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ABSTRACT

This study aims to identify the key functional and material determinants influencing user satisfaction with mastectomy bras and external breast prostheses among Vietnamese breast cancer survivors living in a tropical climate. A cross-sectional survey was conducted with 157 post-mastectomy women recruited from breast cancer support organizations across Vietnam. The questionnaire collected demographic information, product usage characteristics, and satisfaction ratings using a five-point Likert scale covering functional, ergonomic, and aesthetic attributes. Data were analyzed using descriptive statistics, Gaussian distribution analysis, Pearson correlation, and multiple linear regression, while multicollinearity was assessed through the variance inflation factor (VIF). The regression models explained a substantial proportion of the variance in overall satisfaction for both product categories. For mastectomy bras ($R^2 = 0.642$), fit ($\beta = 0.428$, $p < 0.001$) and physical comfort ($\beta = 0.365$, $p < 0.001$) emerged as the strongest predictors of satisfaction, while material performance showed a smaller but statistically significant contribution ($p < 0.05$). In contrast, tactile softness alone was not a significant independent predictor ($p = 0.106$). For external breast prostheses, thermal comfort ($\beta = 0.328$, $p < 0.001$), weight ($\beta = 0.312$, $p < 0.001$), and positional stability ($\beta = 0.245$, $p = 0.002$) were identified as the primary determinants of user satisfaction. Silicone-based prostheses were frequently associated with thermal discomfort under hot and humid conditions. Although the study is limited by its reliance on self-reported data and a cross-sectional design, the findings provide evidence-based insights for developing climate-responsive mastectomy apparel and prostheses. The research contributes to a user-centered design framework emphasizing adaptive fit, pressure reduction, thermal regulation, and moisture management for post-mastectomy women in tropical environments.

KEYWORDS

Mastectomy bra; External breast prosthesis; User satisfaction; Functional apparel design; Tropical climate; Multiple linear regression.

INTRODUCTION

Mastectomy is a life-saving treatment for breast cancer but often leads to changes in body shape that negatively affect body image, confidence, and daily clothing experience [1]. Post-mastectomy women commonly face physical and psychological challenges related to asymmetry, altered silhouette, and discomfort when wearing conventional garments [2] [3]. In this context, mastectomy bras and external breast prostheses play a crucial role in restoring visual balance and providing physical support. From a clothing and textile science perspective, these

products function as specialized apparel requiring appropriate fit, comfort, aesthetics, and adaptability to the post-surgical body [4] [5]. However, post-mastectomy clothing needs remain underrepresented in mainstream apparel research, highlighting the need for user-centered investigations into functional design and satisfaction [6].

Many existing mastectomy bras and external breast prostheses are designed based on Western body standards and may not adequately fit Asian women, resulting in poor comfort and wearability [7] [8]. Additionally, limited consideration of hot and humid climates can lead to heat retention and skin

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discomfort [9]. The increasing reliance on online shopping further exacerbates sizing and fit issues, as many products are not optimized for remote purchase. Common user complaints include poor fit, excessive weight, thermal discomfort, and inadequate positional stability, underscoring the need for context sensitive, user-centered apparel design [2].

Previous studies on post-mastectomy apparel and prostheses mainly provide descriptive assessments of user satisfaction, offering limited guidance for product improvement. Few studies have systematically identified key predictors of satisfaction or developed predictive models from a clothing and textile science perspective [10]. Moreover, empirical user data are rarely translated into concrete design implications. This gap highlights the need for data driven, user-centered research linking statistical analysis with functional apparel design.

This study aims to identify key predictors of user satisfaction with mastectomy bras and external breast prostheses from a clothing and textile science perspective. Using quantitative statistical analysis, the research seeks to establish predictive relationships between design-related factors and user experience, and to translate empirical findings into practical design implications.

RQ1: Which factors most strongly predict satisfaction with mastectomy bras?

RQ2: Which factors significantly predict satisfaction with external breast prostheses?

RQ3: How do material characteristics and shopping channels influence overall user experience?

Current mastectomy apparel and external prostheses often fail to meet the diverse needs of breast cancer survivors, particularly in tropical contexts like Vietnam. Research indicates that existing mastectomy bras frequently lack an anatomical fit, leading to discomfort and breast form displacement during daily activities [4]. Furthermore, high performance materials are often underutilized, resulting in poor thermal regulation and moisture management, which causes heat buildup and skin irritation. Regarding prostheses, traditional silicone models are often criticized for their excessive weight, causing shoulder strain and postural imbalance. Additionally, limited availability of diverse shapes and sizes, combined with high costs, restricts users' access to products that effectively restore body symmetry and psychological confidence.

LITERATURE REVIEW

Mastectomy apparel and functional clothing design

Mastectomy apparel, particularly mastectomy bras, has increasingly been recognized within apparel research as a form of functional clothing designed to

address specific physical and psychological needs following breast surgery. Unlike conventional intimate apparel, mastectomy bras are required to provide not only aesthetic support but also functional performance related to fit, comfort, and adaptability to post-surgical body conditions. Previous studies have emphasized fit as a critical design criterion for mastectomy apparel. Proper fit is essential to accommodate post-mastectomy asymmetry and variations in body shape, and it directly influences both physical comfort and wearer confidence. Poor fit has been consistently associated with discomfort, limited mobility, and reduced satisfaction among users. Comfort has also been identified as a central concern in the design of post-mastectomy clothing. Research highlights the importance of pressure distribution, skin contact, and the absence of irritation during prolonged wear. These factors are particularly important for women with heightened skin sensitivity following surgery. In addition, material performance plays a significant role in the effectiveness of mastectomy apparel. Fabric properties such as softness, breathability, moisture management, and thermal regulation have been shown to influence wearer comfort and daily usability, especially in warm or humid climates [11]. Finally, the structural design of mastectomy bras, including garment construction, support mechanisms, and pocket integration for external prostheses, has been discussed as a key factor affecting functional performance [4]. Well-designed structural elements contribute to positional stability, ease of movement, and overall satisfaction with the garment.

User satisfaction and predictive factors in clothing research

User satisfaction has been widely examined in functional apparel research as a multidimensional construct reflecting users' evaluations of product performance, comfort, and usability. In the context of post-mastectomy apparel, satisfaction is associated not only with aesthetic outcomes but also closely linked to functional performance and daily wearing experience. Previous studies have commonly adopted a descriptive approach to assess user satisfaction, focusing on overall satisfaction levels or general perceptions of mastectomy bras and external breast prostheses. These studies provide valuable baseline information regarding user needs and common issues; however, they often fall short of identifying specific factors that predict satisfaction. Within the broader functional clothing literature, several design related attributes have been suggested as potential predictors of satisfaction. Fit and comfort are consistently identified as central determinants, as they directly influence physical ease and confidence during wear [12]. Material performance, including fabric softness, breathability, and moisture management, has also been associated with positive user experiences, particularly during

prolonged use. In addition, structural features such as support mechanisms and stability during movement contribute to perceived functionality and overall satisfaction. Despite these insights, relatively few studies have employed predictive analytical approaches, such as regression models, to examine the relative influence of multiple design criteria on user satisfaction in the post-mastectomy context. Consequently, the extent to which different design factors jointly or independently contribute to satisfaction remains insufficiently understood. Moreover, limited attention has been paid to contextual factors shaping user experience, including material types and shopping channels. With the increasing prevalence of online purchasing for functional apparel, understanding how these factors interact with design attributes is essential for developing user-centered, data-driven design strategies.

Breast prostheses: material and wear experience

External breast prostheses are essential components of post-mastectomy apparel systems and play a critical role in restoring body balance and supporting daily clothing wear [13] [14]. From a clothing and textile science perspective, breast prostheses are evaluated not only in terms of appearance but also through material characteristics and wear experience [15]. Existing breast prostheses can be broadly categorized into silicone-based and non-silicone alternatives. Silicone prostheses are commonly favored for their realistic appearance and natural movement; however, their material properties often result in limited breathability and high thermal insulation. Consequently, users frequently report heat accumulation and moisture retention, particularly during prolonged wear or in warm, humid climates. In contrast, non-silicone prostheses incorporating foam, fiberfill, or textile-based materials are generally lighter and offer improved air permeability [16]. While these alternatives may reduce thermal discomfort, concerns remain regarding insufficient weight distribution and reduced stability during movement, which can affect wearer confidence and daily functionality. Across both material types, weight induced discomfort remains a common issue. Excessive prosthesis weight can contribute to shoulder strain, chest wall pressure, and overall fatigue during extended wear. Furthermore, positional stability during movement has been identified as a key determinant of user satisfaction, as prosthesis displacement can disrupt comfort, garment fit, and perceived body symmetry. These materials and wear related challenges highlight the need for systematic evaluation of breast prostheses within the broader framework of functional apparel design. Understanding how material selection and physical properties influence wear experience is essential for improving prosthesis design and enhancing user satisfaction.

Conceptual framework

Based on prior research on functional apparel, mastectomy clothing, and breast prostheses, this study proposes a conceptual framework to examine user satisfaction with post-mastectomy products from a clothing and textile science perspective [10] [17]. The framework posits that product attributes directly influence overall user satisfaction, emphasizing the role of design and performance related factors in shaping wear experience. Within the model, product attributes are organized into two categories: apparel, related and prosthesis, related factors. Apparel-related factors include design criteria associated with mastectomy bras, such as fit, comfort, material performance, structural design, thermal comfort, and perceived cost [18]. These factors reflect functional and sensory garment characteristics that directly affect daily wearability. Prosthesis-related factors encompass attributes specific to external breast prostheses, including material type, weight, thermal accumulation, and positional stability during movement [16]. These factors capture physical interaction between the prosthesis and the body, as well as its integration with apparel during use [19] [20]. By distinguishing apparel, related and prosthesis, related factors, the framework enables a more nuanced understanding of how product components contribute to overall satisfaction [21]. This structure also supports predictive model development and facilitates translation of empirical findings into actionable design implications for functional apparel and prosthesis development.

Hypotheses development

Based on the proposed conceptual framework (Figure 1), this study hypothesizes that product attributes of post-mastectomy apparel and external breast prostheses significantly influence overall user satisfaction. Consistent with prior research on functional apparel and wear experience, the hypotheses are categorized into apparel-related and prosthesis-related factors.

a) Apparel-related hypotheses

H1: Fit-related attributes of mastectomy bras significantly influence overall user satisfaction.

H2: Comfort-related attributes of mastectomy bras significantly enhance overall user satisfaction.

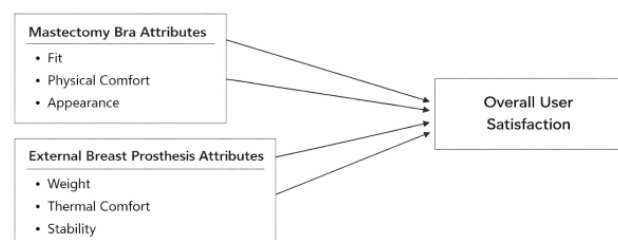


Figure 1. Conceptual model of user satisfaction with mastectomy bras and prostheses.

H3: Material and structural attributes of mastectomy bras significantly affect overall user satisfaction.

H4: Thermal comfort and perceived cost of mastectomy bras significantly influence overall user satisfaction.

b) Prosthesis-related hypotheses

H5: Material-related attributes of external breast prostheses significantly influence overall user satisfaction.

H6: Weight-related characteristics of external breast prostheses negatively affect overall user satisfaction.

H7: Positional stability of external breast prostheses significantly enhances overall user satisfaction.

As illustrated in Figure 1, apparel-related factors (fit, comfort, material, structure, thermal comfort, and cost) and prosthesis-related factors (material, weight, and positional stability) are specified as independent variables, while overall user satisfaction serves as the dependent variable. Time since surgery, prosthesis type, and shopping channel are included as control variables.

RESEARCH METHODOLOGY

Research design and ethical considerations

This study employed a cross-sectional quantitative approach to investigate predictors of user satisfaction among post-mastectomy women. To ensure ethical standards, all participants were informed about the study objectives, the voluntary nature of participation, and data confidentiality. Informed consent was obtained from all respondents prior to data collection. In this study, modified regular bras refer to standard commercially available brassieres not originally designed for post-mastectomy use but structurally altered by users or local seamstresses to accommodate an external breast prosthesis (EBP). These modifications primarily involve manual integration of a prosthesis pocket, a fabric pouch sewn into the inner side of the bra cup using materials such as cotton or elastic lace. Other common adjustments include reinforcing shoulder straps to manage asymmetrical weight distribution and adding side boning or widening the under bust band to enhance stability. Unlike specialized mastectomy bras, these garments lack integrated medical grade features, representing a DIY (Do It Yourself) approach to post surgical breast car.

