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Review

Supportive, Fitted, and Comfortable Bras for Individuals with Atypical Breast Shape/Size: Review of the Challenges and Proposed Roadmap

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Abstract: Individuals with atypical breast shape/size often find it quite challenging to obtain a comfortable, supportive, and fitted bra off-the-shelf. They include people with very large breasts, who have significant breast asymmetry, and/or have undergone mastectomy or mammoplasty. This paper provides insights in their challenges and attempts to fill the gap in terms of critical review of the current state of knowledge around the topic of bras. Poor and ill fitted bras are associated with breast, chest and shoulder pain, embarrassment, and an overall reduction in quality of life among others. Building upon the advantages and limitations of solutions to improve the fit, support and comfort of bras found in the literature, this paper proposes strategies to solve these challenges. As the problem is multidisciplinary, a human-centered interdisciplinary approach is key to ensure that all aspects are considered at all stages of the process. A modular design allows selecting the fabric characteristics based on the requirements of each bra part. In terms of materials, stretch woven fabrics offer a large potential in the production of bras to enhance the support provided by areas such as the under band and back panels. Bespoke manufacturing takes into account the specificities of each individual. The road map proposed here will contribute to enhance the quality of life of individuals with atypical breast shape/size.

Keywords: bra; atypical breast shape/size; modular design; stretch fabrics; bespoke manufacturing

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1. Introduction

The invention of bras can be dated back to the 14th century [1], and has since evolved with tipping points in the early 19th century when the first bra patents were filed [2]. Since then, there have been landmarks, such as the introduction of large-scale production in 1930 [3] and cup and band sizing in 1932 [4]. Today, there are varieties of bra styles and sizes influenced by fashion, culture, and body image perception.

Regardless of this achievement, the degree of bra dissatisfaction is high [5]. Many women find it difficult to obtain a well-fitted, supportive and comfortable bra [6]; more so individuals with atypical breast shapes and sizes. These individuals may have voluminous breasts [7], significant breast asymmetry [8] and/or have undergone breast surgery. These breast surgeries include mastectomy [9], a surgical procedure for the treatment of breast cancer [9], and mammoplasty, a surgical procedure to reduce or increase the breast volume and/or correct the breast shape [8]. Since the primary purpose of a bra is to support the breast, it is important that the breast shape/size is taken into account at the time of production. However, mass-manufactured bras are highly unlikely to cater to individuals with atypical breast shape/size [10]. This is because they are based on a sample range that is not representative of the entire bra user population [10]. In addition, individuals with atypical breast shape/size are varied and unique; each person is different. The most limiting factors are body variations and experiences, which are not taken into account into the bra production. For example, studies by Vasquez show that no two lumpectomies (a partial form of mastectomy where only a part of the breast is removed) are the same [9].

Therefore, there is a need to re-think the bra industry such that it aligns with the changing needs of women [11]. According to the Canadian Cancer Society [12], 25,000 women will be diagnosed with a new breast cancer in 2021 and will require at least one lumpectomy procedure [11,12]. In addition, studies show that more women have larger breasts due to lifestyle changes over the last few decades [13–15]. Thus, more women are likely to end up with significant breast asymmetry making it more challenging to obtain a suitable bra in their lifetime. This is a challenge as it increases the degree and frequency of bra dissatisfaction. Additionally, increased awareness on body image both in terms of perception and appearance is leading to increased occurrences of aesthetic breast surgeries [13,15]. According to literature, predicted surgery outcomes are sometimes inaccurate, driving up the differences between a breast pair [16,17]. According to Sharland, individuals with atypical breast shape/size require special intervention [6]

Furthermore, the human body has variations from person to person; these variations include neck-to-collar bone, shoulder-to-shoulder, and nipple-to-nipple distance [18]. This contributes to the current bra dissatisfaction experienced by bra users. Individuals with atypical breast shape/size experience even greater dissatisfaction due to their experiences. For instance, studies show that as the breast size increases, breast asymmetry becomes significant [18,19].

In an attempt to fill the gap in terms of critical review of the current state of knowledge around the topic of bras, this paper provides a description of individuals with atypical breast shape/size, and details the challenges they face and current strategies employed in an attempt to solve them. It also proposes a roadmap and discusses fabric analysis, bra design and patterning, fitting procedure, wear trials of prototypes, and translational approaches to patients as possible strategies to solve the remaining problems.

2. Individuals with Atypical Breast Shape/Size

This section inventories some conditions that can lead to atypical breast shape/size, either naturally or as a result of a surgery.

2.1. Breast Asymmetry

Most women have some level of breast asymmetry. However, if the difference in size and shape between the two breasts is significant, it can result in a medical condition known as anisomastia [20]. According to Reiley, when one breast is 30% larger or more than the other one, it is considered asymmetric [21]. Significant breast asymmetry has been reported to be present in as much as 44% of women [22]. Breast asymmetry includes also differences in the degree of sagging, position on the chest wall, and nipples placement and shape [10,21,22]. For these individuals, finding the right bra is challenging as the breast pair could be of different cup sizes [20]. The frustration they encounter while shopping for bras often puts them in a position to consider surgery, with all the risks and issues associated with breast surgeries [23,24]. Hence, there is the need to develop a model for bra making on a case-by-case basis that allows for individuality. This could potentially derail individuals from undergoing surgeries due to bra dissatisfaction.

2.2. Macromastia

Macromastia is the medical term for women with bulky breast tissues (plus-sized) that make their breast abnormally large [25]. There are no clinically defined measurements of symptomatic macromastia due to the wide variation of body shapes and sizes [26]. However, women having excess breast tissue between 900 g and 2220 g are considered large breasted [21,26]. Within the industry, large bra sizes are typically cup D and above [21,25]. Breast asymmetry also becomes more obvious as the breast size increases [25]. This contributes to the challenges these individuals experience when shopping for bras. Pandarum et al. studied the dissatisfaction experienced by plus-sized women with poorly fitted bras [27]. They reported the inadequacies of the current sizing system used by bra manu-

facturers in catering to this group of women. A further complication arises when women have excess skin around the armpit and breast base [28].

