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ORIGINAL RESEARCH

The Clinical Significance of Key Pelvic Floor Ultrasound Indicators in POP Management: A Retrospective Study of Diagnostic Accuracy and Therapeutic Intervention

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Objective: To explore the clinical significance of key pelvic floor ultrasound indicators in the treatment of pelvic organ prolapse (POP). This study aims to address the limitations of the subjective POP-Q system and the costly static MRI, optimize objective evaluation metrics, and construct an effective POP risk prediction model.

Methods: A retrospective analysis was conducted on 110 patients with POP or lower urinary tract symptoms. All participants underwent POP-Q assessment and 3D pelvic floor ultrasonography. Following 1:1 age-matched propensity score matching (PSM), Lasso regression was employed to screen variables and establish the POP\u index model. Model efficacy was validated through area under the curve (AUC), sensitivity, specificity, and decision curve analysis.

Results: Eighty-four participants were included after matching. In the POP group, the levator hiatus area was significantly larger, and both bladder neck mobility and rectal prolapse rate were higher (both $p<0.001$). Seven core ultrasound indicators were identified. The POP\U index demonstrated excellent diagnostic efficiency, with an AUC of 0.94, and both sensitivity and specificity at 0.88, yielding an ideal clinical net benefit.

Conclusion: Pelvic floor ultrasound, combined with PSM and machine learning, enables accurate POP assessment. The prediction model and ultrasound indicators provide an objective basis for clinical diagnosis and risk stratification, facilitating individualized intervention and primary-level POP screening.

Keywords: pelvic organ prolapse, pelvic floor ultrasound, risk prediction model, POP_Index, propensity score matching, LASSO regression, pelvic organ prolapse quantification

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Introduction

Pelvic organ prolapse (POP) represents a predominant form of pelvic floor dysfunction in women, stemming from compromised supportive capacity of the pelvic floor musculature and fascia.[1,2] This structural impairment precipitates the descent of pelvic organs, subsequently leading to organ displacement and functional deficits. Clinically, POP is characterized by protruding vaginal tissue, frequently accompanied by urinary retention, defecatory dysfunction, and sexual dysfunction, all of which collectively undermine the patient's physical well-being and quality of life.[3] Notably, epidemiological data indicate that 9.6% of adult women in China experience symptomatic POP, with its prevalence escalating in tandem with advancing age and parity.[4] This trend imposes substantial medical burdens on individuals, families, and healthcare systems alike, underscoring the pressing need for targeted investigative efforts.

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However, the prevailing assessment and prediction paradigms for POP exhibit notable limitations. The clinical gold standard, the Pelvic Organ Prolapse Quantification (POP-Q) system, not only relies heavily on the examiner's subjective assessment, capturing solely the superficial positional alterations of pelvic organs, but also falls short in quantifying pivotal deep-seated pathological features, such as levator ani muscle dysfunction or pelvic diaphragmatic hiatal enlargement.[5,6] Although magnetic resonance imaging (MRI) offers high-resolution static anatomical visualization, its application is hindered by exorbitant costs, prolonged scanning times, and an inability to capture dynamic changes under conditions of increased intra-abdominal pressure, such as during the Valsalva maneuver.[7] In terms of predictive modeling, traditional risk factors, including age, parity, and obesity, merely convey "probabilistic risk" without establishing a direct linkage to core pathological indices. Concurrently, research on serum biomarkers remains in its nascent stages, marked by non-standardized detection protocols and limited specificity, thereby precluding the availability of precise early warning tools for POP.

In contrast, pelvic floor ultrasound represents a non-invasive, cost-effective imaging modality that effectively bridges the aforementioned gap. It facilitates swift outpatient evaluations and enables real-time visualization of pelvic organ movements and the dilation of the pelvic diaphragmatic hiatus under various conditions (namely, rest, Valsalva maneuver, and anal contraction).[8–10] Furthermore, it quantifies critical parameters, such as the levator hiatus area and bladder neck mobility, thereby mitigating the risk of subjective assessment bias. Additionally, its radiation-free nature ensures the safety of repeated monitoring in special populations, including postpartum women. Collectively, these attributes render it exceptionally well-suited for addressing the core pathological mechanisms underlying POP.

Therefore, this study is designed to bridge the specific knowledge gap pertaining to the absence of objective dynamic indicators and effective risk prediction tools in conventional POP assessment methodologies. We hypothesize that integrating pelvic floor ultrasound with machine learning algorithms will enable the development of a reliable and objective POP prediction model, thereby addressing the limitations of traditional assessment approaches and providing precise risk stratification and diagnostic grounds for clinical practice.