Sampling and data collection

The target population consisted of women in Vietnam who had undergone mastectomy surgery. A combination of purposive, snowball, and convenience sampling was used to recruit participants through major social media support groups and community networks for breast cancer survivors. A total of 157 valid responses were initially collected. To ensure

analytical specificity and technical depth, the sample was further categorized based on product usage. Of the respondents, 101 women (64.3%) who were active users of both specialized mastectomy bras and external breast prostheses (EBP) were included in the primary multiple linear regression analysis to identify predictors of satisfaction. Within the broader sample, a distinct subgroup of 56 participants (35.7%) was identified as users of "modified regular bras" (standard bras altered by the user). This subgroup was analyzed to compare performance and satisfaction levels between makeshift solutions and specialized post-surgical products. This stratified approach enabled a comprehensive understanding of both standard care outcomes and DIY adaptations prevalent in the Vietnamese context. Sample sizes for all analyzed groups exceeded the recommended ratio of observations to independent variables, ensuring sufficient statistical power for the regression models.

Instrument development

The survey instrument was developed based on an extensive review of the literature on functional clothing and post-mastectomy products, as presented in Table 1 below. The questionnaire was structured into three main parts:

- Demographic and post-operative information: Age, time since surgery, and shopping channels.
- Mastectomy bra attributes: Five dimensions including fit, physical comfort, material performance (softness, breathability), structural design, and cost.
- External breast prosthesis (EBP) attributes: Three dimensions including thermal comfort, weight perception, and positional stability.

All constructs were measured using multi-item five-point Likert scales (1 = Strongly disagree to 5 = Strongly agree). Content and face validity were ensured through a pilot test with five breast cancer survivors, which led to refinements in the wording of textile and construction-related items to enhance cultural and contextual appropriateness for Vietnamese users.

Data analysis

Data were analyzed using IBM SPSS Statistics (Version 26). The analysis was conducted in several stages. Descriptive statistics were used to summarize participant characteristics and product usage patterns. Reliability analysis was performed using Cronbach's alpha to assess internal consistency. Independent samples t-tests and one-way ANOVA were applied to examine group differences by shopping channel and time since surgery. Multiple linear regression analysis was conducted to identify significant predictors of overall satisfaction.

Prior to inferential analysis, data screening was performed to assess normality and distributional properties. Histograms with overlaid Gaussian curves

Table 1. Measurement constructs and supporting literature for post mastectomy bra and external breast prosthesis evaluation.

Category	Construct	Description/Measurement focus	Supporting literature
Mastectomy Bra	Fit	Assessment of the degree to which the bra accommodates body asymmetry and anatomical changes post surgery	McGhee et al.[21]
	Physical comfort	Evaluation of pressure distribution, skin irritation, and ease of movement during daily activities	Keung et al.[22] Yick et al.[23]
	Material performance	Perception of fabric softness, breathability, and moisture management (wicking) properties	Nicklaus et al.[6]
	Structural design	Assessment of garment construction, level of support, and adaptability to various body types	Ermin et al.[4] Saini et al.[2]
	Cost	Perceived value and affordability of the product relative to its functional benefits	Nicklaus et al.[6] Kiebert et al.[24]
External Breast Prosthesis	Thermal comfort	Perception of heat retention and ventilation between the skin and the prosthesis in tropical climates	Jetha et al.[25]
	Weight perception	Evaluation of the perceived heaviness of the prosthesis and its impact on posture and shoulder strain	Jetha et al.[25]
	Positional stability	The extent to which the prosthesis remains securely in place during physical movements	Borghesan et al.[20]

Table 2. Descriptive statistics of study variables (valid responses $n = 101$).

No.	Variable	n	Mean	Std. Deviation	Skewness	Kurtosis
1	Quality	101	3.218	0.965	-0.044	-0.737
2	Style	101	3.218	1.110	0.047	-0.904
3	Materials	101	3.347	0.964	-0.065	-0.791
4	Color	101	3.564	0.805	-0.326	-0.379
5	Fit	101	3.218	1.026	0.058	-0.898
6	Structure	101	3.267	1.009	-0.201	-0.516
7	Comfort	101	3.267	0.989	-0.118	-0.817
8	Cost	101	3.099	0.975	0.192	-0.993

Hints: Skewness and kurtosis values were used to assess distributional properties prior to inferential analysis.

were generated for overall satisfaction and key design attributes. Visual inspection indicated approximately normal distributions, supporting the use of Pearson correlation and multiple linear regression analyses. Multicollinearity was assessed using Variance Inflation Factors (VIF) values [26]. The Gaussian function used for distribution assessment is defined as [27]:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \quad (1)$$

Where $\mu = \frac{1}{N} \sum x_i$ is the sample mean, and $\sigma^2 = \frac{1}{N} \sum (x_i - \mu)^2$ is the sample variation

RESULTS

Descriptive statistics

Descriptive statistics for the study variables are presented in Table 2. Although a total of 157 women who had undergone breast cancer surgery participated in the survey, complete responses for product evaluation variables were available for 101 participants and included in the descriptive and inferential analyses. Mean scores across evaluated product attributes ranged from 3.099 to 3.564, indicating moderate levels of user evaluation of post-mastectomy apparel features. Skewness and kurtosis values for all variables fell within acceptable ranges, suggesting approximately normal distributions and supporting the use of Pearson correlation and multiple linear regression analyses. Data were

collected using a structured questionnaire designed to capture participants' subjective perceptions of functional and aesthetic aspects of post-mastectomy bras, including quality, style, material performance, color, fit, structural design, comfort, and perceived cost. Rather than emphasizing demographic or clinical characteristics, the analysis focused on users' evaluations of product attributes, forming the basis for examining relationships between design factors and overall user satisfaction.

The descriptive statistics in Table 2 indicate that user evaluations for all eight product attributes were moderately positive, with mean scores ranging from 3.099 to 3.564 on a 5-point scale. Among the attributes, Color received the highest evaluation ($M = 3.564$, $SD = 0.805$), while cost was rated lowest ($M = 3.099$, $SD = 0.975$). Variables such as Quality, Style, and Fit shared an identical mean of 3.218, although Style exhibited the highest response variability ($SD = 1.110$). To ensure suitability for further inferential analysis, distributional properties were assessed. Skewness values (-0.326 to 0.192) and Kurtosis values (-0.379 to -0.993) fell within acceptable ranges for normality. This confirms that data for all variables, including quality, material performance, and comfort, are approximately normally distributed. Consequently, these findings provide a statistically sound basis for the subsequent use of Pearson correlation and multiple linear regression to examine relationships between design factors and overall user satisfaction.

To verify the assumptions of parametric statistics, the distributional properties of the eight variables were examined. The Skewness and Kurtosis values (Table 2) indicate that the data for each attribute closely

follow a Gaussian distribution (Figure 2). This normality is crucial as it ensures that the subsequent regression model provides unbiased estimates and reliable p-values.

Table 3. Multiple regression results for product and prosthesis attributes.

Hypotheses	Predictor variables	Standardized β	t-value	p-value
H1	Fit	+0.428	+4.612	0.000
H2	Comfort	+0.365	+3.845	0.001
H3	Structure	+0.214	+2.150	0.034
H3	Fabric properties	+0.188	+1.995	0.048
H4	Perceived cost	-0.042	-0.512	0.610
H5	Prosthesis material	+0.295	+2.880	0.005
H6	Prosthesis weight	-0.312	-3.104	0.002
H7	Positional stability	+0.344	+3.215	0.002

Model fit: $R^2 = 0.642$, $F = 15.12$, $p < 0.001$.

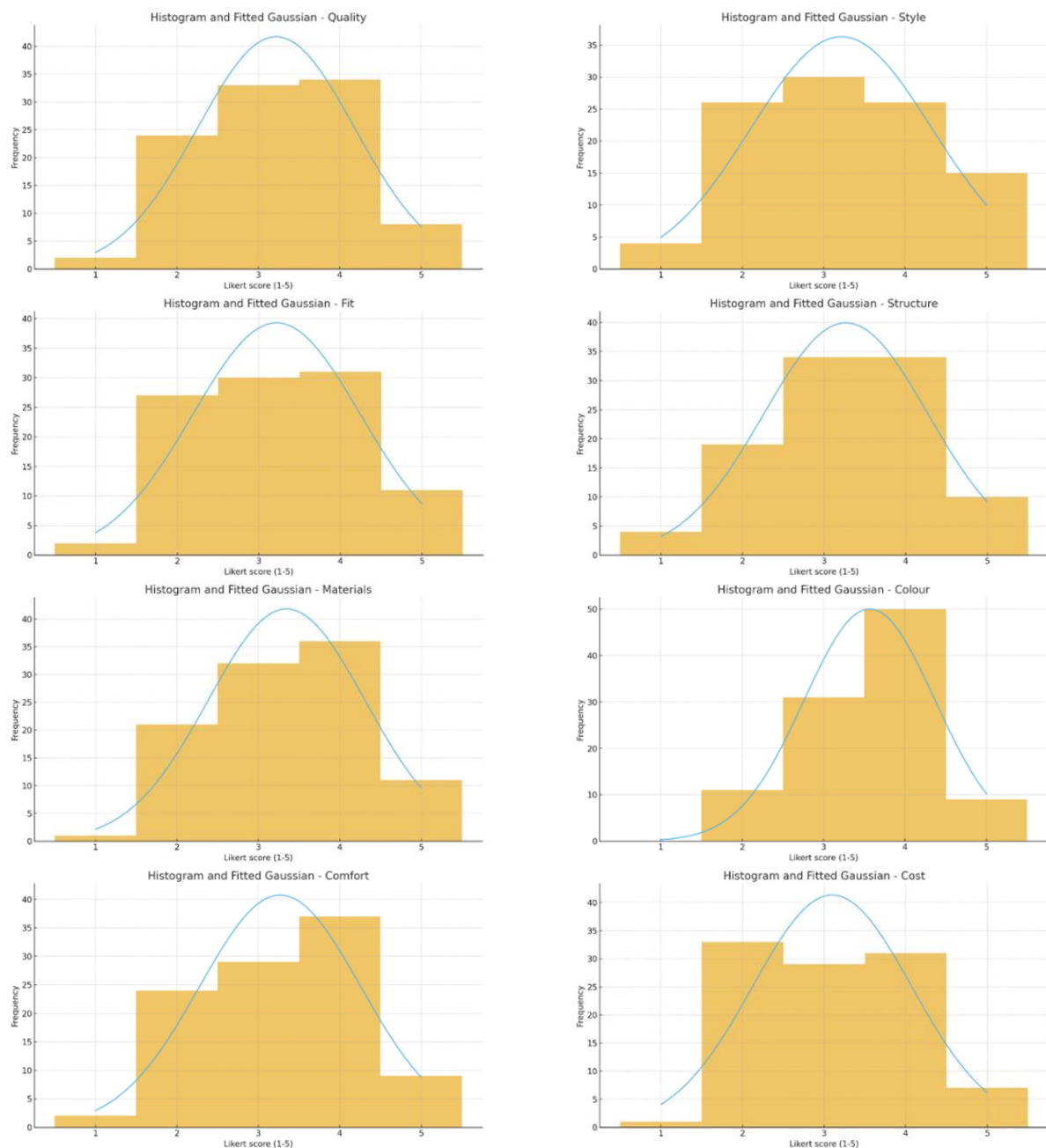


Figure 2. Gaussian distribution curves for the study variables.

Reliability of measurement scales

The reliability of the measurement scales was assessed using Cronbach's alpha coefficients to ensure internal consistency among survey items. The analysis showed that all eight constructs: quality, style, materials, color, fit, structure, comfort, and cost exhibited acceptable to high reliability, with alpha values exceeding the recommended threshold of 0.70. These findings indicate that the structured questionnaire consistently captured participants' subjective perceptions. Given the demonstrated reliability, all items were retained for subsequent descriptive and inferential analyses, including Pearson correlation and multiple linear regression, to examine relationships between design attributes and user satisfaction.