2.3. Mastectomy

Mastectomy is a medical surgery used in the treatment of breast cancer [7]. The procedure involves the partial removal of cancerous lumps in the breast or the complete removal of one breast or both breasts in severe conditions [29,30]. After a mastectomy, many women find it difficult to obtain bras that fit their breasts, especially if they have become significantly asymmetric. In addition, the breast prosthesis will not behave the same way as the remaining breast [31,32]. This issue may affect their physical and psychological health [31]. Furthermore, mastectomy increases the natural body variation that exists from person-to-person. Studies have shown that custom-made bras provide better comfort to those using prostheses after a mastectomy [31–33].

2.4. Mammoplasty

The reduction or augmentation of the breast and/or correction of the breast shape is known as mammoplasty [8]. The reasons why women opt for mammoplasty include improving their sexuality, confidence and appearance [34]. Additionally, studies show that large breasted women go for reduction mammoplasty due to health issues such as back, neck and breast pain [34,35]. Furthermore, having large breasts has been associated with body shaming, reduction in self-esteem and negative bra shopping experiences [34–36]. These issues often prompt the need for mammoplasty. However, things can sometimes go wrong; the procedure may lead to unwanted outcomes, including breast asymmetry [37,38]. Indeed, mammoplasty, as any other surgery, has its own limitations such as poor projection of incisions and scars [38].

3. Challenges for Individuals with Atypical Breast Shape/Size

3.1. Bra Dissatisfaction

Bra users have often expressed dissatisfaction due to poor fitting, low support and overall discomfort [36,39]. Table 1 details some of the common issues reported with bras. Poor and ill fitted bras have been associated with reduction in quality of life [27], increased breast, back and chest pain [6,27], which is intensified during sporting activities [6,39], as well as bra displeasure [5]. In addition, research shows that wearing poor and ill-fitted bras negatively impacts sleep and sexual activity [27,36,39]. On the opposite, well-fitted bras have been linked with reduced instances of breast deformation and sagging that may arise from weakened support tissue after massive weight loss and surgeries [39,40]. They also lead to increased breast firmness [40] as well as reduced post-surgery complications [41]. In addition, well-fitted bras allow for improved mobility and reduce exercise-induced pain by as much as 85% [6,42]. In particular, custom-made bras have positive impacts on the psychological experience of women, thereby improving their mental well-being [34,42]. Furthermore, there is a huge focus on body image driven by the fashion and beauty industries [34]. Thus, more people are concerned about how they look and how others perceive them. In some cases, this leads to body shaming [34]. According to Swami & Furhan and Neto et al., having large breasts has been associated with body shaming and reduction in self-esteem, with impacts on mental, physical and psychological health [34,36].

Table 1. Description of some bra issues, and their common causes.

Issue	Description	Common Causes	Source
Bulging	Skin pushing over or underneath the cup, band or straps	Large breasts, bra size too small or too tight	[43,44]
Digging	Bra parts digging into the skin, especially in individuals with extra under arm and side skin	Bra too small, or too tight	[45]
Lifting away	Centre gore lifts creating space between the bra and the skin.	Under wires, stiff materials, bra too small or too tight	[46]
Gapping	Gaps in the center gore or cups	Large breasts, bra too big or too loose	[44,46]
Double breast	Occurs mostly in deep-V and push-up style bras used for enhancing cleavages. It occurs when a large part of the breast is outside of the cup.	Large breasts, improper fitting or sizing.	[46]

Individuals with atypical breast shape/size have also reported displeasure with the outcome of specialized bras, which would have been expected to solve their bra problems [31,32,47]. Fong conducted a study on the aftermath of mastectomy patients in terms of their adjustment to life using mastectomy bras and prosthesis [47]. The study reported that most post-mastectomy patients find their bras uncomfortable. Similar views on the displeasure of post-mastectomy patients were shared by Jetha et al. [31]. When describing their experiences and what they hoped to find, women who underwent mastectomy indicated a desire to obtain bras that are unique to them [29–31]. Participants of a study carried out by the Breast Cancer Organization expressed their realization of the fact that no two women are the same [30]. Additionally, an investigation of the use of existing commercial bras and prosthesis proved that custom-made bras provide more comfort and satisfaction [32,33]. These studies highlight the need for custom-made bras that are not only unique to each individual, but provide added functionality and overall value.

Complaints made by patients seeking mammoplasty, particularly in case of a reduction, include neck and back pain, embarrassment, harassment, and poor self-image [37]. In such instances, it is quite difficult to deter such persons from going for a mammoplasty. However, Wood et al. [48] suggested that a good support bra could potentially mitigate breast pain and provide adequate support needed by the breast. It will also aid in a stress-free physical activity for large breasted women and perhaps discourage them to go for breast reduction. Outcomes following reduction mammoplasty were studied by Neto et al. [34]. The study was done on two groups of 50 women each; Group A was composed of in-patient (post-operation) and Group B included outpatients (pre-operation) who formed the control sample. Group A women were administered questionnaires six months post-operation. The researchers reported a significant improvement in self-esteem and functional capacity, but noted that a special brassier would aid in the initial recovery process. Therefore, there is the need to have special post-recovery bras that can enhance mobility and keep the breasts in place during physical activities

3.2. Measurement, Fit and Mass-Manufacturing

Inaccurate measurement often results in ill fit [27]. This leaves bra users frustrated [33]. It is challenging to obtain a good fit when it comes to individuals with atypical breast shape/size. Fit is regarded as the accuracy of the measurement done on an individual [49]. Its efficiency is linked to the ability to customize garments [50]. It is done conventionally using a tape rule as the measuring tool. This means measuring an individual standing and transferring those numbers to the flat fabric on a cutting table. This mostly introduces errors; the degree of error often depends on the experience of the measurer [51]. Thus, fitting is highly dependent on the skill of the measurer/fitter and the posture of the individual

during the measurement [52]. The process requires a unique skill set and experience, one that is not often found in the average sales person in the stores [50].