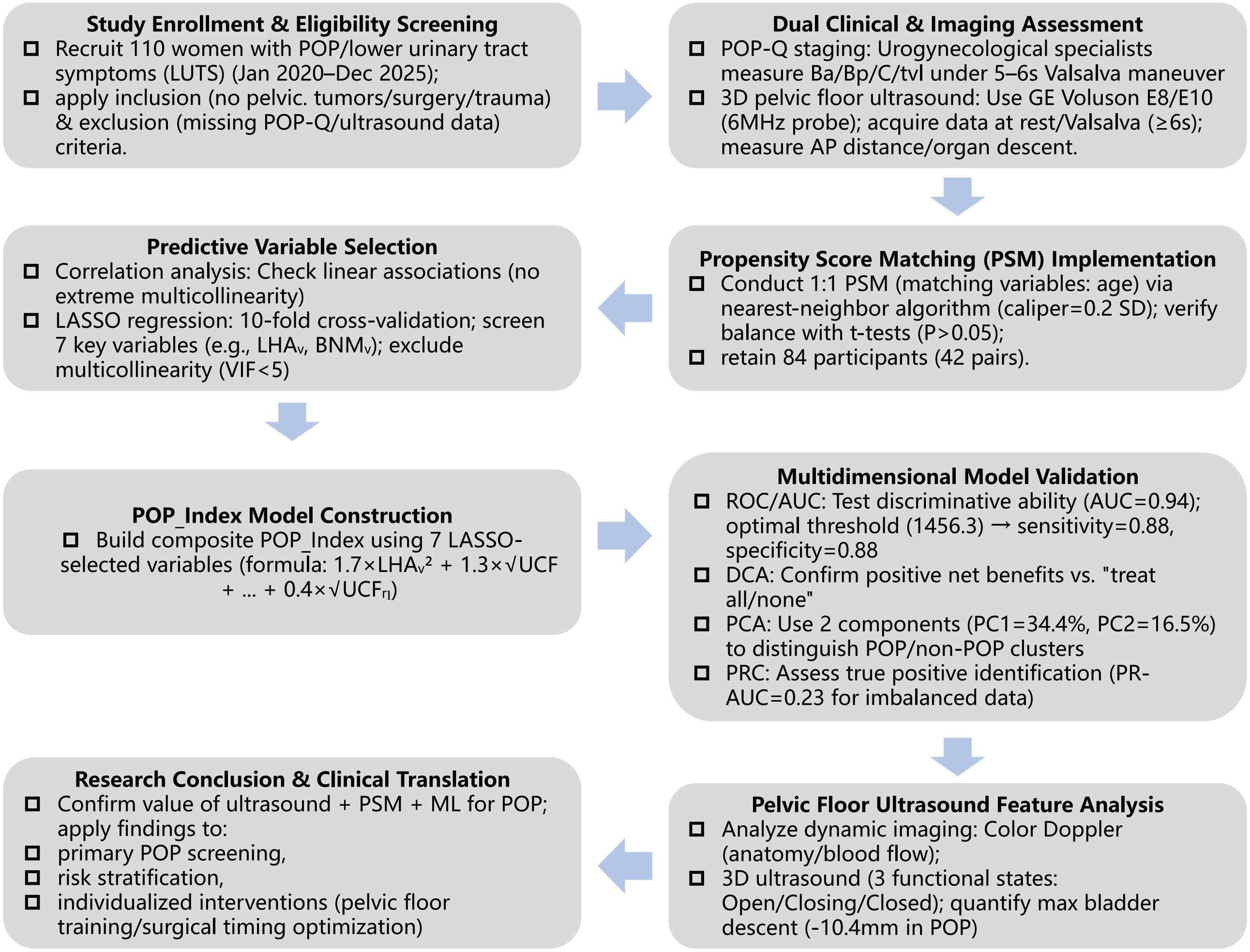
Materials and Methods

Study Population

A retrospective analysis was performed on 110 female patients who sought treatment at the Obstetrics and Gynecology Department of the Jinlong Campus, Enshi Central Hospital, for pelvic organ prolapse (POP) or lower urinary tract symptoms (LUTS) from January 2020 to October 2025. All participants underwent clinical evaluations utilizing the POP-Q system developed by the International Continence Society (ICS), along with standardized pelvic floor ultrasound examinations.[11] The inclusion criteria were as follows: first, no history of pelvic or pelvic floor tumors; second, no prior pelvic or pelvic floor physiotherapy, radiotherapy, or surgical interventions; third, no history of pelvic or pelvic floor trauma; and fourth, the absence of structural abnormalities in the pelvic or pelvic floor region. The exclusion criteria included: first, the absence of clinical records pertaining to POP-Q assessment; and second, the lack of pelvic floor ultrasound image data. This study was approved by the Ethics Committee of Enshi Tujia and Miao Autonomous Prefecture Central Hospital (Approval No. 2025-173-01) and conducted in accordance with the Declaration of Helsinki. The patient registration process is illustrated in Figure 1.

POP-Q Assessment

Different physicians employed a double-blind approach to gather clinical data and ultrasound measurement results from patients. POP-Q staging was conducted and recorded by urogynaecological specialists based on the POP-Q assessment system. The descent or distension of the organ was evaluated under a maximum Valsalva maneuver sustained for at least 5 to 6 seconds. Measurements were taken from the anterior vaginal wall point (Ba), the posterior vaginal wall point (Bp), and the lowest point of the uterus (C) to the hymenal edge, with values below the hymenal edge denoted as "+" and those above as "−". The total vaginal length (TVL) was also measured. POP was classified into grades 0 to IV. Specifically, a value of 0 cm corresponds to grade 0, indicating the absence of POP; a range from −3 to −1 cm corresponds to grade



Study Enrollment & Eligibility Screening

☐ Recruit 110 women with POP/lower urinary tract symptoms (LUTS) (Jan 2020–Dec 2025);

☐ apply inclusion (no pelvic. tumors/surgery/trauma) & exclusion (missing POP-Q/ultrasound data) criteria.

Dual Clinical & Imaging Assessment

☐ POP-Q staging: Urogynecological specialists measure Ba/Bp/C/tvl under 5–6s Valsalva maneuver

☐ 3D pelvic floor ultrasound: Use GE Voluson E8/E10 (6MHz probe); acquire data at rest/Valsalva (≥6s); measure AP distance/organ descent.

Propensity Score Matching (PSM) Implementation

☐ Conduct 1:1 PSM (matching variables: age) via nearest-neighbor algorithm (caliper=0.2 SD); verify balance with t-tests (P>0.05);

☐ retain 84 participants (42 pairs).

Predictive Variable Selection

☐ Correlation analysis: Check linear associations (no extreme multicollinearity)

☐ LASSO regression: 10-fold cross-validation; screen 7 key variables (e.g., LHA_v, BNM_v); exclude multicollinearity (VIF<5)

POP_Index Model Construction

☐ Build composite POP_Index using 7 LASSO-selected variables (formula: $1.7\times LHA_v^2 + 1.3\times\sqrt{UCF} + \ldots + 0.4\times\sqrt{UCF_{rl}}$)

Multidimensional Model Validation

☐ ROC/AUC: Test discriminative ability (AUC=0.94); optimal threshold (1456.3) → sensitivity=0.88, specificity=0.88

☐ DCA: Confirm positive net benefits vs. "treat all/none"

☐ PCA: Use 2 components (PC1=34.4%, PC2=16.5%) to distinguish POP/non-POP clusters

☐ PRC: Assess true positive identification (PR-AUC=0.23 for imbalanced data)

Pelvic Floor Ultrasound Feature Analysis

☐ Analyze dynamic imaging: Color Doppler (anatomy/blood flow);

☐ 3D ultrasound (3 functional states: Open/Closing/Closed); quantify max bladder descent (-10.4mm in POP)

Research Conclusion & Clinical Translation

☐ Confirm value of ultrasound + PSM + ML for POP; apply findings to:

☐ primary POP screening,

☐ risk stratification,

☐ individualized interventions (pelvic floor training/surgical timing optimization)

Figure 1 Flowchart of Pelvic Organ Prolapse (POP) Research and Analysis Workflow.

I prolapse; −1 to +1 cm corresponds to grade II prolapse; +1 to (TVL-2) cm corresponds to grade III prolapse; and values greater than (TVL-2) cm correspond to grade IV prolapse.

Pelvic Floor Ultrasound Examination Protocol

Three-dimensional ultrasound volume acquisition of the pelvic floor was conducted by two physicians, each possessing five years of experience in pelvic floor three-dimensional ultrasonography. The Nuewa R9S color Doppler ultrasound system (asset number: B30120220400023), managed and stored by the Women and Children's Ultrasound Imaging Department, was utilized for this purpose. This system is equipped with 3D volume acquisition capabilities and an abdominal convex probe operating at a frequency of 6 MHz. Following urination, the patient was positioned in the lithotomy position. Subsequently, the probe was placed on the perineum to acquire standard 3D pelvic floor volume data centered on the midsagittal plane, and the dynamic 3D volume sequence during the Valsalva maneuver (lasting for at least 6 seconds) was recorded. More than three sets of 3D volume datasets were stored for subsequent post-processing. The anteroposterior (AP) distance was measured on a 2D midsagittal view derived from 3D volume reconstruction. This distance represents the shortest distance from the posterior-inferior margin of the pubic symphysis to the anterior edge of the puborectalis muscle posterior to the anorectal angle, with precise positioning facilitated by the coronal and axial views of 3D multiplanar reconstruction (3D MPR) (Supplementary Figure 1A). Concurrently, the maximum descent positions of the bladder, uterus, and anterior rectal wall were measured, and 3D volume navigation was employed to confirm the lowest descent point of each organ (Supplementary Figure 1B–D).