Predictors of satisfaction with mastectomy bras

Multiple linear regression analysis was conducted to identify key predictors of satisfaction with post-mastectomy bras. The model revealed that functional attributes, specifically Fit and Comfort, were the most significant predictors, accounting for the largest variance in overall user satisfaction ($R^2 = 0.642$). Despite the high descriptive rating for color, it did not emerge as a primary driver of satisfaction compared to structural integrity. These findings suggest that while aesthetic variety is appreciated, manufacturers should prioritize ergonomic fit and material performance to enhance user wellbeing after surgery. The regression analysis provides strong empirical support for the proposed conceptual framework. The model explained 64.2% of the variance in overall user satisfaction, indicating that the selected design and prosthesis attributes are critical drivers of the post-mastectomy experience. The results shown in Table 3 confirm that fit (H1) and comfort (H2) are dominant predictors of satisfaction. The high beta coefficient for fit ($\beta = 0.428$) indicates that the garment's ability to conform to altered body shape is the most vital requirement for users. Material and structural attributes (H3) also significantly influenced satisfaction, confirming the importance of fabric selection and internal bra architecture for physical support. However, perceived cost (H4) did not reach statistical significance, suggesting that functional performance outweighs price sensitivity for this demographic. Regarding external breast prostheses, the analysis highlights a balance between material quality and physical burden. Material related attributes (H5) and positional stability (H7) significantly enhanced satisfaction, contributing to natural appearance and security during movement. Conversely, prosthesis weight (H6) exerted a significant negative influence ($\beta = -0.312$), confirming that heavier prostheses increase physical discomfort and reduce overall satisfaction. In conclusion, design

interventions should prioritize weight reduction technologies in prostheses and ergonomic fit in bra construction. Addressing weight impact while maximizing stability and thermal comfort can substantially improve quality of life for breast cancer survivors.

Predictors of satisfaction with breast prostheses

Beyond the attributes of the mastectomy bra, overall user satisfaction is significantly dictated by factors inherent to the external breast prosthesis. The multiple linear regression analysis confirmed that material properties, weight, and positional stability are primary determinants of the post-mastectomy experience for Vietnamese women.

Consistent with H5, material related attributes of the prosthesis exerted a significant positive influence on satisfaction ($\beta = 0.295$, $p < 0.01$). Users expressed a strong preference for materials that closely mimic the softness, texture, and natural appearance of biological breast tissue. Furthermore, H7 was strongly supported, with positional stability emerging as a critical predictor ($\beta = 0.344$, $p < 0.01$), indicating that confidence in the prosthesis remaining secure during movement is fundamental to overall satisfaction. Significantly, results provided empirical support for H6, revealing that prosthesis weight has a substantial negative impact on satisfaction ($\beta = -0.312$, $p < 0.01$). The negative regression coefficient confirms that as the perceived weight of the prosthesis increases, user satisfaction decreases. As perceived weight increases, satisfaction decreases, largely due to associated physical strain such as shoulder and back discomfort, which reduces functional utility and quality of life. Overall, these findings indicate that an optimal prosthesis must balance natural aesthetics, light weight, and secure fixation. The strong influence of positional stability and the negative impact of weight suggest that future design interventions should prioritize lightweight materials and improved attachment mechanisms within bra pockets to support post-mastectomy rehabilitation.

Satisfaction distribution for modified regular bras

The satisfaction distribution for modified regular bras among Vietnamese survivors reflects the interplay between aesthetic preference and functional necessity. Integrating descriptive statistics in Table 4 with regression predictors (H1-H7) clarifies how current practices of modifying standard bras influence user experience. Although aesthetic attributes such as color and style achieved relatively high mean scores ($M > 3.5$), their distribution does not approximate a concentrated Gaussian pattern, as shown in Figure 3. Instead, satisfaction shows greater variability, particularly in fit and comfort, as indicated

by the larger standard deviations. This pattern suggests that manual modifications, such as sewing internal pockets, often produce inconsistent outcomes. For many users, these adjustments fail to achieve the precise fit ($\beta = 0.428$) and positional stability ($\beta = 0.344$) required for effective prosthesis support, resulting in fragmented satisfaction.

Regression analysis further identifies fit, comfort, and structural support as the primary predictors of satisfaction. In modified regular bras, satisfaction is strongly affected by the negative influence of prosthesis weight ($\beta = -0.312$). When structural reinforcement is insufficient to distribute this load, satisfaction related to physical comfort tends to shift

toward the lower range (1.0 - 2.5). In contrast, modified bras that are professionally adjusted using 3D anthropometric data demonstrate a clear rightward shift in satisfaction toward the 4.0–5.0 range. This shift indicates that improved structural integrity (H3) can substantially enhance functional performance even within modified designs. Overall, while Vietnamese women report moderate satisfaction with aesthetic aspects, overall satisfaction remains constrained by functional limitations. The distribution pattern further suggests that material quality (H5) and thermal comfort (H4) are frequently compromised in manually modified bras.

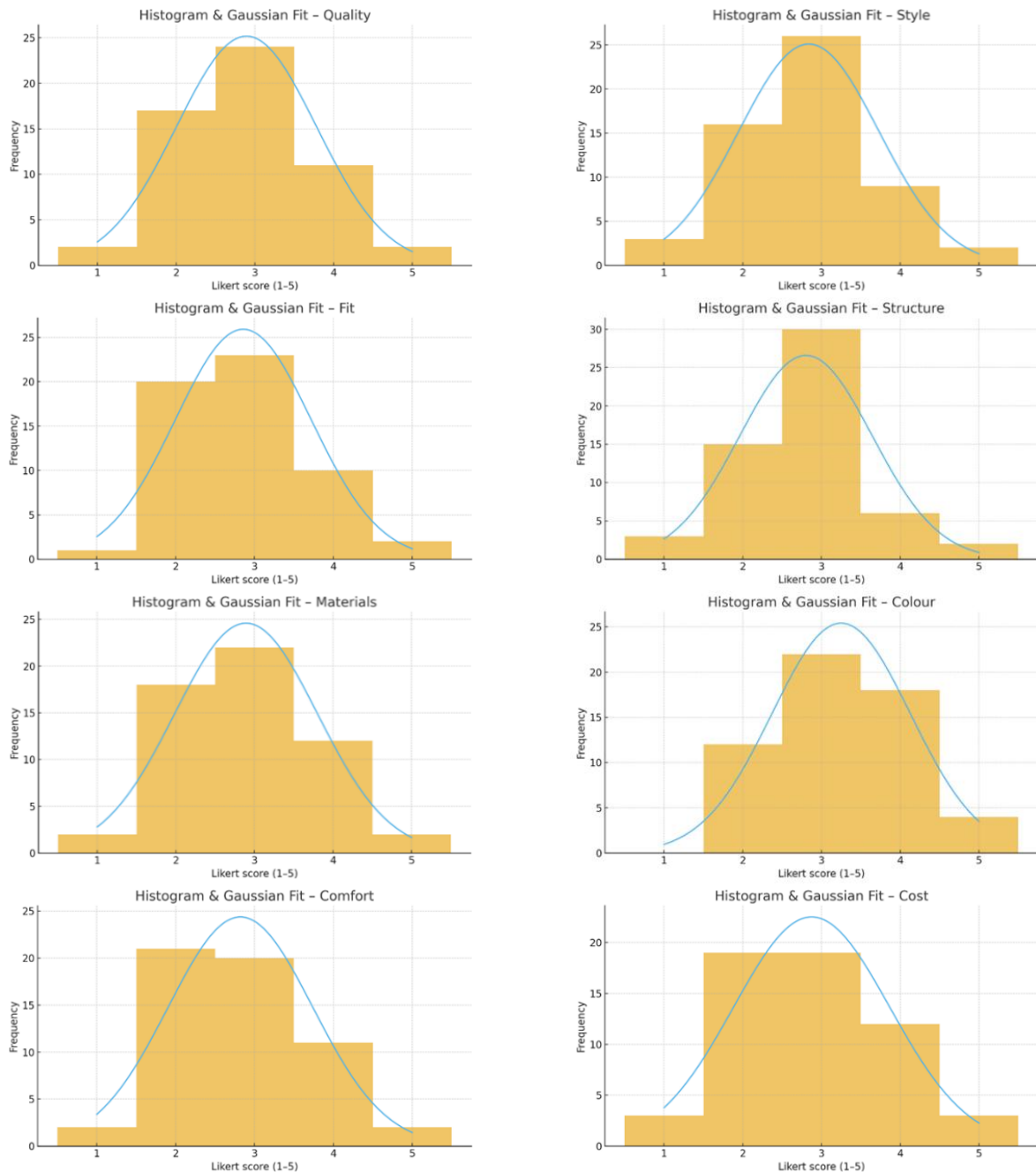


Figure 3. Gaussian distribution curves for each modified regular bra criterion.

Table 4. Gaussian statistics and distribution skew for modified regular bras.

No	Variable	N	Mean	Std	Skewness	Kurtosis
1	Quality	56	2.893	0.888	0.210	-0.246
2	Style	56	2.839	0.89	0.162	+0.018
3	Materials	56	2.893	0.908	0.212	-0.426
4	Color	56	3.250	0.879	0.142	-0.749
5	Fit	56	2.857	0.862	0.449	-0.252
6	Structure	56	2.804	0.84	0.195	+0.597
7	Comfort	56	2.821	0.917	0.359	-0.434
8	Cost	56	2.875	0.992	0.252	-0.541

Table 5. Comparison between general descriptive statistics and modified regular bra satisfaction.

Attribute	General sample (n=101)	Modified regular bras (n=56)	Key observation (performance gap)
Mean satisfaction (M)	3.09-3.56 (moderate)	2.05-2.85 (dissatisfied)	Significant negative shift in satisfaction for modified solutions.
Primary focus	Balanced (aesthetic and functional)	Aesthetic-driven (style/color)	Modified bras retain aesthetics but fail in functional integrity.
Fit and support	$M \approx 3.42$	$M \approx 2.15$	Major deficit: Conventional structures cannot support prosthesis weight
Positional stability	High importance ($\beta=0.344$)	Very low satisfaction	Modified pockets lead to frequent displacement and discomfort.
Thermal comfort	$M \approx 3.15$	$M \approx 2.40$	High moisture entrapment due to non-functional textile layers
Distribution shape	Narrower, centered near "satisfied"	Wide and left-skewed (Gaussian)	High inconsistency; satisfaction depends on random DIY skill
Design logic	Professional functional design	Improvised/manual adaptation	Confirms that modification is not a substitute for engineering

The satisfaction distribution for modified regular bras in Vietnam reflects a transitional stage in current adaptation practices. Although descriptive means indicate moderate user acceptance, the distribution reveals considerable variability, suggesting that satisfaction remains unstable without scientifically informed design. In particular, the lack of optimization for key predictors, especially structural stability and weight distribution, limits the consistency and reliability of user experience. Advancing toward a standardized modified design informed by the 3D simulation framework proposed in this study may produce a more concentrated Gaussian distribution, contributing to improve overall user satisfaction.

The comparative analysis of general descriptive statistics ($n = 101$) and the satisfaction distribution for modified regular bras ($n = 56$) shown in Table 5 reveals a critical performance gap in current post-mastectomy solutions. While the overall sample reported moderate satisfaction levels ($M = 3.09 - 3.56$), the distribution for modified regular bras shows a pronounced negative shift. For key functional attributes, particularly fit and structural support, the satisfaction curve for modified garments peaks at the lower end of the scale (2.0 – 2.8), contrasting sharply with the mean values observed in the broader sample. This divergence indicates that manual modifications, such as sewing pockets into conventional bras, are insufficient to address the complex biomechanical requirements of post-mastectomy users. The large standard deviation observed in the modified bra distribution further suggests that satisfaction levels are highly inconsistent and often depend on individual tailoring practices rather than standardized design

principles. From a functional apparel perspective, although conventional bras may achieve relatively high ratings for aesthetic attributes such as color and style, they fail to provide the positional stability and pressure redistribution necessary for supporting an external breast prosthesis. This functional limitation offers empirical support for the proposed user-centered design framework. The findings highlight the need to approach mastectomy bras as integrated functional systems rather than simple adaptations of existing products. Accordingly, incorporating 3D anthropometric data and climate responsive textile materials represents a critical design direction, enabling the transition from dissatisfaction associated with improvised modifications toward higher and more consistent levels of user satisfaction in professionally engineered functional apparel.

DISCUSSION

Fit and thermal comfort as primary drivers of mastectomy bra satisfaction

The results confirm that fit and physical comfort are the strongest predictors of mastectomy bras satisfaction ($R^2 = 0.642$). The significant effect of fit ($\beta = 0.458$) highlights the challenge of accommodating asymmetrical contours and post-surgical scar sensitivity. Unlike conventional bras, mastectomy bras function as a structural interface between the chest wall and the external prosthesis. Consistent with functional apparel research, survivors view the bra less as an aesthetic garment and more as a medical functional device.

Although material softness alone was not a significant predictor of overall satisfaction ($p = 0.106$), overall material performance (including breathability and moisture management) showed a significant positive impact ($p = 0.048$). In Vietnam's hot and humid climate, the ability of fabrics to dissipate heat and remain dry appears more critical than tactile softness. This emphasis on functional performance over sensory or aesthetic attributes characterizes adaptive clothing for users who perceive their bodies as vulnerable.

