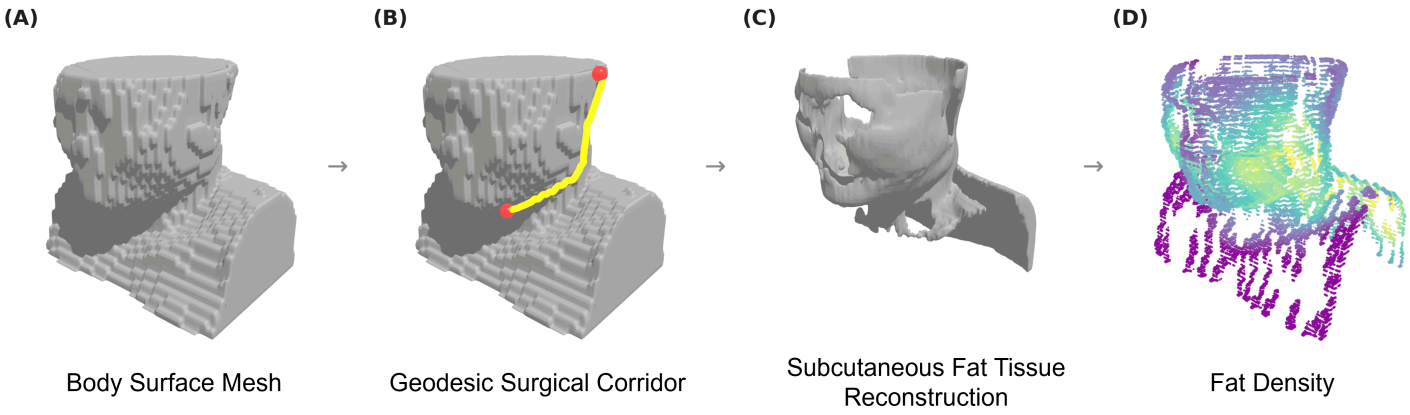


Figure 1

Computational pipeline for surgical corridor characterization from preoperative CT. (A) Voxelized body surface mesh. (B) Geodesic path (yellow) from mastoid tip to thyroid isthmus; red spheres indicate start and end points. (C) Subcutaneous fat tissue mesh. (D) Peritrajectory fat density distribution; color indicates local fat volume (purple = low, yellow = high).

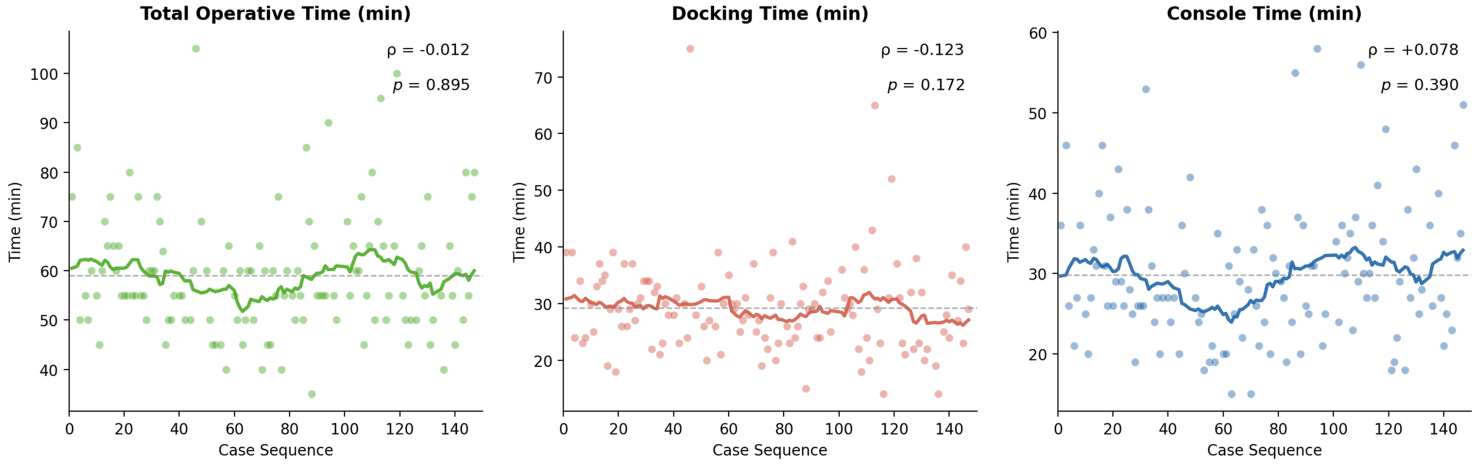


Figure 2

Operative time components show no significant temporal trend across the case series.