Criteria for 3D Ultrasonic Diagnosis of Significant POP

The 3D ultrasound diagnostic criteria for significant POP are outlined as follows. A significant cystocele is defined as the lowest point of the bladder being 10 mm below the reference line; significant uterine prolapse is characterized by the lowest point of the cervix being 0 mm below the reference line; perineal body hypermobility is indicated when the lowest point of the ampulla of the rectum is 15 mm below the pubic symphysis. If this condition is accompanied by a sac-like protrusion of the rectal ampulla towards the posterior vaginal wall exceeding 10 mm, it is diagnosed as rectal ampulla prolapse. 3D volume visualization facilitates the clear identification of the protrusion's morphology and its spatial relationship with adjacent structures. Ultrasonic data derived from 3D volume datasets were independently measured by two physicians for repeatability assessment, and the measurement results were cross-validated using consistent 3D multi-planar reformation (MPR) parameters to ensure consistency.

Propensity Score Matching Analysis

To mitigate potential confounding bias arising from differences in baseline characteristics between patients with POP and those without, this study conducted a 1:1 PSM analysis.[12] The primary matching variables selected were age, height, and weight, as these factors are known to be potentially associated with pelvic floor function and the risk of pelvic floor disorders; failure to control for them could lead to inaccurate comparative analyses between the two groups. For the PSM procedure, the nearest neighbor matching algorithm was employed, with the caliper width set at 0.2 standard deviations of the propensity score. This approach was chosen to minimize differences in propensity scores between matched pairs and optimize the balance of baseline characteristics. After matching, the balance of key variables between the POP and non-POP groups was validated using an independent samples *t*-test. Subsequent analyses included only those pairs that exhibited no statistically significant differences in these variables ($P > 0.05$), ensuring that intergroup comparisons were primarily driven by the presence or absence of POP, rather than by baseline confounding factors.

Variable Selection and ML Model for POP Risk Prediction

Predictor variables for pelvic organ prolapse (POP) risk prediction encompass clinical parameters (eg, age, body mass index [BMI], parity) and pathophysiologically relevant pelvic floor ultrasound indicators Given the relatively small sample size, strategies to mitigate statistical overfitting include strict variable control, dimensionality reduction via least absolute shrinkage and selection operator (LASSO) regression, and cross-validation throughout the entire process.[13]

Variable selection adhered to sequential steps: (1) Variables lacking clinical correlation with POP were excluded; (2) Variables exhibiting a univariate association ($p < 0.2$) with POP status were retained to avoid overlooking potential predictors; (3) LASSO regression with 5-fold cross-validation was applied to retain only variables with non-zero coefficients; (4) A variance inflation factor (VIF) check (threshold: $VIF < 5$) was conducted to exclude variables with multicollinearity. Candidate models (logistic regression, random forest) were trained on the training set, and hyperparameters were optimized using 5-fold cross-validation. The final model was selected based on the validation set performance (evaluated by AUC, accuracy, sensitivity, specificity, and decision curve analysis [DCA]).[14]

Sample Size Estimation

Sample size estimation was conducted based on the Events Per Variable (EPV) principle within the statistical framework of binary logistic regression (used in the POP risk prediction model), which serves as a core criterion for avoiding model overfitting and ensuring stability.[15] Definition of "event" and "variable": The term "event" is defined as "confirmed cases of POP" (42 cases in the POP group after propensity score matching, PSM); "variable" refers to the seven key predictive parameters selected through LASSO regression (since there are no multi-category variables requiring conversion into dummy variables, the number of parameters aligns with the number of variables). Given that pelvic floor ultrasound (USG) indicators have been identified as key predictive variables in the POP\U index model, the sample size was estimated based on the quantity of these critical USG predictors.

EPV Calculation and Threshold Selection: In this study, the actual EPV was calculated as "number of events ÷ number of predictive parameters" = 42 ÷ 7 = 6. Given the use of a retrospective design and 5-fold cross-validation to mitigate overfitting, a conservative EPV threshold of ≥5 was adopted (supported by simulation studies indicating that an EPV ≥5 can restrict the deviation of regression coefficients to within 15%). The actual EPV (6) surpassed this threshold, confirming that the sample size was adequate to ensure the stability of the POP\U index model. The final predictive model utilizes the reserved pelvic floor ultrasound indicators as the POP\U index (comprehensive score) through the following formula:

$$\mathrm{POP\_Index} = 1.7 \times \mathrm{LHA_v}^2 + 1.3 \times \sqrt{\mathrm{UCF}} + 1.2 \times (\mathrm{BNM_v}/2) + 0.9 \times \mathrm{CHL} + 0.5 \times \mathrm{BNP_r} + 0.1 \times \mathrm{CAD}^2 + 0.4 \times \sqrt{\mathrm{UCF_{rl}}}.$$

The abbreviations of ultrasonic indicators in the formula correspond to specific parameters: $\mathrm{LHA_v}$ represents the levator hiatus area measured during the Valsalva maneuver (unit: cm^2); UCF denotes the volume of uterine cavity fluid (unit: mL); $\mathrm{BNM_v}$ refers to bladder neck mobility assessed via the Valsalva maneuver (unit: cm); CHL indicates cervical hyperechoic length (unit: cm); $\mathrm{BNP_r}$ represents the bladder neck position at rest (unit: cm); CAD^2 indicates the anterior-posterior diameter of the cervix (unit: cm); and $\mathrm{UCF_{rl}}$ denotes the separation width of the uterine cavity (unit: cm).

Statistical Analysis

All statistical analyses were conducted using general-purpose clinical research software, including SPSS 26.0 and R 4.3.0. Prior to analysis, the normality of continuous variables was assessed using the Shapiro–Wilk or Kolmogorov–Smirnov tests. Variables with a normal distribution were reported as mean ± standard deviation (SD) and compared between groups using independent t-tests or one-way ANOVA, whereas non-normally distributed variables were reported as median (interquartile range, IQR) and compared using the Mann–Whitney *U*-test or Kruskal–Wallis *H*-test. Categorical variables (eg, gender, disease stage) were presented as frequency (n) and percentage (%) The Pearson chi-square test was employed for intergroup comparisons, and the Fisher exact test was applied when the expected frequency in any cell was less than 5. Missing values with a missing rate of less than 20% were imputed using the mean or median for continuous variables, the mode for categorical variables, or multiple imputation methods; variables with a missing rate exceeding 20% were excluded from the analysis.

Results

Baseline Clinical and Ultrasonographic Characteristics Before and After Propensity Score Matching

Initially, a total of 110 participants were recruited, comprising 42 in the POP group and 68 in the non-POP group. Following 1:1 propensity score matching (PSM), 84 participants (42 matched pairs) were retained for further analysis (Supplementary Figure 2). Prior to PSM, the median age (57.00 [53.00, 59.75] vs 42.00 [39.00, 45.25], $P < 0.001$) and median BMI (26.15 [23.95, 27.28] vs 21.15 [19.88, 23.20], $P < 0.001$) were significantly higher in the POP group compared to the non-POP group. Clinically, all participants in the POP group exhibited anterior wall prolapse (92.9% mild, 7.1% moderate) and cervical prolapse (50.0% mild, 35.7% moderate, 14.3% severe), with 59.5% presenting with rectal eminence. Notably, none of these conditions were observed in the non-POP group (all $P < 0.001$). Ultrasonography revealed that, during the Valsalva maneuver, the POP group had greater bladder neck mobility (2.00 [1.81, 2.21] cm vs 1.52 [1.31, 1.72] cm, $P < 0.001$), more pronounced bladder descent (3.11 [2.88, 3.30] cm vs 2.67 [2.49, 2.89] cm, $P < 0.001$), and a larger levator hiatus area (31.64 [30.30, 33.00] cm^2 vs 27.12 [25.84, 28.26] cm^2, $P < 0.001$). After PSM, significant differences persisted in age, BMI, and the aforementioned clinical/ultrasonographic indicators (all $P < 0.001$), whereas parameters such as uterine size, endometrial thickness, and the lowest point of the bladder wall during the Valsalva maneuver showed no significant differences before and after PSM (all $P > 0.05$). As depicted in Table 1, these data confirm that PSM effectively balanced baseline characteristics while preserving key differences related to POP between the two groups.