A distinct contribution of this research is the empirical link between thermal discomfort and silicone based EBPs in a tropical climate ($\beta = 0.328$, $p < 0.001$). Silicone's low thermal conductivity and non-porous structure create heat accumulation at the skin prosthesis interface. In Vietnam's high temperature, high humidity environment, this buildup can lead to perspiration related skin irritation and reduced wear adherence. These findings indicate that Western-centric designs, optimized for temperate climates, do not adequately address thermo physiological conditions in tropical regions. Consequently, mastectomy bras should incorporate high permeability mesh or moisture wicking textiles to support evaporative cooling that silicone prostheses cannot provide.

Material and thermal issues in tropical contexts

The findings highlight material and thermal comfort as critical determinants of satisfaction with external breast prostheses. Among the evaluated attributes, perceived heat accumulation and thermal discomfort were strongly associated with lower user satisfaction, particularly among silicone prosthesis users. Silicone is widely used because of its realistic appearance and soft tactile properties; however, its low thermal conductivity and limited breathability may promote heat retention at the skin prosthesis interface. In tropical climates with high temperature and humidity, this heat buildup can intensify discomfort, perspiration, and skin irritation during prolonged wear. The results indicate that thermal factors play a central role in shaping overall user experience and product acceptance.

From a textile and apparel perspective, dissatisfaction related to thermal discomfort suggests the need to reconsider both material selection and system level design rather than focusing solely on prosthesis characteristics. The interaction between prosthesis materials, mastectomy bras, and surrounding textile layers collectively affects heat transfer, moisture management, and microclimate regulation. These relationships are particularly relevant in tropical environments.

For mastectomy bra design, fabrics should emphasize high moisture permeability, rapid sweat

evaporation, and improved air circulation to reduce heat accumulation around prosthetic materials. The development of hybrid or composite systems that combine silicone with lightweight, breathable, or phase change materials may further enhance thermal comfort while maintaining aesthetic realism and structural stability. Overall, the findings underscore the importance of addressing thermal comfort as a primary functional requirement in post-mastectomy product design, highlighting the role of textile engineering and material innovation in developing user-centered healthcare apparel solutions for tropical climates.

Implications for apparel fit and sizing

The findings highlight important implications for fit and sizing in post-mastectomy apparel, particularly regarding the limitations of existing sizing systems and the increasing reliance on online shopping. Despite advances in functional apparel design, sizing standards for mastectomy bras still largely replicate those used for conventional bras, which may inadequately accommodate post-surgical body asymmetry and individual variation. The results indicate that fit related dissatisfaction persists across user groups, indicating that standardized band cup sizing systems do not sufficiently address the complex fit requirements of women after mastectomy. Variations in chest wall contour, scar location, and prosthesis volume create fitting challenges that cannot be effectively resolved through traditional size increments. These findings align with prior research emphasizing the need for adaptive sizing approaches in functional and medical related garments.

The expansion of online shopping further intensifies these issues. While online platforms offer accessibility and privacy, factors particularly valued by post-mastectomy users, they limit opportunities for physical fitting and professional adjustment. The results suggest that users who purchase bras online are more likely to report dissatisfaction with fit, reflecting a gap between standardized digital sizing information and the complex bodily changes experienced after surgery.

From both design and retail perspectives, these findings underscore the necessity of integrating enhanced sizing guidance and fit support tools into both product development and online retail environments. Approaches such as adjustable design features, modular components, and personalized sizing recommendations may help bridge the gap between standardized sizing systems and individual fit needs. Overall, the study suggests that improving fit satisfaction in post-mastectomy apparel requires not only innovation in garment construction but also a reconsideration of sizing strategies and consumer support mechanisms, particularly in the context of online purchasing.

DESIGN IMPLICATIONS AND FRAMEWORK

Mastectomy bra design

The findings advocate for a paradigm shift in mastectomy bra construction, moving from modified conventional bras to integrated functional systems.

First, anthropometric adaptation is essential, as current sizing systems, largely based on Western body data, do not adequately represent the chest wall asymmetry and morphological variations common among Asian survivors. Adaptive sizing strategies, such as differentiated cup depths and flexible grading, are therefore recommended.

Second, pressure management is critical to reduce irritation at scar sites. Seamless technologies and soft construction techniques can help minimize localized pressure. Strategic seam placement and the replacement of rigid underwires with localized reinforcement structures may improve comfort while maintaining support.

Third, thermo physiological comfort should be prioritized, particularly in tropical climates. Moisture wicking fabrics and breathable knit structures, including mesh panels, can enhance air circulation and promote faster moisture evaporation, thereby reducing heat accumulation during daily wear.

Finally, functional integration between the bra and prosthesis is necessary to maintain positional stability. Reinforced pocket structures and adjustable pocket depths can help prevent prosthesis displacement, improving both comfort and user confidence.

Breast prostheses: climate-responsive innovation

Future development of external breast prostheses (EBP) should extend beyond aesthetic realism to emphasize thermal regulation and weight optimization. Excessive prosthesis weight is a major source of discomfort; therefore, density graded materials or hollow core structures may help maintain anatomical volume while reducing gravitational load on the shoulders.

Thermal performance is also crucial, as solid silicone tends to trap heat. Climate responsive solutions such as phase change materials (PCMs), micro perforations, or breathable surface textures may improve heat dissipation and stabilize the microclimate at the skin prosthesis interface. In addition, improved anatomical contouring and frictional stability can reduce the need for frequent adjustments. Modular or hybrid prosthesis systems that allow component changes according to activity level or environmental conditions may further support personalized rehabilitation.

Proposed user-centered design framework

Based on empirical findings, this study proposes a three-level user centered design (UCD) framework for post mastectomy products. Level 1 focuses on user needs, integrating physiological requirements (e.g., fit and thermal comfort) with psychosocial considerations such as confidence and body image. Level 2 translates these needs into design parameters, including moisture managing textiles, pressure reducing garment structures, and lightweight prosthesis configurations. Level 3 defines performance outcomes, establishing measurable indicators of satisfaction and functional effectiveness. The framework emphasizes iterative feedback between these levels, enabling continuous refinement of product design.

LIMITATIONS AND FUTURE RESEARCH

This study has several limitations. The use of self-reported data may introduce subjective bias; future research should incorporate objective physiological measurements such as skin temperature or pressure distribution. The cross-sectional design also limits insight into how user needs evolve over time, suggesting the value of longitudinal studies across postoperative stages. Additionally, future work should include material testing and prototype development to evaluate the practical effectiveness of design strategies.

CONCLUSION

This study examined user satisfaction with mastectomy bras and external breast prostheses by analyzing key design attributes and their effects on overall satisfaction. Using data from post-mastectomy women in a tropical context, the findings highlight the critical role of fit, comfort, material performance, thermal regulation, and stability. Fit and comfort emerged as the strongest predictors of satisfaction with mastectomy bras, while weight, thermal comfort, and positional stability were crucial for external prostheses. The results emphasize prioritizing functional and physiological considerations over aesthetics or cost in product design. Differences in shopping channels and postoperative duration indicate how consumer behavior and adaptation influence evaluations. From a clothing and textiles perspective, the study advances a user-centered approach to post-surgical apparel in tropical, non-Western settings. Practical implications include adaptive sizing, pressure-reducing structures, moisture-managing textiles, lightweight materials, and modular solutions. Overall, the study provides actionable insights for designers and healthcare apparel developers, supporting the creation of inclusive, comfortable, and climate-responsive post-mastectomy products that enhance quality of life after breast cancer surgery.

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AUTOMATED DIGITAL EMBROIDERY PATH GENERATION USING CONSTRAINED GRID TRAVERSAL

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ABSTRACT

This paper presents a deterministic method for automated generation of embroidery toolpaths based on constrained traversal of a discrete grid and equal-length diagonal embedding of stitch primitives. The embroidery region is represented as a binary mask, and a single continuous trajectory is constructed through frontier-based expansion with anchor constraints. By enforcing exact point-to-point connectivity between neighboring primitives, the method eliminates non-stitching transitions and produces a continuous embroidery path without thread jumps. A regular-grid geometric embedding ensures equal-length diagonal stitches, providing reproducible and machine-compatible output. Comparative evaluation against classical raster-based strategies shows that the proposed method removes non-stitching transition movements and reduces total thread length while maintaining deterministic behavior and scalability for complex enclosed shapes. The proposed approach is formulated as a constrained grid-traversal method with locality-preserving path-planning logic, rather than as a formal limiting geometric construction.

KEYWORDS

Digital embroidery; Toolpath generation; Constrained grid traversal; Equal-length diagonal embedding; Path planning; Stitch connectivity.

INTRODUCTION

Recent advances in embroidery toolpath generation have shifted the field away from simple raster image translation toward structured representations that explicitly encode stitch geometry, execution order, and manufacturing constraints. In such representations, an embroidery design is treated not merely as a pixel pattern, but as a geometrically and procedurally organized object that can be translated into a machine-executable stitch sequence [1]. This development is consistent with recent studies showing that, even when visual fidelity is a primary objective, reliable digital embroidery generation requires stitch-level modeling rather than purely image-based approximation [2]. From the perspective of scientific reproducibility, this shift is particularly important because it enables algorithmic workflows in which design decomposition, stitch assignment, and sequencing can be analyzed in terms of measurable outputs such as total thread consumption, continuity of execution, and the frequency of non-stitching machine movements [3].

At the same time, embroidery is increasingly being considered a functional and programmable textile

process, especially in the context of smart and morphing materials. In such applications, stitch arrangement affects not only appearance but also mechanical behavior and, in some cases, electrical performance [4-7]. As a result, toolpath generation is no longer only a graphical or decorative task; it is also an engineering problem in which geometric regularity, manufacturability, and execution stability must be considered together.

One of the central challenges in this domain is the construction of efficient continuous stitch sequences that minimize or eliminate non-stitching transitions. Conventional raster-based approaches, such as row-by-row scanning, are straightforward to implement, but they often introduce numerous transition jumps between distant regions. These jumps increase thread consumption, reduce execution efficiency, and can adversely affect mechanical stability during embroidery. Although graph-based routing and heuristic optimization strategies can improve traversal efficiency, they often rely on comparatively complex combinatorial procedures whose behavior may depend strongly on the quality of the intermediate decomposition and routing stages [3][8]. An alternative direction is to use locality-preserving

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grid-traversal principles, in which spatial proximity between consecutive stitched elements is maintained by construction rather than restored through a separate post-processing optimization step.

A deterministic method for embroidery toolpath generation based on constrained traversal of a discrete grid is presented in this work. The embroidery region is represented as a binary mask, and a single continuous path is constructed by means of frontier-based expansion with anchor constraints.

Thus, the proposed method is positioned as a deterministic grid-based path-planning approach for continuous stitch generation, rather than as a formal limiting geometric construction. This formulation ensures that each newly visited cell is connected to the previous one through an exact shared boundary point, thereby enabling point-to-point continuity and eliminating non-stitching transitions.

The proposed method separates the problem into two complementary layers. The first is a topological layer that determines the traversal order of admissible grid cells under continuity constraints. The second is a geometric layer that embeds equal-length stitch primitives within each visited cell. This separation allows global continuity of the toolpath to be achieved while preserving local geometric regularity and machine compatibility.

The main contributions of this work are as follows:

- a deterministic traversal procedure for continuous coverage of a discretized embroidery region;
- an anchor-constrained continuity mechanism that removes non-stitching transitions between neighboring primitives;
- a geometric embedding strategy that ensures equal-length diagonal stitches;
- a reproducible and scalable framework for generating continuous embroidery toolpaths for complex enclosed shapes.

The proposed method is not presented as a formal limiting geometric construction. Rather, it is formulated as a constrained grid-traversal method with locality-preserving path-planning logic and geometric embedding for automated embroidery path generation.

THE DIGITAL EMBROIDERY METHODS

In recent years, computational embroidery has increasingly evolved toward complete digital workflows in which design intent is represented in a machine-operable form and subsequently translated into stitch components under manufacturing constraints. Rather than treating embroidery as a purely visual image-processing task, current approaches emphasize structured representations that encode regions, boundaries, local orientation, and execution-related parameters required for production. This tendency is consistent with recent textile digitization research, where structural

continuity and manufacturability are treated as essential characteristics of the generated pattern rather than as secondary post-processing considerations [9]. In practical terms, such workflows describe not only the geometry of the ornament, but also the constraints of the embroidery process, including stitch length, directional consistency, local curvature, and execution stability.