On the other hand, mass-manufacturing is the industrial process of making clothing for multiple users with sizing based on a select few [10]. Mass-manufacturing comes with its benefits such as increase in productivity and profitability to brands and manufacturers. For users, mass-manufacturing takes away individuality and the ability for users to contribute to their clothing [51]. With regard to bras, the customary process of selecting a few sizes is done through the use of models [10]. These models, selected using clusters of bra sizes, seem not to give a good representation of the entire population [51]. Because of that, bra dissatisfaction is not a thing of the past, and it clearly shows the limitations of mass-manufactured goods. In reality, not everyone fits in the mass-manufacturing models used for products [5]. Participants from a study carried out by the Breast Cancer Organization expressed how they realized through that experience that no two women are the same [40–42]. Two separate studies by Kubon et al. [32] and Shin et al. [33] compared the use of existing mass-manufactured bras and custom-made bras and their compatibility with breast prosthesis. They both reported that custom-made bras provided more comfort and satisfaction. Therefore, there is the need to produce bras that are not only unique to each individual, but takes their experiences into account.

3.3. Breast Pain

Pain of any sort reduces a person's quality of life, and breast pain is a common occurrence in women [40]. When assessing breast pain prevalence in women with small to medium breasts, Sharland reported that most women will experience breast pain in their lifetime [6]. Similarly, Scurr et al. evaluated the prevalence, severity and impact of breast pain in the average population [40]. They reported that at least 50% of women in the general population suffer from breast pain. This ratio increases to about 65% for women with breast cup size larger than DD. This occurs particularly as the breast volume increases, which suggests the need for well-fitted bras to reduce breast pain for large breasted individuals. Furthermore, Sharland's study evaluated the possibility of well-fitted bras to reduce breast pain [6]; they concluded that wearing a bra that fits well and provides adequate support will greatly reduce the risk of breast and chest pain.

Breast pain has also been linked to poor bra fit. Xiaomeng investigated the pressures and sensations caused by wearing a bra and the influence on bra fit on them [39]. The results showed that the pressure and sensations due to ill-fitted bras result in discomfort, and although they are not always the direct cause of breast pain, ill-fitted bras can aggravate the associated discomfort. As part of their results, the author reported that keeping the breast in position, especially during intense activities like exercising, is important. As echoed by White & Scurr [53] and Sharland [6], keeping the breast in position can significantly reduce breast pain intensity caused by motion. It becomes more critical for individuals with large breasts [54]. A firm breast support has been the most commonly reported solution to reduce breast pain [27,31,40]. It is estimated that an effective supporting bra can reduce instances of breast pain by 85% [54–56]. Wearing the right bra has even been suggested as potentially offsetting for many cases the need for reduction mammoplasty [56].

4. Current Strategies

The current strategies to improve bra satisfaction are mainly two folds: the use of sizing tools and software, and increasing bra styles and design.

4.1. 3D Scanners and Other Measuring Software

There are a number of sizing software/3D scanners that are used to automate the sizing/measuring process. Some of them such as VickingSlice, Physio easy, Posture print, SAPO, and Fisiometer originate from the medical field where they were designed for the purpose of posture and body measurements [57]. Most clothing manufacturers use conventional 3D body scanners, which are cheaper, more accessible and easier to use

compared to the medical systems [50,58–61]. These sizing software/3D scanners help manufacturers by increasing the production speed. However, they do not appear to help bra users [61–64]. Other software such as mybraFit^{TM} designed by the company Wacoal and Upbra designed for Upbra are widely used by bra manufacturers [65]. Although these sizing applications were designed for the company's specific products, a good number of shop owners and users have now adopted them. Reviews on these applications have indicated that they are not useful for everyone, and most customers make a return [43,57].

Researchers estimate that in most cases, 3D scanners have automated the measuring process, but because of their limitations, they have not improved bra fit [27,59]. The limitations of 3D scanners include the fact that people's breathing during scanning affects the accuracy of the measurement [27]. In addition, 3D scanners are not able to capture the full breast volume, especially above a cup F, as the breast is likely to be in "fall" position during scanning [60,62]. Furthermore, measurements by 3D scanners are impacted by postures and the eventual positioning of physical features such as the back curvature and collar bone [28,61]. Figure 1 shows the 3D scanning of individuals with different sizes/shapes of breasts [28]. They show differences in the nipple position on the chest, nipple to nipple distance, and nipple to collar bone distance. This ultimately leads to profiling and sampling [5,28,61]. Profiling groups individuals based on the assumption that the measurements of a few can be projected on larger populations without errors. However, research has shown that not only are there errors, but also that these errors are larger than is acceptable and result in bra dissatisfactions [10,28,51].

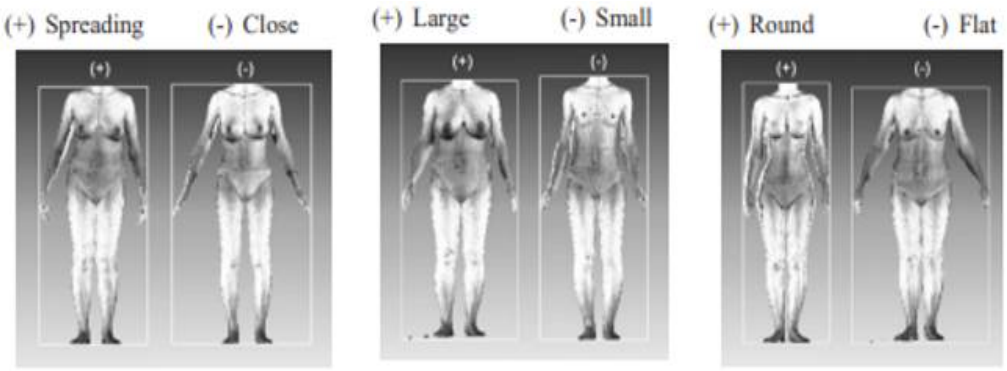


Figure 1. 3D scanning images showing differences in breast shape, size, and nipple position (reproduced from [28] with permission from Elsevier).