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Table 1 Baseline Clinical and Ultrasonographic Characteristics of Patients with and without Pelvic Organ Prolapse (POP) Before and After Propensity Score Matching (PSM)

Variables	Before PSM			P-value	After PSM			P-value
	Overall (n=110)	POP (n=42)	Non-POP (n=68)		Overall (n=84)	POP (n=42)	Non-POP (n=42)	
Age (median [IQR])	46.00 [41.00, 54.00]	57.00 [53.00, 59.75]	42.00 [39.00, 45.25]	<0.001	49.00 [45.00, 57.00]	57.00 [53.00, 59.75]	45.00 [42.00, 46.00]	<0.001
BMI (median [IQR])	23.00 [20.50, 25.70]	26.15 [23.95, 27.28]	21.15 [19.88, 23.20]	<0.001	23.40 [20.73, 26.42]	26.15 [23.95, 27.28]	20.80 [19.83, 23.20]	<0.001
Anterior Wall Prolapse Grade (%)								
No prolapse	68 (61.8)	0 (0.0)	68 (100.0)	<0.001	42 (50.0)	0 (0.0)	42 (100.0)	<0.001
Mild prolapse	39 (35.5)	39 (92.9)	0 (0.0)		39 (46.4)	39 (92.9)	0 (0.0)	
Moderate prolapse	3 (2.7)	3 (7.1)	0 (0.0)		3 (3.6)	3 (7.1)	0 (0.0)	
Cervix Prolapse Degree (%)								
No prolapse	68 (61.8)	0 (0.0)	68 (100.0)	<0.001	42 (50.0)	0 (0.0)	42 (100.0)	<0.001
Mild prolapse	21 (19.1)	21 (50.0)	0 (0.0)		21 (25.0)	21 (50.0)	0 (0.0)	
Moderate prolapse	15 (13.6)	15 (35.7)	0 (0.0)		15 (17.9)	15 (35.7)	0 (0.0)	
Severe prolapse	6 (5.5)	6 (14.3)	0 (0.0)		6 (7.1)	6 (14.3)	0 (0.0)	
Rectal Bulge (%)								
No rectal bulge	85 (77.3)	17 (40.5)	68 (100.0)	<0.001	59 (70.2)	17 (40.5)	42 (100.0)	<0.001
Presence of rectal bulge	25 (22.7)	25 (59.5)	0 (0.0)		25 (29.8)	25 (59.5)	0 (0.0)	
Uterus Length (cm, median [IQR])	6.15 [5.95, 6.40]	6.14 [5.95, 6.36]	6.16 [5.96, 6.40]	0.726	6.14 [5.95, 6.37]	6.14 [5.95, 6.36]	6.14 [5.96, 6.38]	0.907
Uterus Width (cm, median [IQR])	4.64 [4.45, 4.82]	4.59 [4.41, 4.76]	4.67 [4.48, 4.82]	0.133	4.61 [4.46, 4.80]	4.59 [4.41, 4.76]	4.64 [4.49, 4.81]	0.243
UterusAnteroposterior Diameter (cm, median [IQR])	3.79 [3.64, 3.91]	3.76 [3.61, 3.85]	3.80 [3.68, 3.95]	0.065	3.79 [3.64, 3.88]	3.76 [3.61, 3.85]	3.80 [3.71, 3.96]	0.059
Endometrium Thickness (cm, median [IQR])	0.66 [0.56, 0.73]	0.66 [0.54, 0.74]	0.66 [0.57, 0.73]	0.892	0.65 [0.56, 0.73]	0.66 [0.54, 0.74]	0.64 [0.57, 0.73]	0.922
CervixAnteroposterior Diameter (cm, median [IQR])	2.88 [2.76, 2.98]	2.94 [2.86, 3.05]	2.83 [2.75, 2.94]	0.003	2.91 [2.78, 3.01]	2.94 [2.86, 3.05]	2.84 [2.74, 2.94]	0.013
Uterine Cavity Separation (cm, median [IQR])	0.21 [0.18, 0.26]	0.22 [0.18, 0.26]	0.21 [0.18, 0.25]	0.639	0.21 [0.19, 0.25]	0.22 [0.18, 0.26]	0.21 [0.19, 0.25]	0.441
Cervix Hyperecho Length (cm, median [IQR])	3.21 [3.07, 3.35]	3.38 [3.29, 3.51]	3.13 [3.02, 3.24]	<0.001	3.27 [3.10, 3.42]	3.38 [3.29, 3.51]	3.16 [3.03, 3.26]	<0.001
Cervix Hyperecho Width (cm, median [IQR])	1.87 [1.78, 1.96]	1.88 [1.78, 1.97]	1.86 [1.79, 1.96]	0.703	1.88 [1.78, 1.96]	1.88 [1.78, 1.97]	1.88 [1.77, 1.96]	0.837
Uterine Cavity Fluid (mL, median [IQR])	1.21 [0.92, 1.45]	1.46 [1.27, 1.63]	1.02 [0.84, 1.26]	<0.001	1.27 [1.00, 1.51]	1.46 [1.27, 1.63]	1.04 [0.87, 1.27]	<0.001
Bladder Neck Position at Rest (cm, median [IQR])	3.50 [3.26, 3.68]	3.55 [3.37, 3.72]	3.42 [3.24, 3.67]	0.027	3.53 [3.29, 3.70]	3.55 [3.37, 3.72]	3.44 [3.23, 3.68]	0.092
Bladder Angle at Rest (deg, median [IQR])	114.98 [112.33, 118.14]	115.43 [112.44, 117.53]	114.78 [112.26, 118.22]	0.973	115.15 [112.02, 118.06]	115.43 [112.44, 117.53]	115.02 [111.99, 119.12]	0.971
Bladder Neck Mobility at Valsalva Maneuver (cm, median [IQR])	1.69 [1.46, 1.94]	2.00 [1.81, 2.21]	1.52 [1.31, 1.72]	<0.001	1.75 [1.46, 2.02]	2.00 [1.81, 2.21]	1.46 [1.28, 1.72]	<0.001
Bladder Wall Lowest Point at Valsalva Maneuver (cm, median [IQR])	2.47 [2.27, 2.66]	2.48 [2.27, 2.71]	2.46 [2.29, 2.66]	0.88	2.46 [2.26, 2.65]	2.48 [2.27, 2.71]	2.45 [2.24, 2.57]	0.347
Bladder Maximum Descension at Valsalva Maneuver (cm, median [IQR])	2.83 [2.59, 3.09]	3.11 [2.88, 3.30]	2.67 [2.49, 2.89]	<0.001	2.91 [2.60, 3.12]	3.11 [2.88, 3.30]	2.63 [2.40, 2.91]	<0.001
Bladder Neck Mobility (Anterior Direction) (cm, median [IQR])	1.23 [1.14, 1.38]	1.24 [1.10, 1.37]	1.23 [1.16, 1.38]	0.516	1.23 [1.13, 1.37]	1.24 [1.10, 1.37]	1.22 [1.15, 1.37]	0.809
Urethral Rotation Angle (Anterior Direction) (deg, median [IQR])	22.62 [19.92, 24.33]	23.54 [20.07, 24.62]	22.48 [19.80, 24.02]	0.28	22.72 [19.66, 24.36]	23.54 [20.07, 24.62]	22.46 [19.55, 24.12]	0.262
Cervix Distance to Pubis at Rest (cm, median [IQR])	2.86 [2.69, 2.97]	2.82 [2.65, 2.95]	2.87 [2.70, 2.99]	0.364	2.84 [2.70, 2.96]	2.82 [2.65, 2.95]	2.88 [2.72, 2.98]	0.428
Cervix Distance to Pubis at Valsalva Maneuver (cm, median [IQR])	3.52 [3.28, 3.67]	3.58 [3.29, 3.74]	3.49 [3.28, 3.62]	0.127	3.54 [3.28, 3.71]	3.58 [3.29, 3.74]	3.52 [3.28, 3.66]	0.352
Cervix Mobility at Valsalva Maneuver (deg, median [IQR])	18.56 [17.08, 19.49]	18.99 [17.10, 19.51]	18.50 [17.10, 19.48]	0.576	18.56 [17.10, 19.42]	18.99 [17.10, 19.51]	18.34 [17.14, 19.36]	0.485
Levator Hiatus Area at Valsalva Maneuver (cm^2, median [IQR])	28.26 [26.47, 30.94]	31.64 [30.30, 33.00]	27.12 [25.84, 28.26]	<0.001	29.07 [26.63, 31.61]	31.64 [30.30, 33.00]	26.86 [25.74, 28.12]	<0.001
Urethral Meatus Dilation at Rest (%)								
No urethral meatus dilation	93 (84.5)	35 (83.3)	58 (85.3)	0.996	71 (84.5)	35 (83.3)	36 (85.7)	1
Presence of urethral meatus dilation	17 (15.5)	7 (16.7)	10 (14.7)		13 (15.5)	7 (16.7)	6 (14.3)	
Anal Fiber Continuity (Ultrasound) (%)								
Disrupted anal fiber continuity	16 (14.5)	5 (11.9)	11 (16.2)	0.735	11 (13.1)	5 (11.9)	6 (14.3)	1