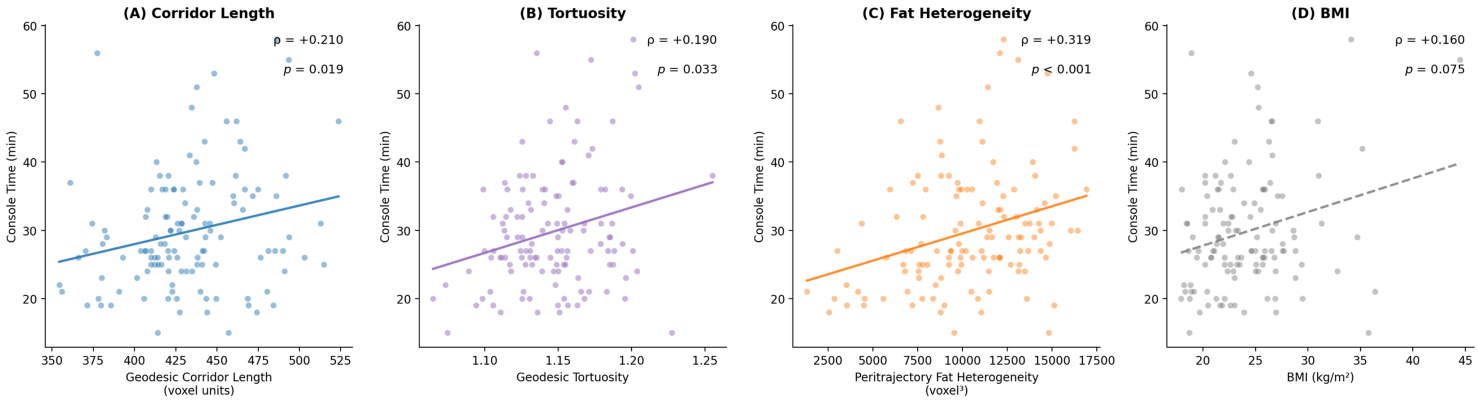


Figure 3

Corridor length, tortuosity and peritrajectory fat heterogeneity, but not BMI, are significantly associated with console time (solid line: $p < 0.05$; dashed line: $p \geq 0.05$).

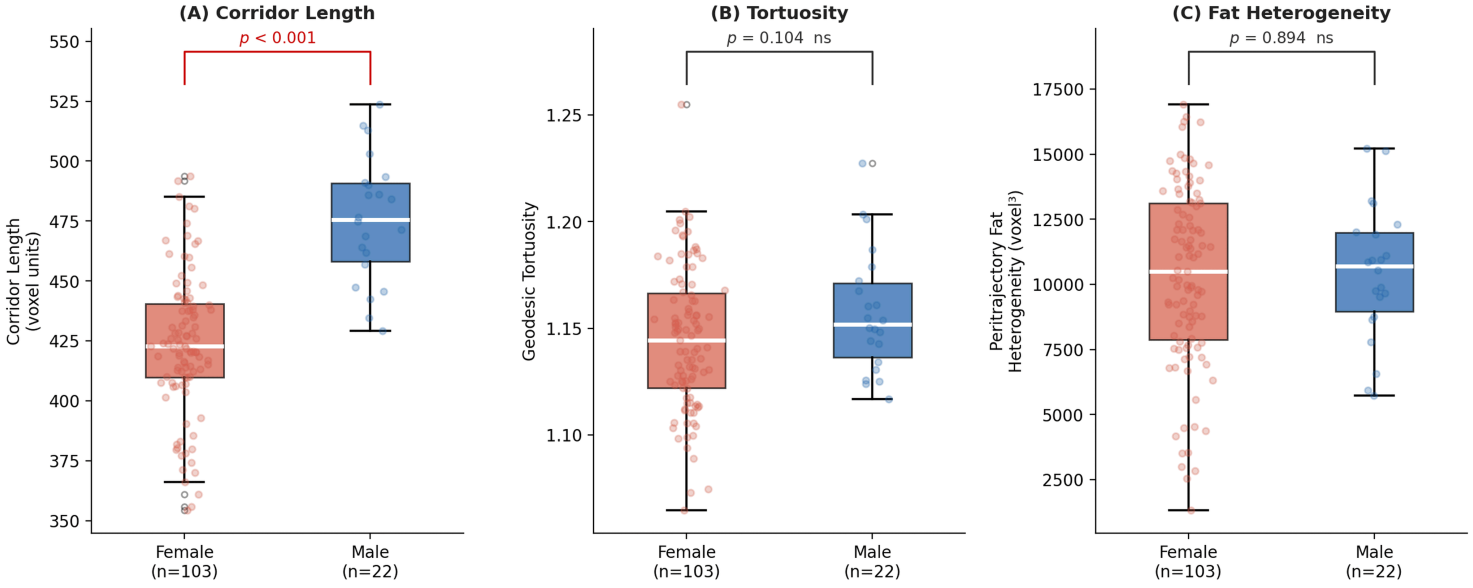


Figure 4

Sex differences in CT-derived corridor variables. Corridor length was significantly greater in male patients, whereas tortuosity and peritrajectory fat heterogeneity did not differ significantly by sex.