Bougourd et al. measured 22 young females using both 3D scanner and traditional tapes [49]. They found that in practice, issues when using 3D scanners increase rather than decrease when increasing the number of subjects. The issue appears to be related to the choice of posture and differences in sensitivity between instruments. In addition, some 3D scanners require the location of certain landmarks such as the collar bone to establish their focus [62]. This poses a major challenge because of the inherent variations in the location of these landmarks on the human body between different people [19]. In addition, greater variations in the position of these landmarks occur above cup F [60]. Studies by Catanuto et al. [63] and Bengston & Glicksman [5] also reported variations in 3D scanner measurements due to differences in breast shape even with breasts of identical volume. A similar study by Ancutiene targeting silhouette gowns concluded that due to different postures, it is difficult to achieve a measurement with 3D scanners that offers optimal fit [62]. In addition, different scanners may provide different results [63]. This can influence clothing sizes and contribute to the already existing confusion regarding chart sizing across brands and countries [64]. In general, statistical analysis suggested that most women are likely to wear a bra with an under-band that is too large or too small when measured with a 3D scanner [60].

4.2. Specialization and Production

There are a variety of specialized products commercially available that ought to cater to certain categories of the bra user population, including individuals with atypical breast shape/size. These include extra-large, sport and mastectomy bras. However, research has shown they do not mitigate bra problems to the level that brings consumer satisfaction.

"Extra-large" bras designated specifically for individuals with large breasts are increasingly common in stores. Unfortunately, these bras are only made bigger in terms of size but the design remains the same [66–68]. Additionally, they do not have the performance, for example in terms of strength, that is required for such "extra-large" bras to function properly [68]. Large breasted women need bras with added support to limit chest pain [48,54]. Articles by Eva's Intimate [66] and Forever Yours Lingerie [68] highlighted some of the issues associated with voluminous breasts:

- Back band rising: this is mostly due to the weight of the breast dragging it downwards with little or no support from the under band and/or strap;
- Falling straps: when the band is too narrow, too big or the shoulders of the individual are slopped, the straps are likely to fall;
- Displacement of the centerpiece (gore): the gore should rest on the sternum, otherwise the breast will put pressure on the gore causing it to bend, break or poke through the ends;
- Side boobs: this occurs when the side breast tissue is peeking out of the bra. In most cases, this adds an extra layer of excess skin to what may already exist under the armpit;
- Quad boobs: this happens when the cup is too small or the style does not fit. Unfortunately, women with big breasts often cannot afford to wear certain styles as their breasts require to be enclosed.

Sports bras have gained a large visibility and are one of the fastest selling bras. Today many top brands including lululemon, adidas and GymShark, who are key players in sports bras, still use mass-manufacturing. Their bras are marketed on the basis of fit and comfort; however, studies continue to show that bra users do not get the desired outcome [69]. Chung & Jang evaluated the comfort of sports bras with a focus on style and their corresponding compression levels after walking and running [70]. The study reported that "racker back" compression sports bras were uncomfortable due to high compression levels. The high compression led to an increase in skin pressure, thereby causing pain in the upper torso. On the other hand, they resulted in reduced breast displacement during exercise activities.

In another study, Lawson [71] assessed the comfort and support provided by eight selected sports bras of four different breast sizes (A–D). Lawson recorded that women with size D require extra support to significantly minimize breast displacement during intense activities. Thus, even for sports bras, women with large breasts have requirements that are different from small to medium breast sizes. Sports bra design, whether they include front zippers, back hooks, or ease of donning and doffing, has also a significant impact on the fit, comfort and wearability of the bra. Better fitting sports bras will also be critical to allow the proper operation of wearable vital sign monitoring. Navalta et al. [72] evaluated sports bras with integrated smart technology to monitor heart rate. They reported that proper fit are critical for the accuracy of the biometric data obtained.

Post-surgical bras are designed to cater to individuals who have undergone breast surgery [73]. Makers of post-surgical bras in the commercial space include Dale by Dale medical products Inc., CareFix by Tytex Inc., and Amoena by Amoena Ltd. However, reports show that their level of satisfaction is still low [33]. This research hypotheses that it is because the production process is still based on mass-manufacturing. Even though the benefits of these bras such as the reduction in infection rate and prevention of stitch raveling are well documented [73,74], the main challenge lies in finding one with the right fit for optimum functionality [74].

Hummel & Charlbois investigated the support level of post-surgical bras. The study had 20 post-cardiac surgery females who wore the bras between one to three weeks after surgery [74]. In the findings, they recorded that 77% of the participants indicated that the bra was helpful and would recommend it to a peer. However, about 65% of the participants reported displeasure regarding fit and wear-ability. In another study specific to post-mastectomy patients, Nicklaus et al. reported that bra fit is currently lacking in most post-surgical bras [75]. However, a well fitted bra can significantly improve the quality of life of those who have undergone breast surgeries. The authors also stated that available products do not meet the needs of breast cancer patients. Their findings also suggested that changes should be made, for example so that the bra does not irritate the scar.

Therefore, the existence of different bra styles and varieties without a change in the production process will make no significant difference to improve bra satisfaction. It is clear from the literature that the availability of specialized (custom-designed) bras is not enough. Custom-made bras are thus thought to be a better strategy towards improving the satisfaction of individuals with atypical breast shape/size.