Within computational embroidery systems that automatically transform design intent into machine-executable stitch configurations, an important methodological tendency is the use of explicit intermediate representations that make the generation process analyzable and reproducible. In these systems, embroidery is treated as a programmable production process rather than as a direct raster-to-stitch conversion. As a result, the transformation from high-level motif description to executable stitch sequence can be decomposed into interpretable stages, such as region segmentation, stitch-type assignment, geometric path generation, and traversal ordering. This structured view is also reflected in recent work on region-aware and multi-stitch embroidery synthesis, where different parts of a design are assigned different stitch characteristics according to local geometry and visual requirements [10] [11]. Such approaches demonstrate that modern embroidery generation is no longer based on uniform filling alone, but increasingly relies on differentiated stitch organization guided by region-specific geometric and manufacturing rules.

Accordingly, multi-stitch synthesis and region-specific stitch assignment can be understood through two closely related problems: the selection of an appropriate stitch family for each region and the generation of geometrically feasible stitch paths that satisfy spacing, continuity, and curvature constraints while reducing boundary artefacts. Recent studies indicate that these two tasks are increasingly integrated rather than treated independently. In particular, area-aware synthesis frameworks incorporate classification directly into the generation process, allowing stitch attributes to be adapted to local structural conditions instead of being imposed through a uniform sequential filling strategy [11]. From the perspective of embroidery automation, this development is important because it links visual structure, geometric feasibility, and production behavior within a single computational framework.

At the same time, the optimization of traversal order and travel distance remains one of the central unresolved problems in digital embroidery. While many existing systems are capable of generating acceptable local stitch patterns, the global sequencing of these patterns often remains inefficient, especially when non-stitching transitions between disconnected fragments are introduced. This issue is highly relevant in manufacturing practice because excessive jumps increase thread

consumption, prolong machine time, and may reduce execution stability. Although some sequencing strategies are implemented in commercial digitizing software and patent-based solutions, their internal optimization logic is often not described in sufficient detail in open scientific literature. Consequently, the development of deterministic and reproducible methods for continuous embroidery path generation remains a relevant research problem, particularly for applications that require both geometric regularity and strict control of non-stitching movements.

The presence of path sequencing components that select fragment order to reduce thread trimming and optimize entry and exit locations is clearly recorded in open patent sources, which supports the relevance of this manufacturing objective, even though such sources do not provide the same level of methodological transparency as peer-reviewed journal articles [12]. In the scholarly textile fabrication literature, a similar optimization perspective appears in related fields such as sewing line arrangement, where short and direct technological routes are treated as desirable for production efficiency. This literature also reviews meta-heuristic optimization techniques, including genetic algorithms and simulated annealing, which are relevant to routing and sequencing problems when exact optimization is computationally difficult [13].

From a technical perspective, the cost of transitions between non-adjacent areas is where current digital embroidery workflows vary the most, because it is where topology and neighborhood information enter the sequencing process rather than being determined by geometry alone [9].

Contemporary digital embroidery workflows that automatically transform design intent into executable stitch arrangements are characterized by the presence of explicit intermediate representations that connect high-level pattern specification and machine-level operation. This connection is implemented through a series of geometric and topological adjustments that map areas, perimeters, and texture characteristics into constrained stitch paths that can be performed dependably by a computer-driven embroidery machine. In the most developed pipelines, the design input is not viewed as a bitmap but as an organized representation, such as an area diagram with directional vectors and stitch-type tags. This framework is then compiled into a sequenced collection of needle penetration points that meets machine limitations, including stitch-length limits, curvature constraints, and controlled gap spacings. This principle is illustrated by contemporary interactive embroidery applications that reconstruct and visualize stitching procedures and allow parameter-controlled generation of embroidery sequences [14].

The fact that such frameworks are intended to reveal stitch geometry in three dimensions rather than solely

show two-dimensional surfaces is important because it permits the same representation to be used both for visual verification and for machine operation. Thus, such frameworks provide relevant reference points for reproducible toolpath analysis. In real-world digitizing workflows, this representation enables functions such as area segmentation, perimeter following, streamline-like filling, and sequenced joining of sections. These actions are mathematically similar to solving a constrained path-planning problem on a planar domain, even if the software is presented as a creative utility rather than as a technical design tool [15].

Multi-stitch synthesis and area-aware stitch-type allocation have emerged as an essential advancement in digital embroidery workflows, since realistic and manufacturable embroidery cannot be created with a single uniform stitch type. Therefore, contemporary systems must assign a stitch type to every region and subsequently generate paths that achieve the visual and structural characteristics of that stitch type while adhering to machine constraints. In this context, each region is linked to a category tag that dictates stitch alignment, density, underpinning structure, and fill behavior. Thus, the synthesis challenge becomes one of choosing both a tag and a geometry that reduce visual error and production cost under curvature and stitch-length restrictions. This corresponds to the linkage between categorization and geometric refinement mentioned in recent area-aware embroidery synthesis studies that depend on stitch classifiers and region-specific synthesis frameworks [16]. The practical implication is that the stitch sequencing issue is no longer distinct from stitch-type selection, because different stitch families yield different connection patterns and consequently alter the structure of the path graph. This is why modern simulation and visualization systems predict embroidery effects prior to manufacturing and present stitch parameters as primary design elements [17].

This integration of region semantics with geometry explains why edge quality, density transitions, and alignment coherence have become primary evaluation criteria.

The refinement of traversal order and the minimization of non-stitching transitions are critical for industrial efficiency. Once the embroidery area is discretized and stitches are generated, the remaining optimization problem is the sequence in which the segments are traversed. Numerically, the embroidery layout can be represented as a collection of line segments that must be joined into a single continuous path with minimal travel distance, which makes the problem related to constrained graph-based routing and path-planning tasks. While many commercial solutions remain proprietary, this objective is explicitly addressed in research where sequencing and connectivity are treated as distinct phases [18], as well as in production optimization studies that employ

evolutionary algorithms to reduce redundant machine motion [16] [19].

From a physical execution viewpoint, the significance of reducing interruptions is also supported by automated sewing studies, where dynamic tension management and continuous trajectories are shown to yield more stable and efficient sewing compared to interrupted motion. This is directly relevant to embroidery machines, which operate at high speed and are susceptible to tension variations [20].

For generating toolpaths, locality-preserving grid-traversal strategies offer practical advantages due to their ability to maintain spatial proximity between consecutive points. While such traversal principles are useful for organizing coverage over discrete regions, they are seldom highlighted in current embroidery literature as a core methodology for stitch sequencing. Instead, prominent research predominantly features region-based partitioning, field-guided patterns, and constraint-based ordering derived from graph structures. For example, established approaches [1] address the challenges of continuity and non-adjacency through the lenses of graph theory and geometric optimization. In these frameworks, intricate shapes are converted into stitch sequences using algorithms that prioritize region awareness and path routing. Consequently, while locality-preserving grid traversal can support the coverage of discrete areas, its practical application in embroidery remains subject to strict manufacturing constraints, including stitch type selection and exact point-to-point connectivity.

Within this context, developing embroidery techniques based on constrained locality-preserving grid traversal is a relevant scientific task. Such methods can bridge the gap between high-level motif representation and the low-level mechanical requirement for a single, continuous, and efficient toolpath.

THE DIGITAL EMBROIDERY TOOL PATH GENERATION PROCESS

Contemporary embroidery toolpath generation can be described as a series of mathematically distinct transformations that map a complex pattern into a machine-executable stitch sequence while maintaining shape fidelity and manufacturing feasibility, and the overall process may be represented as a chain of functions that progress from a concept space into a surface structure, subsequently into a flow pattern, then into a group of lines and finally into a sequenced progression. The comparative positioning of representative embroidery toolpath generation strategies in terms of total thread length and aesthetic score is shown in Figure 1.

This transformation can be formulated as a compositional function in which a layout item Λ is converted into a sectional breakdown B via a

function S , next into a directional map J by a function H , then into a set of paths P by a function F , and ultimately into a time-indexed stitch arrangement T by an ordering operator R such that

$$T = R(F(H(S(\Lambda)))) \quad (1)$$

where each symbol denotes a space of objects and not a single vector, so that each mapping operates within a domain appropriate to the corresponding stage of the generation process. The geometry stage is governed by a first-order differential equation that generates streamlines aligned with local texture or boundary orientation and is written as (2):

$$\frac{d\Theta}{ds} = \zeta(\Theta) \quad (2)$$

in which $\Theta \in \mathbb{R}^2$ is a stitch point parameterized by arclength s and ζ is a bounded vector field derived from region skeletons, and the step size s controls stitch spacing independently of image resolution. Trajectory regularity and boundary adherence, however, depend on the construction of the underlying vector field rather than being guaranteed by the differential formulation alone. The benefit of this continuous field-driven generation is that continuity and boundary adherence are supported by geometric construction, while the disadvantage is that the resulting curve set possesses no inherent execution order and consequently must be routed.

When several stitch families are permitted, the problem becomes a hybrid discrete-continuous optimization task in which each region r must be assigned a class label C_r from a finite set and a continuous parameter vector θ_r that controls spacing, angle and underlay for that family, and the global objective couples visual fidelity and manufacturing feasibility as

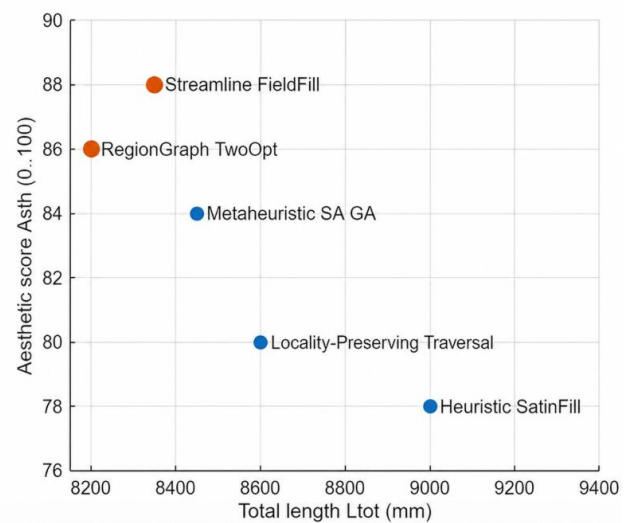


Figure 1. Trade-off between total thread length and aesthetic quality for different embroidery toolpath generation strategies.

$$\min_{c_r, \theta_r} \sum_r E_r(c_r, \theta_r) + \lambda_1 \sum_k g(\ell_k) + \lambda_2 \sum_k h(\kappa_k) \quad (3)$$

where E_r measures region-specific appearance error, ℓ_k are consecutive segment lengths penalized by a convex function g to enforce stitch-length limitations, κ_k are local curvatures penalized by a function h to prevent high-speed needle oscillations, and λ_1 and λ_2 weigh the geometric constraints. The advantage of this formulation is its expressive capacity, as it can blend satin, fill, and contour characteristics within one motif, while the drawback is combinatorial complexity, because altering a single c_r changes the connectivity of the path graph and thus modifies the routing structure.

The execution sequence is obtained by solving a constrained routing problem on a weighted graph whose nodes represent stitch segments and whose edges represent feasible transitions with costs that reflect both spatial separation and execution disruption. The optimal permutation μ for fragments minimizes the expression (4):

$$\min_{\mu} \sum_{i=1}^{N-1} \eta(\mu_i, \mu_{i+1}) \quad (4)$$

where N is the number of fragments and η is a composite cost that usually takes the form $\eta = \lambda_1 d + \lambda_2 u + \lambda_3 t$ with d the Euclidean step length, u a flag for a non-stitching action, and t an indicator of a trim or tie-off. This structure reflects the industrial aim of reducing thread consumption and machine interruptions. The merit of this routing formulation is that it directly optimizes manufacturing-relevant criteria, while the drawback is that it is NP-hard and consequently solved in practice by greedy linking, nearby two-edge exchanges, or metaheuristics that rely heavily on the quality of the region graph generated beforehand.

Locality-preserving traversal mappings may be considered within this structure as proximity-maintaining parameterizations of two-dimensional space. In their classical mathematical form, such mappings can be represented by a continuous surjection C from a unit interval to a square that satisfies

$$C : [0,1] \rightarrow [0,1]^2 \quad (5)$$

with the property that points close in the parameter may remain spatially close in the plane. This makes such mappings potentially useful for traversing dense fill regions with reduced long-distance transitions. Their benefit is that they reduce nonlocality inside an

area without demanding extensive streamline optimization, whereas their limitation is that they cannot by themselves handle arbitrary boundary perimeters, stitch family variations, or entrance and exit choices. Therefore, in the present formulation, they are treated only as a conceptual reference for locality-preserving traversal within the geometric layer F rather than as a substitute for the constrained routing operator R .

The main implication for the present study is that field-driven geometry, region-wise stitch-family generation, and graph-based constrained routing constitute a three-layer mathematical framework in which locality-preserving traversal principles may support localized coverage but do not define the proposed method as a formal limiting geometric construction. Instead, they must be situated within region-aware synthesis and constrained routing to yield effective and manufacturable embroidery toolpaths.