Intact anal fiber continuity	94 (85.5)	37 (88.1)	57 (83.8)		73 (86.9)	37 (88.1)	36 (85.7)	
Levator Sphincter Rupture (%)								
No levator sphincter rupture	98 (89.1)	34 (81.0)	64 (94.1)	0.066	73 (86.9)	34 (81.0)	39 (92.9)	0.196
Presence of levator sphincter rupture	12 (10.9)	8 (19.0)	4 (5.9)		11 (13.1)	8 (19.0)	3 (7.1)	
Levator Hiatus Dilation (%)								
No levator hiatus dilation	98 (89.1)	39 (92.9)	59 (86.8)	0.496	73 (86.9)	39 (92.9)	34 (81.0)	0.196
Presence of levator hiatus dilation	12 (10.9)	3 (7.1)	9 (13.2)		11 (13.1)	3 (7.1)	8 (19.0)	
Cervix Abnormal Echo Type (%)								
No abnormal cervical echo	90 (81.8)	34 (81.0)	56 (82.4)	0.688	69 (82.1)	34 (81.0)	35 (83.3)	1
Mild abnormal cervical echo	19 (17.3)	8 (19.0)	11 (16.2)		15 (17.9)	8 (19.0)	7 (16.7)	

Abbreviations: POP, Pelvic Organ Prolapse; PSM, Propensity Score Matching; BMI, Body Mass Index; IQR, Interquartile Range; cm, Centimeter; kg/m^2, Kilogram per square meter; mL, Milliliter; cm^2, Square centimeter.

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Variable Selection via Correlation Analysis and LASSO Regression

Correlation analysis was conducted on key pelvic floor variables to investigate linear associations. The heatmap (as depicted in Figure 2A) illustrated varying degrees of correlation strength among the indicators, with no evidence of extreme multicollinearity. To identify predictors for POP, LASSO regression with 10-fold cross-validation was employed. The cross-validation error curve (shown in Figure 2B) facilitated the determination of the optimal regularization parameter ($\lambda_{\min}$) and the parsimony parameter (λ_{1se}, where the standard error of λ is within 1 of $\lambda_{\min}$). Ultimately, seven key variables associated with POP were selected. The standardized coefficients of these seven variables in the $\lambda_{\min}$ model (illustrated in Figure 2C) were all positive, indicating a positive correlation with POP and its potential as a risk factor. The variable importance ranking based on absolute standardized coefficient values (as shown in Figure 2D) revealed that the levator hiatus area during the Valsalva maneuver and the cervical-to-pubic distance during the Valsalva maneuver were the most significant contributors. These findings demonstrate that LASSO regression effectively reduced dimensionality and identified the most critical variables for POP, thereby supporting subsequent model development.