5. Proposed Roadmap

5.1. Selecting the Right Type of Fabric Depending on the Bra Part

The primary raw material in making a bra is fabric. The fabric type and properties are key in determining the quality and performance of the bra delivered to users. Findings from the literature show that most, if not all, commercially available tight fitting garments including bras are made from knitted fabrics [51,76]. Because of their structure, knitted fabrics have certain characteristics that make them suited to this application. They have a very high stretch with the potential to recover fully after an extension provided that the elastic limit is not exceeded [76–78]. In addition, they are highly flexible and provide significant drape over the body [79]. This makes them well suited to applications where tight fitting is required. This includes socks, compression garments, bras and breast bands [79,80]. However, for individuals with atypical breast shape/size, knitted fabrics alone may not provide the properties required for optimum bra functionality. For instance, properties such as strength may not be fulfilled by knitted fabrics. This is particularly true in areas such as the back and side panels that provide support, form and structure to the bra.

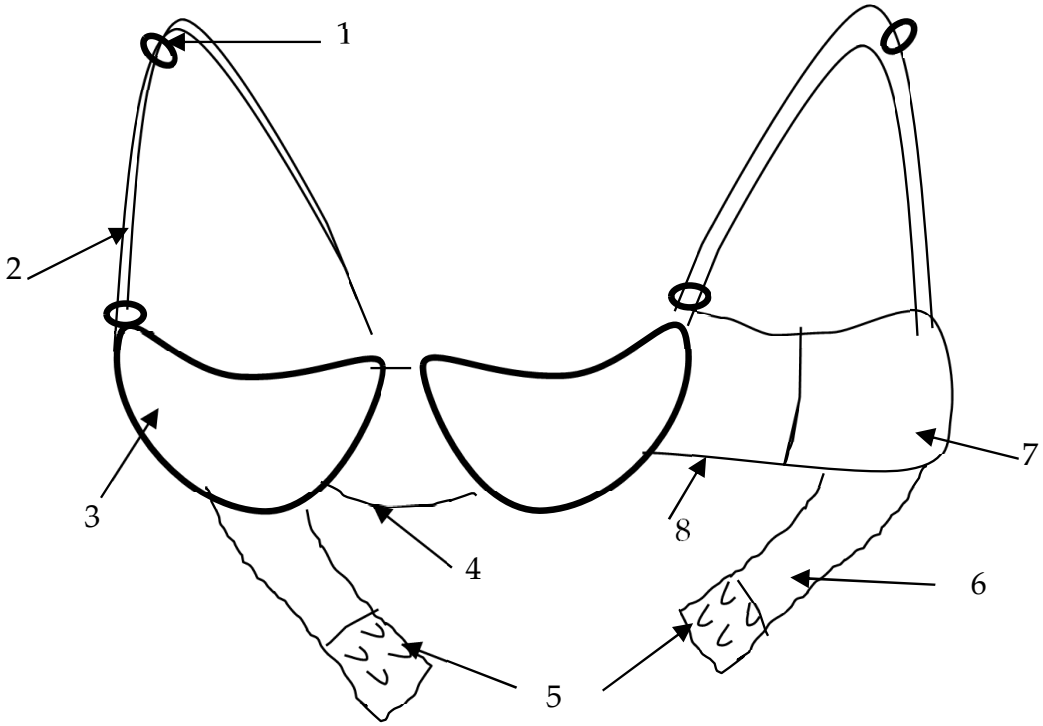
Furthermore, a complete understanding of the fabric used is needed to improve the performance of the bra [10]. As already mentioned, it is important that the fabrics used in the production of bras provide the necessary support in terms of strength [81] and have adequate flexibility to drape over the breast tissue [81,82]. In addition, they should have adequate stretch to allow for good rotation of the arm [81], be breathable and well ventilated to allow for perspiration to be evacuated [81–83], and do not cause irritation or skin allergies [75].

Lawson and Lorentzen assessed seven commercial sports bras in terms of their performance for different breast sizes (small, medium and large) [84]. They reported that subjective measures of support and comfort were not correlated: bras that provided effective support were the least comfortable and vice versa. Having the proper balance in terms of support and comfort is thus quite complex. In another study, Norris et al. evaluated commercially available sports bras for their performance and function [85]. The study involved 77 females and 94 commercial bras. They reported that the bras did not provide enough support. In addition, if bras are supposed to provide support during exercise when the breast is in motion, support requirements are not the same for everyone [18]. These authors showed that support requirements increase as the breast volume increases.

Therefore, looking into other types of fabrics such as woven structures could be very useful. Woven fabrics have high strength due to their mode of construction [86]. However, since the bras are worn next to the skin, it is important that the fabrics have some degree of flexibility to allow for ease of movement while in motion [87]. Woven fabrics by themselves are rigid, stiff and have very little to no extensibility [88]. However, the addition of

elastomeric yarns during the fabric production reduces the rigidity, increases its flexibility and improves hand feel [89]. These fabrics are known as stretch woven fabrics [85].

It is thus proposed to look at the bra and its parts from a functional lens in order to decide what fabric type is most suited to which part. Figure 2 shows the different parts of a typical bra. The different bra parts can be considered as individual modules in order to optimize their functions. This will ensure that the right fabric is employed depending on the intended function of each part. Table 2 shows the different parts and the fabric types that could be the most suited in order to optimize function. In this roadmap, we propose the use of stretch-woven fabrics in areas that provide support, form and structure such as the gore (4), back panel (6) and side panel (7) (Figure 2). On the other hand, knitted fabrics could be used for areas such as the cup (3), where drape, stretch and flexibility are key factors. We hypothesize that a bra made from a combination of these fabrics will deliver a more supportive, comfortable and durable bra that is well suited to individuals with atypical breast shape/size.