The process of creating a continuous embroidery toolpath that covers a designated area using repeated basic units, such as the double-cross primitive, can be interpreted within the framework of combinatorial optimization on geometric networks and arc-routing problems. The effectiveness of different solution approaches is closely related to established theoretical results and their practical implications. In computational geometry and operations research, the routing of a path that must traverse all required line segments while minimizing total traversal cost and eliminating unnecessary transitions belongs to the class of arc-routing problems represented by the Rural Postman and Chinese Postman models. In these models, arcs represent required stitch segments, while transitions correspond to non-stitching thread movements. The Rural Postman Problem seeks a minimum-length circuit that covers a designated subset of arcs in a network, which directly parallels the requirement that all stitches in a region be covered while minimizing additional non-stitching movements. It is well established that even constrained versions of this problem become NP-hard when the required arcs are disconnected or when the domain has an arbitrary configuration. This implies that no general polynomial-time solution is available and that practical embroidery planners must rely on heuristic or approximation-based strategies rather than exact solvers in typical cases [21]. This fundamental complexity result has a direct implication for embroidery path planning: an exact universal optimum for minimal thread length and complete area coverage may be computationally infeasible for large or highly disconnected regions. Therefore, methods that decompose the task into smaller segments or approximate the optimal routing become necessary.

One category of computational methods for embroidery toolpath generation uses concepts from

region decomposition and continuous path-sweeping methods, where the fill area is split into adjacent sub-areas that can be filled consecutively. In quilting and similar textile path-planning tasks, a segmented image is initially reduced to relevant boundaries, and then approximate solutions of the Rural Postman Problem are calculated to construct a connected sewing route that covers all boundaries without major gaps. This shows that spatial decomposition followed by localized traversal is effective in reducing transition jumps while remaining manageable for real-sized designs [22]. The benefit of this technique from an embroidery viewpoint is that it inherently respects the geometric boundaries of the region and creates locally efficient paths, but the drawback is that it frequently requires careful decomposition heuristics and may result in suboptimal global connectivity when the area contains voids or multiple separate substructures, because localized decomposition does not always capture global linkage.

An alternate theoretical viewpoint originates from concepts that attempt to transform the embroidery domain into an Eulerian or Hamiltonian configuration, where an Eulerian tour would traverse every line exactly once and a Hamiltonian cycle would visit every node exactly once. The Chinese Postman Problem and comparable arc-routing problems examine methods that augment a given structure so that an Eulerian circuit exists or that locate circuits under different constraints. Although such methods can offer guarantees in specific situations, their direct application to embroidery is not straightforward because the augmentation may introduce segments representing artificial transitions that are not relevant for stitches, and because enforcing even node degrees or other necessary properties may conflict with the physical constraints of embroidery machines and thread dynamics [23]. The main benefit of methods influenced by Eulerian or Hamiltonian models is that, when their criteria are satisfied, they yield a single closed circuit covering all required elements with minimal excess, which corresponds to the desired practical attribute of minimal thread cuts. However, the disadvantage is that substantial preprocessing or structure modification is required before the tour can be found, and such preprocessing frequently fails to preserve the original embroidery geometry accurately.

Combined approaches that merge decomposition, local sweep sequences, and approximate circuit assembly have consequently appeared in textile and fabrication path planning because they balance computational manageability with solution quality [24]. For instance, two-dimensional arc-routing algorithms take advantage of planar geometry and restrict close-proximity checks to generate near-optimal circuits without fully solving the NP-hard problem, which makes them appropriate for stitching or cutting continuous textile outlines where enclosed loops and minimal movement are important [23] [25].

The practical consequence for primitive-based embroidery fills, such as double-cross grids, is that region-proximity-guided traversal, greedy nearest-neighbor sequencing, and restricted local refinement provide predictable and manufacturable stitch arrangements that maintain coverage and mechanical reliability, even though they do not guarantee a globally optimal solution.

THE TOOLPATH GENERATION FOR DOUBLE-CROSS EMBROIDERY

A traditional coverage technique for filling a closed area with identical double-cross embroidery motifs can be devised as a standard grid decomposition followed by a fixed raster scan, which is the most basic mathematically tractable benchmark. In this classical approach the closed region $\Omega \subset \mathbb{R}^2$ is first approximated by a union of identical square cells of side length $\delta > 0$, and every square whose center lies inside Ω is selected for stitching, while the others are ignored, so the discrete admissible set is

$$A_\delta = \{(i, j) \in \mathbb{Z}^2 \mid (i\delta, j\delta) \in \Omega\} \quad (6)$$

where $(i\delta, j\delta)$ denotes the physical coordinates of the square center. The number of stitched squares is $N = |A_\delta|$ and this determines the resolution of the discretization, with smaller δ giving higher geometric fidelity at the cost of more stitches.

Each square $(i, j) \in A_\delta$ is assigned one identical double-cross primitive that is geometrically represented by a fixed closed polyline $q_k \in \mathbb{R}^2$ for $k = 1, \dots, m$ with $q_1 = q_m$, scaled and translated to the square by

$$p_{i,j,k} = r(i, j) + \alpha q_k \quad (7)$$

where $r(i, j) = \begin{bmatrix} i\delta \\ j\delta \end{bmatrix}$ is the square center and

$\alpha > 0$ is a scale factor chosen so that the primitive fits inside the square. The intrinsic stitched length inside one square is therefore

$$L_{in} = \sum_{k=2}^m \|\alpha(q_k - q_{k-1})\|_2 \quad (8)$$

which is constant for all squares because the same primitive is used everywhere.

The traditional technique then arranges the squares in a simple raster layout that does not rely on the form of Ω other than through A_δ . A typical arrangement is a row-by-row serpentine traversal, which can be expressed as a bijection $\mu: 1, \dots, N \rightarrow A_\delta$ such that if $\mu(k) = (i_k, j_k)$ then the sequence (i_k, j_k) is obtained by scanning increasing j and alternating

the orientation of i in each row. This ordering is straightforward to calculate and predictable. The centers of the visited squares are

$$v_k = r(i_k, j_k) \quad (9)$$

and the total length of transitions between squares is

$$L_{tr} = \sum_{k=2}^N \|v_k - v_{k-1}\|_2 \quad (10)$$

which represents the total length of all non-stitching jumps of the embroidery unit between the end of one double-cross primitive and the start of the next. The total thread length consumed by the classical raster method is therefore described by the expression:

$$L = NL_{in} + L_{tr} \quad (11)$$

which explicitly separates the useful stitched length NL_{in} from the wasteful transition length L_{tr} .

The basic disadvantage of this classical model is that L_{tr} scales with the extent of the area rather than with neighborhood connectivity, because the raster sequencing frequently jumps from the close of one line to the start of the subsequent one, and more broadly from one remote cell to another that is not contiguous in A_δ . If the area covers a roughly rectangular block of extent ΔX and depth ΔY measured in counts of cells, then a crude asymptotic estimate of the transition length is

$$L_{tr} \approx \delta \cdot \Delta X \cdot \Delta Y \quad (12)$$

which grows faster than the intrinsic stitched length $N \cdot L_{in} \approx \delta^2 \cdot \Delta X \cdot \Delta Y$ as ΔX and ΔY increase, meaning that for large patterns the fraction of thread spent on transitions becomes significant. This inefficiency motivates more sophisticated techniques

aiming to reduce or eliminate the L_{tr} element by enforcing proximity and continuity in exploring A_δ .

Regardless of its poor performance, the traditional raster paradigm is useful because it is mathematically straightforward, numerically justified, and easily implemented in commercial digitizing applications, establishing it as a typical benchmark.

It furthermore offers a distinct standard for assessing newer procedures since any approach that attains a total thread length near the minimum threshold

$$L_{\min} = NL_{in} \quad (13)$$

can be considered near optimal in terms of thread usage, whereas the raster method generally satisfies the condition (14)

$$L > L_{\min} \quad (14)$$

for non-trivial regions, which shows its limited efficiency.

The procedure for double-cross stitch coverage of an enclosed area is detailed below. Based on the conducted numerical trials, the selected area is covered by double-cross stitches, with the corresponding route shown in Figure 2.

Figure 2 shows numerous non-stitching transition jumps that do not coincide with the main stitches. Such transition jumps cause significant additional thread consumption and can be reduced or eliminated by more advanced embroidery toolpath generation methods.

The proposed interpretation of the stitch path is based on constrained traversal of a discrete grid rather than on a formal limiting geometric construction. The double-cross primitive defines a closed local stitch element λ_3 that returns to its beginning after a finite

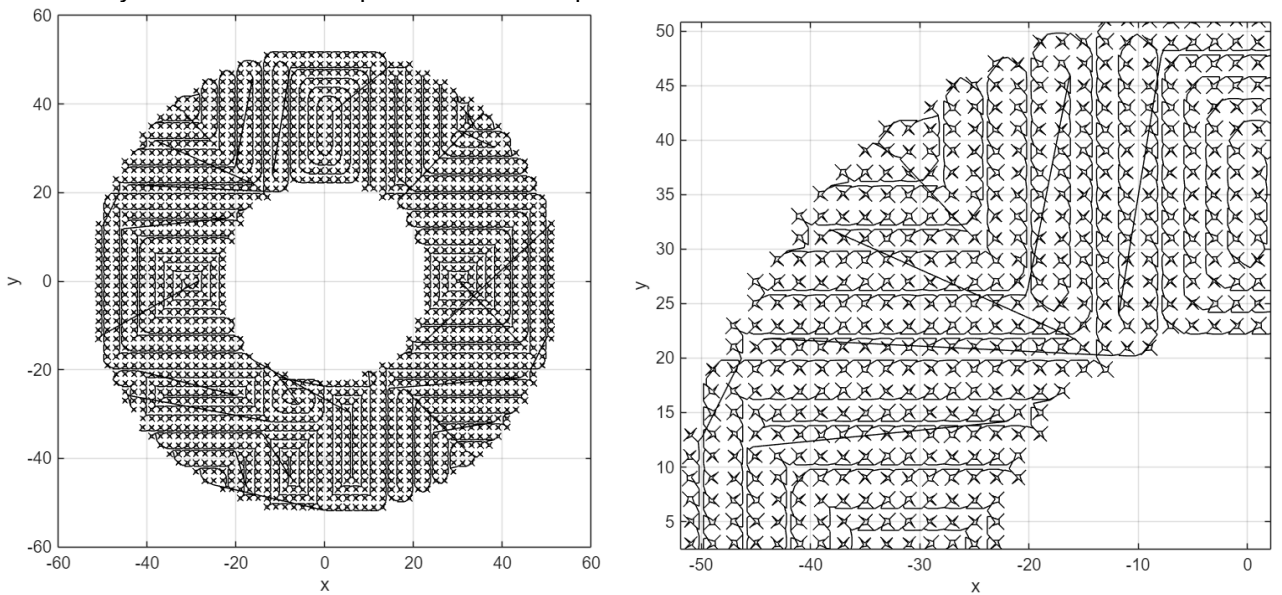


Figure 2. Double-cross embroidery toolpath for an enclosed area: a) overall coverage pattern; b) enlarged fragment showing local stitch connectivity.

series of segments of the same length, and when these elements are positioned on a uniform square lattice that tiles a closed domain Ω , the overall stitch route becomes a joining of turned and shifted instances of λ_3 whose midpoints obey a deterministic neighborhood-based traversal rule governed by local proximity and occupancy constraints, which extends only into permitted squares.

If the lattice is depicted by a binary mask $M(u, v) \in \{0, 1\}$ where $M = 0$ signifies permitted cells and $M = 1$ signifies prohibited cells, and if V_k is the collection of cell indices filled after k stages, then the admissible expansion frontier is defined by $H_k = (x, y)$, such that

$$H_k \notin V_k \mid M(x, y) = 0 \wedge \exists (x', y') \in V_k \quad (15)$$

where $\|(x, y) - (x', y')\|_1 = 1$, where the norm $\|\cdot\|_1$ enforces four-connectivity. The selection of the subsequent cell from H_k based on a deterministic selection rule ensures that the expansion is local, non-overlapping, and restricted to the unvisited admissible interior of Ω . Thus, the procedure is formulated as constrained frontier expansion on a binary mask rather than as a formal limiting geometric construction. The resulting embroidery trajectory is continuous because every primitive λ_3 is closed and because the traversal procedure connects each newly filled cell to the previously visited set through an admissible neighboring cell. After the final permitted cell is filled, the closure condition of the trajectory can be expressed as

$$\sum_{i=2}^n (p_i - p_{i-1}) = 0 \quad (16)$$

where p_i are the successive stitch points of the full embroidery trajectory.