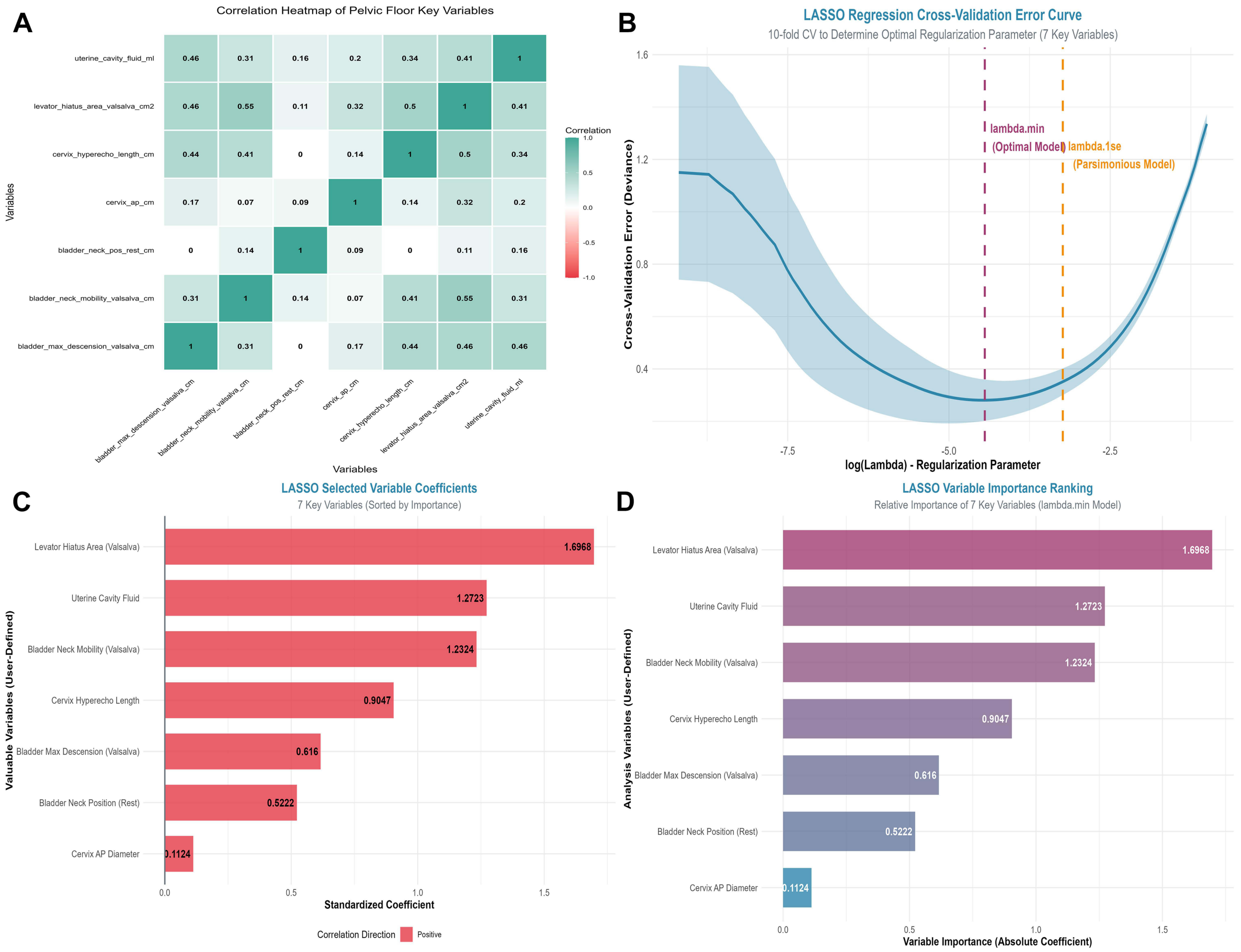

Figure 2 Correlation Analysis, LASSO Regression Cross-Validation, and Variable Importance Ranking of Key Pelvic Floor Variables.

Notes: (**A**) Correlation heatmap of key pelvic floor variables. It shows pairwise correlation magnitude/direction; color intensity (linked to correlation values) indicates linear association strength. (**B**) LASSO 10-fold cross-validation (CV) error curve for optimal regularization parameter (7 key variables). Marks $\lambda_{\min}$ (optimal, minimizes CV error) and λ_{1se} (parsimonious, within 1 SE of $\lambda_{\min}$). X-axis: log-transformed λ; Y-axis: CV error. (**C**) Standardized coefficients of 7 LASSO-selected variables ($\lambda_{\min}$ model). Variables sorted by importance (positive correlation direction noted). Y-axis: coefficients (reflect variable contribution to the model). (**D**) Importance ranking of 7 key variables ($\lambda_{\min}$ model). Importance = absolute value of LASSO standardized coefficients. X-axis: importance score; variables ordered by descending importance.

Predictive Performance of the POP_Index for Pelvic Organ Prolapse

The POP\U index is constructed using seven variables selected by LASSO, demonstrating excellent predictive performance for POP. The AUC of the ROC curve (as depicted in Figure 3A) was 0.94. At an optimal threshold of 1456.3, the model achieved a sensitivity of 0.88 and a specificity of 0.88, reflecting its high accuracy in identifying POP patients. DCA (as shown in Figure 3B) indicates that the POP\U index provides a positive net benefit across a broad range of threshold probabilities, outperforming the "treat all" or "no treat" strategies commonly employed in clinical decision-making. For imbalanced datasets (with fewer POP cases), the PRC (as illustrated in Figure 3C) exhibits a PR-AUC of 0.23, suggesting that the model can accurately identify true positive POP cases among predicted positives. PCA (as shown in Figure 3D) reveals that the first two components (PC1: 34.4% variance; PC2: 16.5% variance) clearly distinguish between POP and non-POP sample clusters. To further investigate the clinical relevance of the POP\U index, we analyzed its correlation with the severity of POP symptoms as assessed by the POP-Q staging system (the clinical gold standard for evaluating POP severity). Correlation analysis demonstrates a significant positive correlation between the POP\U index score and the POP-Q stage ($r = 0.78$, $P < 0.001$), indicating that the POP\U index score is positively associated with the severity of POP symptoms. Stratified analysis reveals that the mean POP\U index score for patients with mild POP (POP-Q stages I–II) is 1289.5 ± 102.3, for those with moderate POP (POP-Q stage III) is 1567.8 ± 115.6, and for those with severe POP (POP-Q stage IV) is 1892.4 ± 131.2. Post hoc pairwise comparisons confirm significant differences in POP\U index scores between each POP-Q stage (all $P < 0.05$), suggesting that the POP\U index