1. **Sliders**: to adjust the strap length.
2. **Straps**: link the cups to the bank panel.
3. **Cup**: hosts the breast.
4. **Gore**: connects the two cups.
5. **Hooks & eyes**: connect the two back panels & to adjust the panels
6. **Back panel**: provides support
7. **Back side panel**: enhances support & links the side & back panel.
8. **Front side panel**: inks the cup to the side panel &provides lift to the breast.

Figure 2. Front view of a typical bra.

Table 2. Different bra parts, their function, most suited fabric type, and rational for the fabric selection.

Bra Part	Function	Knitted	Stretch Woven	Rational for Fabric Selection
Strap (2)	Support the cups & back panels		✓	Good strength to ensure connections between the cup and the back panel
Cup (3)	Hold the breast	✓		Excellent drape to host the breast tissue, good breathability to prevent sweat & irritation between the breast and the upper stomach area
Gore (4)	Connect the two cups	✓		Good stretch to accommodate different breast sizes and breathability to promote ventilation
Back panel (6)	Support the side panels & straps		✓	Rigid enough to provide support
Side panel (7 & 8)	Link between the back panels & cups		✓	Good stretch and elasticity to provide good silhouette. This is especially important for those with excess skin around the armpit

Knitted and stretch woven fabrics come in varieties of styles and properties. A number of their characteristics such as weight, knit type, spandex content (in the case of stretch woven fabrics), and yarn density can impact the performance of the fabric [76,90]. Air permeability, stretch and recovery, tear strength, tensile strength, moisture management, and dimensional stability, for instance, are important in different measures depending on the bra part. The choice of the fabric type—knitted vs. stretch woven -is the first step. The next phase is to assess if these fabrics possess the required properties/performance required for the specific bra part they are intended for. Literature shows that selecting fabrics with adequate mechanical properties, comfort and durability will improve bra satisfaction [10]. The ASTM D7019 standard is a document that outlines the standard performance specifications for brassier, slip, lingerie and underwear fabrics [91]. It provides a guideline to manufacturers and other trade partners in terms of acceptable fabrics with respect to bras. Table 3 lists various mechanical performance (e.g., burst strength, tear strength and breaking strength) and durability properties (e.g., dimensional stability, pilling and color fastness) and the associated requirements found in ASTM D7019.

Table 3. Mechanical and durability requirements according to ASTM D7019 [91].

Property	Test	Requirement	
		Knitted	Woven
Mechanical	Burst strength	220N	-
	Tensile strength	-	111N
	Tear strength	-	6.7N
Durability	Pilling	Grade 4	Grade 4
	Dimensional stability	5%	5%
	Colorfastness: Laundering	Grade 4	Grade 4
	Colorfastness: Perspiration	Grade 4	Grade 4

Interestingly, the ASTM D7019 document makes no mention of comfort and stretch and recovery. However, these characteristics are critical to insure the performance of a

bra and the satisfaction of the user. Stretch properties determine the clothing pressure on the skin [79] and the ability of the fabric to recover after stretch [92], and contributes highly to ease of motion [90]. It can also impact aesthetic properties and the production process in terms of cutting [82]. The stretch and recovery property of fabrics is influenced by weight, yarn type and structure amongst others [93,94]. Different standard test methods are available to assess the fabrics' stretch and recovery of textiles. This includes for example ASTM D4864, ASTM D3107, and ASTM D2594 [95–97]. The fabric comfort characteristics play a vital role as well [98,99]. Comfort properties include physical characteristics (e.g., air permeability, porosity, cover factor) and hand properties (e.g., smoothness, softness). In addition to being multifactorial, comfort is also high subjective, which makes it a relatively complex phenomenon [100]. However, researchers agree that clothing should maintain a good microclimate as a basis for providing comfort [74,101].

5.2. Bra Design

Bra design can vary greatly depending on the style and function [10]. Understanding that each part is designed to achieve a specific task is an integral part of the process. For example, the strap connects the cup and the back panel; while the back panel provides support (Table 2). As a result, the strap and back panels must have adequate strength to support the cup. Different requirements in terms of strength for the strap and back panels will exist for different cup sizes because of the weight of breast tissues. In addition, the bra should be designed in modules, such that the parts can be fitted to the individual body shape. Modularity is a concept that was imported from computer science and engineering into textiles to enhance textile design [102]. It is defined as the degree to which a product may be separated, combined and recombined [103]. The purpose is to enhance performance through versatility and accommodate differences [102].

Chen & Lapolla [104] explored the concept of modularity within Bye's "research through practice" design approach [105]. They described the benefits of modularity for textiles in terms of waste reduction in labor, time and material. They also mentioned that the infusion of modularity and design through practice optimizes garment design and fit. In this roadmap, we propose that modularity is used to optimize the overall performance of a bra beyond its design. An example of the implementation of modularity in bras design and beyond can be found in the patent by Krawchuck [106]. The bra parts are preassembled during production. They are adjusted during a one-fitting session before the final stitching is done. Designing bras as modules that are adjustable during the fitting process is a fundamental step in this roadmap. Each part of the bra is adjusted individually and relative to each other to fit different breast shapes/sizes and overall body shapes prior to final assembly.

Another important point of note in the design is interaction and compatibility. It is vital to consider how each part will interact with the others to enhance the compatibility between the different bra parts as well as the final fit, support, and comfort of the bra [102,107]. For instance, accessories such as the hook and eye (item 5 in Figure 2) and strap sliders (item 1 in Figure 2) must be compatible with the whole bra assembly. In particular, they should not cause any form of discomfort and/or limit the donning and doffing of the bra [108,109]. These accessories could potentially impact the wearability and useability of the bra. For example, in the case of an early post-surgery state, great care should be taken to favor the healing of the wound.