The mechanical and algorithmic benefits of this constrained filling method arise from the locality-preserving nature of the traversal. This approach limits the Euclidean separation between consecutive primitives, reducing the need for long non-stitching transitions. If δ is the side length of one grid cell and p is the perimeter length of one double-cross primitive, then the traversal defined by the frontier H_k together with the anchor-based continuity constraint, yields a continuous trajectory without additional non-stitching thread jumps between neighboring primitives. This deterministic traversal also promotes uniform coverage density, and, for a fixed grid resolution, the number of stitches scales linearly with the area of Ω , providing an efficient area-filling pattern without unnecessary overlaps.

The primary constraint of this method is that it requires the region mask M to be specified on a uniform grid, and consequently it approximates curved edges by stepped polygons unless an adequately fine grid is employed, which increases the overall stitch number and processing cost. Nevertheless, from the perspective of stitching execution, this compromise is frequently acceptable because finer grids yield smoother visual edges and still maintain the locality and completeness attributes that reduce or eliminate additional non-stitching transitions between neighboring primitives. For these reasons, the proposed constrained grid-traversal method provides a practical way to construct embroidery toolpaths that are area-covering, continuous, locally connected, and mechanically stable, making it an appealing framework for fully automatic double-cross-based digital embroidery.

An explicit description begins by separating the construction into a discrete topological layer that ensures complete coverage and containment on the grid and a geometric placement layer that ensures the projected stitches adhere to the physical requirements of uniform length, diagonal feasibility, and the absence of unnecessary overlaps. The topological layer operates on cell coordinates and thus is unaffected by floating-point deviations, whereas the geometric layer is a predictable affine transformation plus deterministic re-sampling so that the resulting stitch polyline is repeatable and numerically consistent. The method is therefore formulated as an iterative constrained grid-traversal procedure, in which the path proceeds locally through unvisited adjacent admissible cells along the current frontier. The crucial factor that removes non-stitching transitions is that the traversal maintains a reference point on the cell lattice, and every new cell is entered precisely at that reference and is exited at a fresh reference that is also a vertex shared with the subsequent cell, so joining becomes precise point coincidence. The procedure concludes only when all permissible cells have been filled and the concluding reference matches the starting reference, which produces one single continuous closed embroidery trajectory.

Let the cell index set be $I = 0, \dots, g-1 \times 0, \dots, g-1$ and let a binary mask $M(x, y) \in \{0, 1\}$ represent the enclosed target domain, with admissible cells defined by

$$A = \{(x, y) \in I \mid M(x, y) = 0\} \quad (17)$$

and let $N = |A|$ be the number of admissible cells. Let $V_k \subseteq A$ be the set of already filled cells after k macrosteps and let $v_k = (x_k, y_k) \in A$ be the current cell, with initialization

$$V_0 = \{v_0\} \quad (18)$$

and traversal update

$$V_{k+1} = V_k \cup \{v_{k+1}\} \quad (19)$$

with the invariant

$$v_i \neq v_j \quad \forall i \neq j \quad (20)$$

which enforces that no cell receives more than one completed double-cross primitive. Define the four connected neighborhood of a cell by unit vectors $e_0 = (1, 0)$, $e_1 = (0, 1)$, $e_2 = (-1, 0)$, $e_3 = (0, -1)$ and define the adjacency predicate

$$v \sim v' \Leftrightarrow |x - x'| + |y - y'| = 1 \quad (21)$$

for $v = (x, y)$ and $v' = (x', y')$. The constrained frontier expansion is defined by a frontier set that contains exactly those unfilled admissible cells adjacent to the already filled set, namely

$$H_k = \{v \in A \setminus V_k \mid \exists v' \in V_k, v \sim v'\} \quad (22)$$

where A is the set of all admissible cells within the embroidery region; V_k is the set of cells already included in the trajectory at step k ; $v \sim v'$ denotes the adjacency relationship, indicating that cells v and v' share a common edge.

This boundary limitation keeps the expansion confined to the admissible interior, as new segments are placed only where unoccupied interior remains and never in prohibited outward paths. To render the selection localized and deterministic, establish the permissible movement array from the current cell as

$$S_k = h \in \{0, 1, 2, 3\}, \quad v_k + e_h \in H_k \quad (23)$$

where h denotes a candidate direction index and vector addition is understood in index space. To penalize sharp macro-turns, let us introduce the current heading $\delta_k \in \{0, 1, 2, 3\}$ and a turning metric:

$$\Delta(\delta_k, h) = \min(|h - \delta_k|, 4 - |h - \delta_k|) \quad (24)$$

and define a fixed deterministic priority key $K(x, y)$ on the grid. A stable choice of K is any fixed bijection of I to integers, and the method only requires that K be time-invariant and independent of runtime floating arithmetic. This priority key is used only for deterministic tie-breaking and is not used to define any limiting geometric construction. The next move index is then chosen by (25)

$$\begin{aligned} \delta_{k+1} &= \\ &= \arg \min_{\delta \in S_k} (\lambda_1 \Delta(\delta_k, \delta) + \lambda_2 K(v_k + e_\delta)) \end{aligned} \quad (25)$$

with fixed weights $\lambda_1 > 0$ and $\lambda_2 > 0$, and the next cell is

$$v_{k+1} = v_k + e_{\delta_{k+1}} \quad (26)$$

which is a deterministic constrained grid-traversal step, because it selects one admissible neighboring

cell from the frontier according to the turning penalty and the fixed priority key.

The traversal procedure needs to be able to escape dead ends when $S_k = \emptyset$ while $|V_k| < N$, and this is managed deterministically by backtracking or by a deterministic local redirection guideline that alters the chosen minimizer to the subsequent best prospect while maintaining the same feasibility constraints. A convenient invariant that detects successful completion is described by (27):

$$|V_N| = N \quad (27)$$

and the closure requirement is enforced through anchor equality defined later, which ensures that the final point equals the initial point in physical coordinates.

The geometric embedding is described in a normalized local coordinate system, in which each cell is represented as a 2×2 reference square. Let the physical coordinate of the lower-left corner of cell (x, y) be

$$b(x, y) = 2 \begin{bmatrix} x \\ y \end{bmatrix} \quad (28)$$

and let the center be

$$m(x, y) = b(x, y) + \begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad (29)$$

then the four corners are given by the expressions:

$$\beta_1(x, y) = b(x, y) + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (30)$$

$$\beta_2(x, y) = b(x, y) + \begin{bmatrix} 2 \\ 0 \end{bmatrix} \quad (31)$$

$$\beta_3(x, y) = b(x, y) + \begin{bmatrix} 2 \\ 2 \end{bmatrix} \quad (32)$$

$$\beta_4(x, y) = b(x, y) + \begin{bmatrix} 0 \\ 2 \end{bmatrix} \quad (33)$$

where each corner index is in $\{1, 2, 3, 4\}$.

The requirement for all diagonal stitch lengths to be identical is fulfilled by requiring that each stitch must link the central point to one of the vertices, as the straight-line distance from the center to any corner endpoint is uniformly the same, namely

$$\|\beta_i(x, y) - m(x, y)\|_2 = \sqrt{2} \quad (34)$$

which implies that if the micro-trajectory alternates between a corner and the center then every stitch has identical length $\sqrt{2}$ for $i \in \{1, 2, 3, 4\}$. Let a corner index sequence within one cell be $\alpha = (\alpha_1, \dots, \alpha_r)$

with each $\alpha_j \in \{1, 2, 3, 4\}$, and define the micro-trajectory points μ_j by

$$\mu_1 = \beta_{\alpha_1}(x, y) \quad (35)$$

$$\mu_{2j} = m(x, y) \quad (36)$$

$$\mu_{2j+1} = \beta_{\alpha_{j+1}}(x, y) \quad (37)$$

for $j = 1, \dots, r-1$. Then every segment length satisfies

$$\|\mu_{s+1} - \mu_s\|_2 = \sqrt{2} \quad (38)$$

for all valid indices s index, and every segment lies on a diagonal of the square because each vector $\mu_{s+1} - \mu_s$ has components ± 1 in the local square frame. A rigid physical realization is established for diagonal stitches of identical length, offering numerical robustness by relying only on integer coordinates and the fixed value $\sqrt{2}$.

The double-cross structure can likewise be situated as a connected line segment within each unit cell. However, adherence to the equal-length diagonal requirement requires that the physically implementable version must be expressed as an alternating series of corner and center points, rather than arbitrary internal coordinates. For practical alignment between the appearance of the polyline and the equal-length stipulation, the provided polyline should be regarded as a target contour, subsequently mapped onto the permissible diagonal-only topology within the cell – specifically, the star graph linking the cell's center to its four corners. This mapping procedure is formally defined by selecting a specific corner ordering, denoted by α , that minimizes the geometric difference from the target contour, while strictly adhering to the allowed set of corner indices $\{1, 2, 3, 4\}$. Should the vertices of the target contour be represented as $q_j \in \mathbb{R}^2$ for $j = 1, \dots, 9$, then a scaled and positionally shifted representation within cell (x, y) becomes $\Theta_j = m(x, y) + \alpha q_j$, where $0 < \alpha < 1$. Despite this formulation, the resulting segment lengths may lack uniformity and are not exclusively constrained to diagonal paths. The substitute structure, which enforces equal-length diagonals, determines the corner sequence α by minimizing aggregate squared error when matching each target contour vertex to its closest corner point in a standardized coordinate system. If $p_i \in \mathbb{R}^2$ are the normalized corners $(-1, -1)$, $(1, -1)$, $(1, 1)$, $(-1, 1)$, then define the quantizer

$$w(q) = \arg \min_{i \in \{1, 2, 3, 4\}} \|q - p_i\|_2 \quad (39)$$

and define the corner sequence for the cell as $\alpha_j = w(q_j)$ for $j = 1, \dots, 9$, which yields a discrete

corner itinerary consistent with the intended double cross topology and executable with equal length diagonal stitches. The resulting micro-trajectory is closed if $\alpha_1 = \alpha_r$, and closure can be enforced by attaching α_1 to the finish if necessary, which is a finite deterministic correction.

The removal of non-stitching transitions in the overall route is accomplished by passing an anchor vertex along the traversal so that the finish of the micro-trajectory in cell v_k is precisely the beginning of the micro-trajectory in cell v_{k+1} . Let the current anchor be a lattice vertex point $\varphi_k \in \mathbb{R}^2$ and let $\varphi_k = \beta_{\ell_k}(x_k, y_k)$ for some vertex index $\ell_k \in \{1, 2, 3, 4\}$. Then the entry corner of the micro-trajectory in cell v_k is fixed by

$$\mu^{(k)} = \varphi_k \quad (40)$$

and the exit corner is defined as the final corner point of the micro-trajectory

$$\varphi_{k+1} = \mu_{T_k}^{(k)} \quad (41)$$

where T_k is the number of points in the micro-trajectory for cell k . The no-transition condition is then the concatenation identity

$$\mu_{T_k}^{(k)} = \mu^{(k+1)} \quad (42)$$

for all k , which holds if and only if the exit corner φ_{k+1} is also a corner of the next cell.

This presents a compatibility limitation between following cells that is narrower than basic four-connected adjacency of cell indices, since two neighboring cells share a side but not always the identical corner, and the anchor propagation necessitates that the subsequent cell be selected so that it encompasses the current anchor. This condition restricts the traversal to adjacent cells that share the current anchor point, ensuring point-to-point continuity between consecutive micro-trajectories. If the anchor grid is the collection of all lattice points at whole-number coordinates, then the group of cells touching a specific corner φ is at most four, and the viable cell shifts from a given anchor are thus constrained by a fixed number, which reduces processing overhead and makes the traversal procedure scalable.

To define this anchor-restricted viability precisely, define the corner lattice as $L_{lat} = (x, y) \in \mathbb{Z}^2$ and define the incidence predicate that a corner φ belongs to the cell (x, y) as (43):

$$\begin{cases} \xi(x, y, \varphi) = 1, \\ \varphi \in \{\beta_1, \beta_2, \beta_3, \beta_4\}, \end{cases} \quad (43)$$

and define the anchor-feasible neighbor set at the k -th step:

$$F_k = \{v \in A \setminus V_k, \mid \xi(v, \varphi_k) = 1\} \quad (44)$$

where $\xi(v, \varphi)$ abbreviates $\xi(x, y, \varphi)$ for $v = (x, y)$. The adjusted constrained traversal procedure then picks $v_{k+1} \in F_k$ instead of H_k , and this is the precise method that removes non-stitching transitions because the trajectory is continued through a common boundary point.