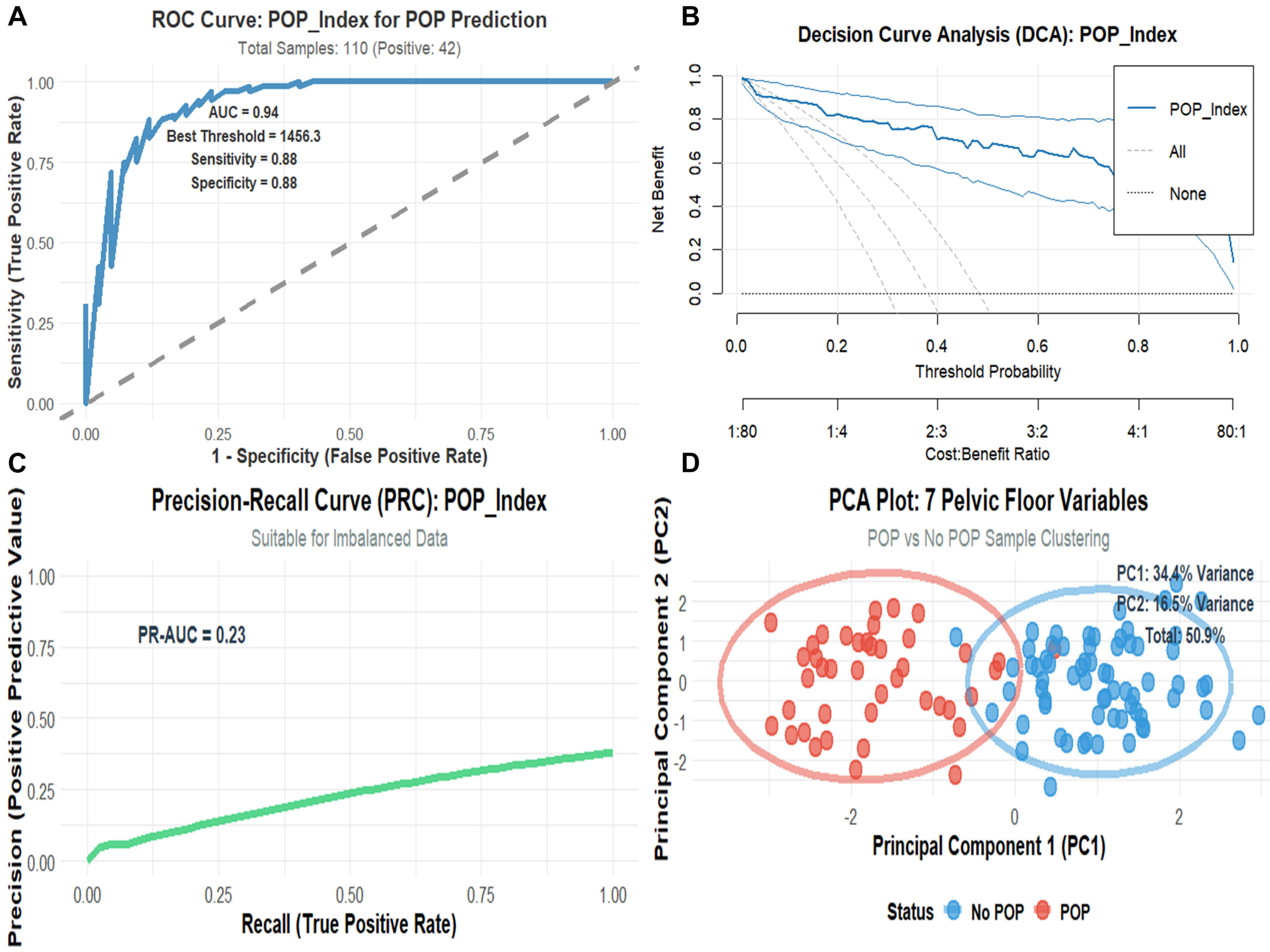

Figure 3 POP_Index for Pelvic Organ Prolapse (POP) Prediction with ROC Curve, Decision Curve Analysis, Precision-Recall Curve and Principal Component Analysis Plot.
Notes: (**A**) ROC curve of POP_Index for POP prediction, with AUC=0.94, best threshold=1456.3, sensitivity=0.88 and specificity=0.88. (**B**) Decision curve analysis (DCA) of POP_Index, showing net benefit across different threshold probabilities. (**C**) Precision-Recall Curve (PRC) of POP_Index (suitable for imbalanced data) with PR-AUC =0.23. (**D**) PCA plot of 7 pelvic floor variables (PC1 explains 34.4% variance, PC2 explains 16.5% variance) demonstrating clustering of POP and No POP samples.

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can effectively reflect the severity of POP symptoms and provide an objective quantitative metric for assessing POP severity. In summary, these findings confirm that the POP\U index exhibits robust predictive performance and can effectively differentiate between POP patients and non-POP patients.

Ultrasound Imaging Features and Clinical Impact of the POP Prediction Model

Pelvic floor ultrasonography offers detailed morphological and functional insights into POP. Color Doppler ultrasound, as depicted in Figure 4A, visualizes the pelvic floor anatomy and blood flow, thereby establishing a foundation for evaluating POP-related characteristics. Three-dimensional (3D) pelvic ultrasound, shown in Figure 4B, captures three functional states of the pelvic floor (open, closed, and closing), dynamically reflecting structural changes in pelvic organs during physiological maneuvers. Continuous multi-frame 3D ultrasound, illustrated in Figure 4C, quantifies pelvic structural displacement, revealing a maximum bladder descent of −10.4 mm in POP participants, a value consistent with the ultrasound indicators presented in Table 1. The clinical impact curve (CIC), depicted in Figure 4D, correlates the risk threshold with the proportion of high-risk patients and the true positive rate, facilitating POP risk stratification in real-world settings. These findings demonstrate that pelvic floor ultrasound provides comprehensive evidence for POP assessment and, when integrated with the POP-Q index, serves as a practical tool for the clinical management of POP.

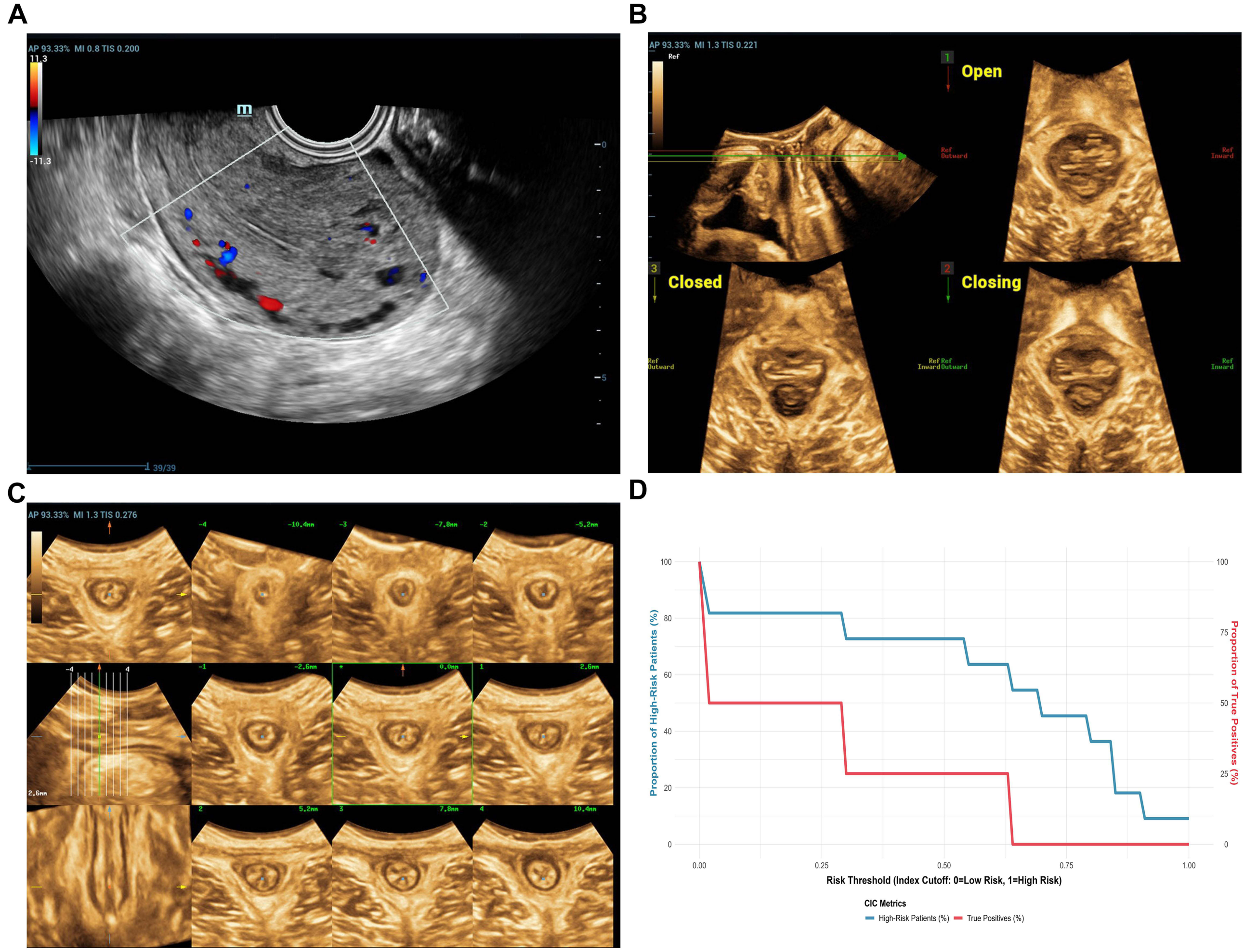

Figure 4 Ultrasound Evaluation and Clinical Impact Curve for Pelvic Organ Prolapse (POP) Clinical Prediction.