5.3. Customization and Fitting

Customization (also known as bespoke) is the process by which clothing is made for a specific individual [110,111]. This process takes individuality into account by tailoring a garment to a specific body type. This opposes to mass-production, where a few sizes and body types are selected to cater to all [10]. Customization is popular in suit making and less common in other forms of clothing [112]. This is due to certain limitations such as time,

design and labor [53,112]. However, customized garments have been proven to offer better fit and clothing satisfaction [113].

In reality, not everyone fits into mass- manufactured goods that are based on models [111]. Custom-made bras as an alternative to mass-manufactured bras could mitigate the dissatisfaction of users [51]. Custom-made bras made with carefully selected fabrics for the individual bra parts are likely to provide maximum mechanical support and functionality. Furthermore, custom-made bras will factor in the experience of the user, such as breast surgery and weight loss. Based on the intended use of the bra, customization also allows users to determine the level of performance such as strength needed. This may be based on the type of activity, breast volume, and/or previous experience [54,55,114].

Mass-production of specialized bras such as sports bras and mastectomy bras limits their performance as it does not allow them to take into account each user's body type and/or breast shape/size. Thus, it reduces the potential to provide optimum fit, support, and comfort [113]. Therefore, we hypothesize that these bras could perform better if they were not mass-manufactured but custom-made.

A limitation to custom-made bras is higher cost and limited variety of styles [113]. However, in terms of cost, research has shown that consumers are willing to pay for value and comfort [114,115]. According to Tsorenko & Lo, custom-made bras are more comfortable [114]. Regarding styles, every woman has their "favorite bras "; these are bras that fit the most, and come in their desired style [56]). Getting one's favorite bra style may be difficult with currently available custom-made bras [69]. Thus, we hypothesis that increasing the choice of styles in custom-made bras will greatly improve the adoption of custom-made bras. In addition, the associated cost is generally not likely to be a limiting factor if there is a significant gain in fit, support, and comfort.

Finally, it is critical to differentiate between custom making and custom design as the two expressions are often used interchangeably. Custom making is bespoke, i.e., fitted to the wearer, while custom design is a unique concept, idea or innovation that can be applied to a variety of bra sizes during production.

5.4. Wear Trial

Wear trials can be conducted either by interviews or through online or paper-based surveys [116]. They have been successfully used to analyze the performance of finished goods. The purpose is to test functionality, compatibility and user-friendliness of the goods [117]. With regard to bras, very little information in terms of the results of wear trials has been documented or shared by manufacturers. However, some investigations have been performed for research purposes using mass-manufactured bras.

Bowles et al. administered a mail survey to quantify the breast support obtained from different bra styles in regular bras [118]. Their survey results showed that over 65% of the participants chose an encapsulating bra especially for intense activities, because it reduced breast motion significantly. However, in terms of fit, they went for other options such as a V-shaped bra. Furthermore, they reported that the difficulty to obtain a good fit increased with increasing breast volume. Similarly, Chan et al. conducted an interview survey with 80 women to gain women's perspective on bra design and common causes of discomfort [119]. The focus was on fit, support, cup shape, underwire, sizing, elasticity and fasteners. The survey results highlighted bra straps, cups and underwire as major areas of discomfort. Accordingly, Brown et al. carried out an online survey involving 30 marathon female athletes [55]. 75% of participants reported bra fit issues that included shoulder straps digging in, which was predominant in women with bigger breasts.

Naismith & Street compared the usefulness of a special post-surgical bra called *Cardibra* with that of a regular bra [120]. The method involved clinical trials where participants wore the bras and then answered interview questions. The results indicated that the Cardibra might have beneficial therapeutic effects on pain levels and wound healing up to day 14 after cardiac surgery due to the ability of the bra to keep the breast in position and provide the needed support. In another study, Bolling et al. used a paper-based

investigator-developed survey to evaluate the satisfaction and compliance level of commercial mastectomy bras [121]. The study involved 60 post-cardiac surgery large-breasted women. They reported that the bras fell short of compliance and were uncomfortable, which made the clients dissatisfied. Furthermore, Hummel & Charlbois surveyed 20 post-cardiac surgery female patients wearing post-surgical bras for one to three weeks after surgery [73]. The participants answered survey questionnaires after each week. In their findings, over 75% of them acknowledged the usefulness of the post-surgical bra but indicated the need for fit. Additionally, Greenbaum et al. interviewed 103 women who were using a post-surgical bra and/or breast prosthesis [56]. They concluded that women who undergo surgery often experience difficulty in obtaining a well-fitted bra, which would significantly improve their quality of life after surgery. These studies show that different bra products can provide different levels of satisfaction. Thus, conducting a wear trial of products before their commercialization is important to ensure that they meet the users' needs.

Human trials thus appear as an effective way to test product performance and customer satisfaction. In addition, for individuals with atypical breast shape/size, it is critical to ensure that they obtain functional bras that respond to their needs.

5.5. Translational Approaches to Patients

The reduction in quality of life experienced by those with atypical breasts shape/size includes ill-fit, uncomfortable pressure sensations, and breast pain especially those with large breasts [39,40]. For those with large breasts, most studies have assessed the impact of bra fit and support on their overall comfort during intense activities, but rarely from a patient perspective. Individuals with voluminous breasts tend to have increased breast displacement as motion increases. McGhee et al. [122] assessed the bra-breast force and its implication on sports bra design. They found a significant correlation between breast mass and breast displacement. They concluded that developing bras that can significantly reduce breast displacement is critical to the comfort of these individuals during physical activities even in motion as low as walking [122]. Coltman et al. [19] conducted an analysis to assess which bra components contribute to incorrect bra fit in women across a range of breast sizes. Incorrect fit was predominantly due to the cups, front band and straps [19].