A predictable choice rule can be applied to F_k by incorporating a penalty factor that discourages selecting a cell that would subsequently create a dead end for instance by favoring cells with lower remaining degree. If $d_k(v)$ is the number of unfilled admissible cells incident to a candidate anchor after choosing v , then a stable heuristic is

$$v_{k+1} = \arg \min_{v \in F_k} (\lambda_3 d_k(v) + \lambda_2 K(v)) \quad (45)$$

with $\lambda_3 > 0$, and this is a deterministic variant of Warnsdorff-style degree minimization adapted to anchor incidence.

The closure condition is now expressed purely in terms of the anchor, because the global embroidery trajectory starts at φ_0 and ends at φ_N after stitching all N cells. The global closure invariant is

$$\varphi_N = \varphi_0 \quad (46)$$

Under these two conditions, the entire polyline formed by joining all micro-trajectories is one closed embroidery trajectory constructed by constrained local traversal within the admissible interior. The overall thread length under uniform-length diagonal stitching is particularly straightforward because each segment has the same length $\sqrt{2}$, thus if U is the aggregate number of segments in the overall polyline then the lattice-based stitched length is

$$L_{lat} = \sqrt{2}U \quad (47)$$

and if each cell uses exactly m segments then $U = mN$ and therefore we obtain the lattice condition (47)

$$L_{lat} = \sqrt{2}mN \quad (48)$$

which makes sensitivity analysis straightforward because variability arises only from m if the micro-trajectory is changed, while the macro-level traversal order does not change length when non-stitching transitions are eliminated. If the design-intent polyline is used and resampled into equal-length diagonal segments, then m becomes a deterministic function of a discretization parameter, and if ℓ is the desired stitch length and L_{in} is the geometric length of the

intent polyline in local coordinates then an approximate segment count is given by (49):

$$m = \left\lceil \frac{L_{in}}{\ell} \right\rceil \quad (49)$$

and the resampled stitch length becomes

$$\ell = \frac{L_{in}}{m} \quad (50)$$

which is numerically stable because it depends only on sums of square roots computed once and then a deterministic ceiling operation.

The computational complexity of the constrained traversal is low because each step considers only a constant number of candidate cells incident to the current anchor and updates membership in V_k with a boolean array. If each step examines at most four candidate cells and at most four candidate exit corners, the per step work is $R(1)$ and therefore the overall traversal is

$$T(N) = R(N) \quad (51)$$

in the absence of backtracking. Should backtracking happen, the worst case is exponential in N since the task becomes related to a constrained Hamiltonian-type search, but the deterministic degree rule substantially reduces backtracking in typical simply connected areas. A repeatable fallback involves implementing a deterministic tie-breaking sequence in every arg min operation so that two executions with the same M and identical settings always yield the same stitch sequences, which is vital for highly sensitive analyses. Within this structure, the locality-preserving behavior is not merely heuristic, because the trajectory is constructed through repeated selection from a finite set of admissible local moves limited by an inner mask and an empty set, resulting in localized traversal while preventing outward branching, unnecessary overlaps, and long-distance non-stitching transitions.

The double-cross embroidery obtained by the proposed constrained grid-traversal method is displayed in Figure 3.

Figure 3 displays the absence of non-stitching transitions in the embroidery toolpath obtained by the proposed constrained traversal method. This result is achieved through constrained local traversal with anchor-based continuity, which progressively fills adjacent squares without thread jumps.

RESULTS AND DISCUSSION

A formal evaluation comparing the double-cross embroidery element covering approach using the proposed constrained grid-traversal method against conventional raster or path-based techniques for a bounded area is feasible. Within the traditional raster

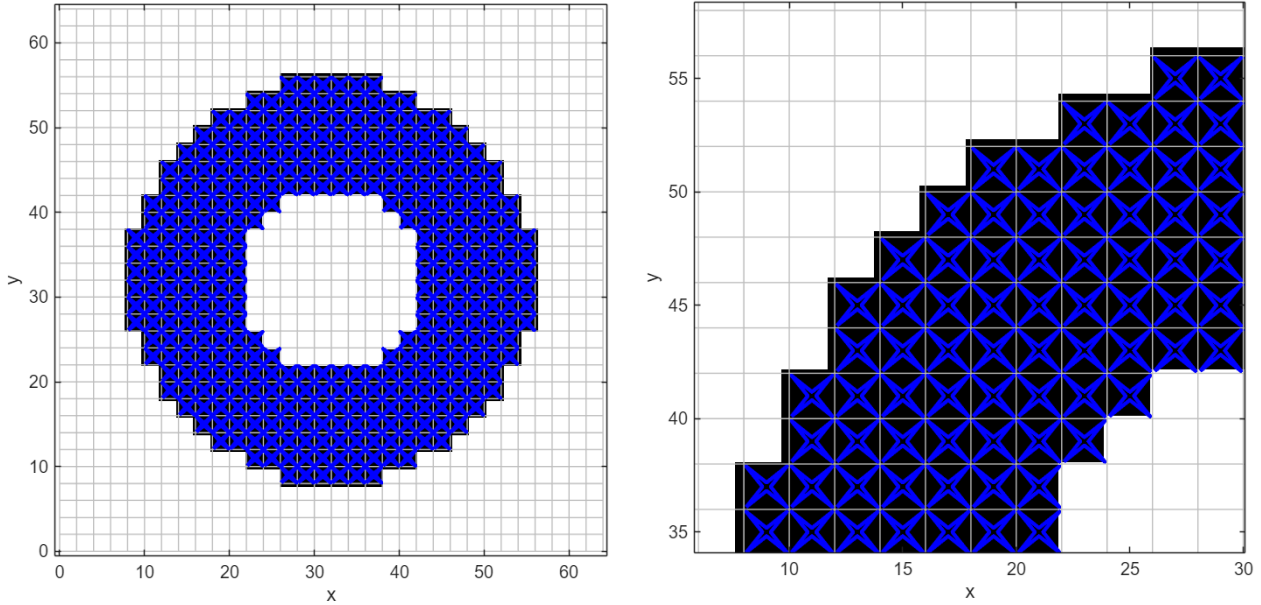


Figure 3. Double-cross embroidery toolpath generated by the proposed constrained traversal method: a) overall view; b) enlarged local connectivity view.

approach, the permissible set, denoted as A_h , is navigated via a straightforward one-to-one mapping, μ , which disregards proximity relationships between points unless they reside on the identical scan line, so the total thread length is governed by

$$L = NL_{in} + L_{tr} \quad (52)$$

with a non-stitching transition term L_{tr} that grows with the diameter of the region, therefore, the fraction of additional thread length L_{tr} / L does not vanish even for large N . In contrast, the proposed method enforces the anchor constraint, which signifies that the macro-level traversal is one continuous path that does not leave the boundary of the already connected set and never leaps to an unattached square, thus the additional non-stitching linking term is exactly zero and the total length reduces to

$$L = NL_{in} \quad (53)$$

which is exactly the theoretical lower bound. This gives the proposed method an inherent efficiency in thread utilization that no standard raster approach can attain without an extra optimization phase.

From a topological viewpoint, the conventional method yields a grouping of N separate closed micro-trajectories that are connected solely by explicit non-stitching transition links, whereas the proposed constrained traversal method generates one continuous macro-level trajectory that connects all micro-trajectories through anchor-based continuity. This distinction can be made precise by observing that in the raster scenario the embroidery diagram possesses N multiple connected components prior to adding couplers, while in the proposed method the

diagram remains connected throughout the traversal because the anchor-continuity condition $\varphi_{k+1} = \varphi_k$ is maintained for consecutive cells.

The benefit is that physical strains are more evenly distributed across one unbroken circuit and thread trimming is not needed, while the drawback is that thread breakage anywhere on the circuit may potentially jeopardize the whole design, whereas in a conventional pattern one broken segment might only affect one localized section. When considering computational complexity, the standard raster algorithm is simple, with time and no need to retrace steps, since the order μ is explicitly defined. In contrast, the proposed traversal is related to a constrained Hamiltonian-type routing problem on the anchor incidence graph, potentially requiring backtracking in the worst case, which grows exponentially with N in extreme instances. Nevertheless, the practical performance of the proposed method with a fixed deterministic degree rule remains near linear for masks without holes because each anchor usually has few viable successors, and traps are uncommon. Consequently, the proposed method exchanges a minor increase in procedural complexity for a substantial improvement in physical performance.

From a geometric perspective, the traditional technique places the basic element via basic shifting and imposes no limits on the successive elements' relative alignment or sequencing, meaning the overall route has discontinuities whose spans are controlled by L_{tr} and whose headings are unconstrained. Conversely, the proposed method employs the uniform-length diagonal principle and anchor connection, compelling every joint to share the same

measurement and align along one of four diagonal directions. This consistency enhances strain balance, lessens needle acceleration, and results in more consistent textile formation.

From the viewpoint of numerical stability and reproducibility the classical method is robust because it uses only simple translations and does not require solving a global combinatorial problem, but it is sensitive to floating point drift when accumulating long transition vectors $V_k - V_{k-1}$. The proposed method, on the other hand, is driven by integer grid logic for V_k , H_k , and F_k , and by exact lattice coordinates for anchors and centers, so topological correctness is maintained by integer arithmetic and floating-point operations appear only in the final plotting of the diagonals, which means that two runs with the same mask and parameters produce bitwise identical stitch sequences. The drawback is that a poorly chosen mask that violates the anchor incidence constraints may lead to failure to complete the traversal, in which case the algorithm must either backtrack or declare failure, whereas the classical method will always produce some traversal regardless of shape.

In conclusion, the proposed method possesses a structural benefit not accounted for solely by length, specifically locality-preserving traversal, continuous connectivity, and geometric regularity. Since the traversal proceeds from the current boundary through admissible neighboring cells, the resultant macro-level trajectory remains spatially concentrated and mechanically coherent. This characteristic renders it highly suitable for embroidery designs demanding uniform coverage and balanced physical reinforcement. Conventional grid techniques miss this degree of local continuity because they are essentially one-dimensional sweeps across a two-dimensional area, thus favoring lengthy straight segments and sudden column shifts that accumulate strain and cause noticeable unevenness in the sewn textile.

CONCLUSIONS

The proposed constrained traversal method offers an approach to construct a single continuous closed embroidery toolpath that covers a discrete representation of a closed area using double-cross primitives while eliminating non-stitching transitions and maintaining strict spatial regularity for all stitch segments. Its primary attribute is the division between a discrete topological traversal layer, which provides complete coverage and closure through boundary and anchor constraints, and a geometric placement layer, which ensures equal-length diagonal stitches and mechanical balance, rendering the entire procedure both formally clear and numerically consistent.

The main benefit compared to traditional grid or scanline techniques is that the overall thread length reaches the minimal theoretical value since no additional linking segments are required, while concurrently the resulting trajectory remains locally connected and spatially coherent, reducing strain concentrations and visual unevenness in the material. The fixed and localized nature of the traversal renders the procedure repeatable and adaptable to large designs without the need for travelling-salesman-type refinement, while retaining the capacity to conform to arbitrary closed forms via the binary mask representation.

From a practical viewpoint, this framework supports the fully automated generation of manufacturing-standard stitch sequences that are efficient in thread consumption, mechanically balanced, and directly controlled by a small set of interpretable parameters. From an academic viewpoint, it provides a basis for subsequent extensions, such as multilevel primitive units, flexible cell dimensions, and combined locality-preserving traversal strategies that may connect creative intent with rigorous production requirements in future digital embroidery systems. Since such computational methods allow the generation of ornamental structures, they may also be used in graphic design to create patterns, decorative textures, and identity elements for the modern digital textile industry.

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AIMS AND SCOPES

“Vlákna a Textil” is a peer-reviewed scientific journal serving the fields of fibers, textile structures and fiber-based products including research, production, processing, and applications.

The birth of this journal is connected with three institutions, Research Institute for Man-Made Fibers, Svit (VÚCHV), Research Institute of Chemistry of Textiles (VÚTCH) in Žilina and Department of Fibers and Textiles at the Faculty of Chemical Technology, Slovak Technical University in Bratislava, having a joint intention to provide, utilize and deposit results obtained through the research, development and production activities dealing with the aforementioned scopes. „Vlákna a Textil“ journal has been launched as a consequence of a joining of existing magazines „Chemické vlákna“ (VÚCHV) and „Textil a chémia“ (VÚTCH). Their tradition should provide a good framework for the new journal with the main aim to create a closer link between the basic element of the product - fibre and its fabric - textile.

Since its founding in 1994, the journal introduces new concepts, innovative technologies and better understanding of textile materials (physics and chemistry of fiber forming polymers), processes (technological, chemical and finishing), garment technology and its evaluation (analysis, testing and quality control) including non-traditional applications, such as technical textiles, composites, smart textiles or garment, and nano applications among others. The journal publishes original research papers and reviews. Original papers should present a significant advance in the understanding or application of materials and/or textile structures made of them.

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