Notes: (**A**) Pelvic ultrasound (with color Doppler) showing pelvic floor anatomy and blood flow signals. It provides morphological/hemodynamic views, foundational for assessing POP-related features. (**B**) 3D pelvic ultrasound views showing three pelvic floor functional states (Open, Closing, Closed). They capture dynamic pelvic organ structural changes, key for POP evaluation. (**C**) Serial multi-frame 3D ultrasound demonstrating pelvic structure displacement and positional variation. This sequence quantifies organ mobility, a critical parameter for grading POP severity. (**D**) The Clinical Impact Curve (CIC) for Pelvic Floor Outcome is a plot linking risk thresholds to high-risk patient proportion and true positives. It supports POP risk stratification in real-world cohorts.

Discussion

POP is a highly prevalent pelvic floor dysfunction among women, and its adverse effects on physical health and quality of life impose a significant burden on individuals and healthcare systems globally.[16,17] As previously discussed, traditional POP assessment tools, such as the POP-Q system, heavily rely on the examiner's subjective judgment and are incapable of quantifying deep pelvic pathological changes. Although magnetic resonance imaging (MRI) offers high-resolution static anatomical images, it is costly and fails to capture the dynamic changes of the pelvis during maneuvers like the Valsalva maneuver.[18,19] Pelvic floor ultrasound, characterized by its non-invasive nature, cost-effectiveness, and capability for real-time dynamic imaging, exhibits significant potential in the assessment of POP. However, few prior studies have systematically integrated it with clinical parameters and machine learning techniques to enhance the assessment and prediction of POP.[20,21] The innovation of this study resides in the systematic integration of three pivotal factors to enhance the assessment and prediction of POP: Firstly, we employed PSM to effectively eliminate confounding variables such as age and BMI, thereby ensuring that the disparities in ultrasound indicators between the POP and non-POP groups are genuinely attributable to the pathogenesis of POP, rather than baseline characteristics. Secondly, we utilized LASSO regression to identify key pelvic floor ultrasound indicators, thereby preventing overfitting and ensuring the rationality of the predictive model. Thirdly, we developed a high-performance POP\U index prediction model with an AUC of 0.94, providing an objective, dynamic, and precise tool for POP risk stratification and addressing the limitations of single-indicator predictions observed in previous studies. This novel clinical approach to ultrasound measurement also holds promise for predicting the progression of POP in young women, offering new avenues for early intervention.

A major strength of this study lies in its use of PSM to rigorously control for confounding factors, addressing a common limitation observed in previous studies related to POP. Most prior research compared POP and non-POP groups without adequately balancing baseline characteristics, which are recognized as influential factors on pelvic floor function.[22,23] This imbalance makes it challenging for these studies to ascertain whether the observed differences in ultrasound indicators are independently associated with POP. In contrast, this study performed a 1:1 PSM based on age. Even after matching, the POP group exhibited a significantly larger levator hiatus area (31.64 cm^2 vs 26.86 cm^2, $P < 0.001$), greater bladder neck mobility (2.00 cm vs 1.46 cm, $P < 0.001$), and a higher rectal bulge rate (59.5% vs 0%, $P < 0.001$) during the Valsalva maneuver compared to the non-POP group. These findings confirm that these ultrasound and clinical indicators are influenced not only by demographic factors but are also genuinely related to the pathogenesis of POP, offering more reliable evidence for their use as POP-related markers than earlier studies that lacked effective confounding control.

Another pivotal innovation in this study is the development of the POP index, a multidimensional predictive model constructed utilizing LASSO regression and validated through multiple metrics. Previous studies predominantly relied on a single ultrasound parameter (eg, levator hiatus area or bladder neck descent) for POP prediction, yielding limited accuracy with AUC values typically below 085.[24–27] In this study, LASSO regression effectively reduced dimensionality and identified seven key variables that integrate clinical parameters such as age and BMI with ultrasound indicators like levator hiatus area, while mitigating the risk of overfitting. The resultant POP index demonstrated an AUC of 0.94, along with sensitivity and specificity both reaching 0.88, significantly outperforming single-index models. Furthermore, decision curve analysis revealed that the POP index offered a positive net benefit across a broad range of threshold probabilities, underscoring its clinical utility in guiding intervention decisions. Principal component analysis further corroborated that these seven variables could distinctly differentiate between POP and non-POP samples, highlighting the model's capacity to capture the multifactorial nature of POP.

This study also underscores the clinical significance of dynamic pelvic floor ultrasound assessment, thereby complementing the static emphasis of prior imaging research. The majority of previous MRI-based studies have solely evaluated static pelvic anatomy, whereas the 3D ultrasound employed in this study captured the dynamic alterations in pelvic floor function across three states (open, closed, and closed) during the Valsalva maneuver and quantified organ displacement.[28–30] For instance, the maximum bladder descent among POP participants reached −10.4 mm. This dynamic assessment aligns with the pathophysiology of POP, wherein pelvic support weakening is most pronounced with increased abdominal pressure, and offers more actionable insights for clinical practice. This aids clinicians in identifying high-risk patients with severe POP. Furthermore, a detailed analysis of the anterior, middle, and posterior pelvic indices facilitates targeted evaluation of distinct pelvic compartments, thereby addressing the necessity for compartment-specific assessment, which has often been overlooked in earlier ultrasound studies.

This study harbors certain inevitable limitations. Firstly, it employed a retrospective design with a relatively small sample size (initially comprising 110 participants, reduced to 84 after PSM), which may constrain the generalizability of the findings to a broader and more diverse population, such as women from different ethnic or geographical backgrounds. Given the study design, the results should be interpreted with caution. Future research should involve prospective multicenter studies with larger sample sizes to further validate the stability and generalizability of the study findings and the POP\U index model. Secondly, the analysis did not account for certain potential confounding factors, such as lifestyle habits (eg, physical exercise levels) or hormonal status, which could influence pelvic floor muscle function and the risk of POP Thirdly, the absence of long-term follow-up data in this study precludes verification of whether the POP index can predict POP progression or postoperative recurrence, a critical outcome for guiding long-term clinical management.

Conclusion

In conclusion, this study indicates that the integration of pelvic floor ultrasound with propensity score matching and machine learning offers a robust approach for the assessment and prediction of POP. The identification of crucial ultrasound indicators, including the levator hiatus area and the distance from the cervix to the pubic symphysis during the Valsalva maneuver, along with the development of a high-performance POP index (AUC=0.94), have overcome the limitations of traditional assessment tools and single-index models. These findings not only provide objective and dynamic evidence for POP diagnosis but also offer practical tools for risk stratification and personalized interventions, such as targeted pelvic floor muscle training or optimized surgical timing. Ultimately, this study enhances the evidence base for pelvic floor health management and supports the wider adoption of pelvic floor ultrasound in primary care screening for POP.

Data Sharing Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics Approval and Consent to Participate

This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Enshi Tujia and Miao Autonomous Prefecture Central Hospital (Approval No. 2025-173-01). Written informed consent was obtained from all individual participants included in the study.

Consent for Publication

Written informed consent for publication of identifying information/images in an online open-access publication was obtained from all participants.

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Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors declare that they have no conflicts of interest for this work.

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