Regarding postmastectomy and/or mammoplasty patients, most studies have been from a clinical perspective [74]. Hummel & Charlebois [74] assessed the effectiveness of surgical support bras after a cardiac surgery. A total of 77% of the participants expressed that the bras contributed to a reduction in pain by providing support. However, some participants stated that the bras did not fit and was unwearable. They reported that appropriate training on bra use and making available a broader range of sizes would help improve fit and wear-ability [74]. Nicklaus et al. [75] assessed the need for undergarment for post-mastectomy patients as a key survivorship consideration. They concluded that ready-to-wear surgical bras do not adequately cater to the needs of postmastectomy patients.

This roadmap will have evident benefits on mastectomy patients and those undergoing various medical treatments affecting the breasts and the torso as it allows providing a more holistic perspective and improve their overall quality of life beyond the medical treatment. As illustrated in Figure 3, the process begins with determining the specific category of the intending bra user (T1), which defines the purpose of the bra. Next, the best fabric is selected for the production of the modular parts (T2), which are pre-assembled. The fitting (T3) is done within one session and allows that each client is catered for based on their specific needs. Finally, the modular pieces are stitched to their final position and the bra is delivered to the client who wears it to assess its fit, support, and comfort.

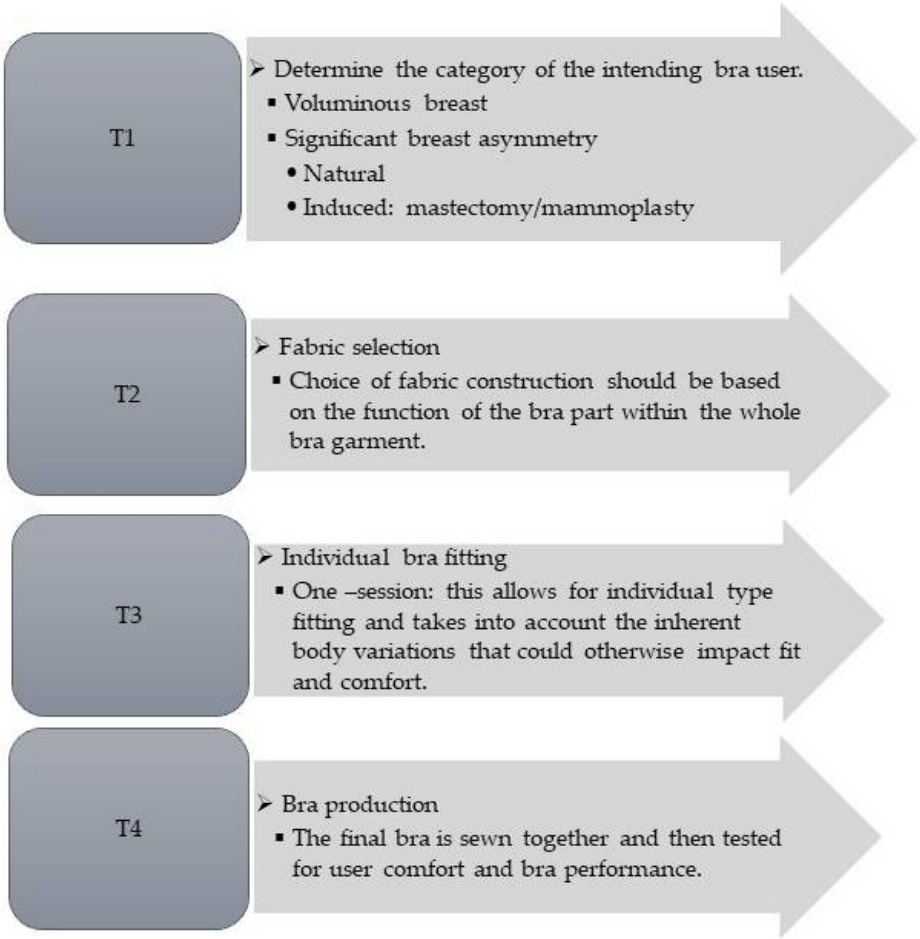


Figure 3. Translational pathway to bras well suited to those with atypical breast shape/size.

6. Conclusions

The objective of the paper is to contribute to filling the gap in terms of critical review of the current state of knowledge around the topic of bras and identify possible avenues of improvements in this area. The challenges experienced by bra users, especially those with atypical breast shape/size and body type are mainly related to issues of fit, support and comfort. As the current strategies to solve the challenges do not appear to have yield successful results yet, a need exists to re-evaluate bras from the user's perspective, especially within the context of individuals of the target audience. As a result, a road map is proposed to provide bras suited to individuals with atypical breast shape/size and body type, and improve the bra performance and functionality.

This roadmap takes the perspective of the bra user. As the problem is multidisciplinary, a human-centered interdisciplinary approach is key to ensure that all aspects are considered at all stages of the process: (1) fabric analysis, (2) bra design and patterning, (3) fitting procedure, and (4) wear trials of prototypes. The fabric should have the ability to provide the necessary mechanical support and provide breathability to increase comfort. In addition, the fabric choice should be based on the function and requirements of each bra part. Stretch woven fabrics offer a large potential in the production of bras to provide added support in areas such as the under band and back panels. Furthermore, custom-making the bra by fitting it directly on the user will increase the likelihood that optimum fit is achieved. Finally, it is important that the bra design, selected fabrics, fitting procedure, and performance of the bra as a whole assembly are tested by the intended user. This will ensure the useability, wearability, and durability of the bra.

The novelty of this review thus lies in the proposed scientific approach in the analysis of fabrics for the purpose of bra production from the lens of the bra parts and the function

they perform, with the use of stretch woven fabrics to provide the needed strength and support required by bra users. This article also describes a new custom-fitting process for bespoke bras using pre-assembled modular pieces that is currently put to the trial. If current limitations exist in terms of cost and limited variety of styles, the change in paradigm brought by this new bespoke manufacturing process along with the implementation of the different aspects of the proposed roadmap, including in terms of translational approaches to patients, will hopefully allow progress to be made in improving the comfort, support and fit of bras and enhancing the quality of life of individuals with atypical breast shape/size and body type.

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