Quantification of gravity-induced skin strain across the breast surface

SANCHEZ, Amy, MILLS, Chris, HAAKE, Steve <http://orcid.org/0000-0002-4449-6680>, NORRIS, Michelle and SCURR, Joanna

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Quantification of gravity-induced skin strain across the breast surface.

Amy Sanchez[1], Chris Mills[1], Steve Haake[2], Michelle Norris[1] and Joanna Scurr[1]

[1] Department of Sport and Exercise Science, Spinnaker Building, University of Portsmouth, PO1 2ER, UK.

[2] Centre for Sports Engineering Research, Sheffield Hallam University, Sheffield, S10 2BP, UK.

Corresponding Author:

Dr Chris Mills

Department of Sport and Exercise Sciences

University of Portsmouth

Spinnaker Building

Portsmouth

PO1 2ER

United Kingdom

Email: chris.mills@port.ac.uk

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Abstract

Background

Quantification of the magnitude of skin strain in different regions of the breast may help to estimate possible gravity-induced damage whilst also being able to inform the selection of incision locations during breast surgery. The aim of this study was to quantify static skin strain over the breast surface and to estimate the risk of skin damage caused by gravitational loading.

Methods

Fourteen participants had 21 markers applied to their torso and left breast. The non-gravity breast position was estimated as the mid-point of the breast positions in water and soybean oil (higher and lower density than breast respectively). The static gravity-loaded breast position was also measured. Skin strain was calculated as the percentage extension between adjacent breast markers in the gravity and non-gravity loaded conditions.

Findings

Gravity induced breast deformation caused peak strains ranging from 14 to 75% across participants, with potentially damaging skin strain (>60%) in one participant and skin strains above 30% (skin resistance zone) in a further four participants. These peak strain values all occurred in the longitudinal direction in the upper region of the breast skin. In the latitudinal direction, smaller-breasted participants experienced greater strain on the outer (lateral) breast regions and less strain on the inner (medial) breast regions, a trend which was reversed in the larger breasted participants (above size 34D).

Interpretation

To reduce tension on surgical incisions it is suggested that preference should be given to medial latitudinal locations for smaller breasted women and lateral latitudinal locations for larger breasted women.

Keywords

Breast; surgery; strain; skin; damage; density

Highlights

- Quantification of breast skin strain to inform incision locations during surgery
- Up to 75% skin strain in the longitudinal direction in upper region of breast
- Smaller-breasted participants experienced greater strain on lateral breast regions
- Larger-breasted participants experienced greater strain on medial breast regions

1.0 Introduction

The female breast is a highly malleable structure that is easily deformed by external forces (Rajagopal *et al.,* 2008). Deformation of the breast has been hypothesised to damage the breast structure, which may lead to breast sag (ptosis) (Page & Steele 1999). Measurements of strain can be used to evaluate the magnitude and reversibility of a biological tissue's response to external loading (Gao & Desai 2010; Hull *et al.*, 1996; Lim *et al.*, 2008; Miller 2001; Toms *et al.,* 2002). One of the breast's primary support systems is the skin (Hindle 1991) and during breast surgery an incision must be made in this supporting tissue.

Previous research has investigated numerous methods of identifying the correct placement and direction of surgical incisions, to minimise tissue damage and long term scarring (Seo, Kim, Cordier, Choi, & Hong, 2013). These have included the identification of Langer's Lines (where surgical incisions are performed in the direction of maximum skin tension) (Gibson, 1978), Kraissl's Lines (where surgical incisions coincide with wrinkle lines) (Kraissl, 1951), and relaxed tissue lines (similar to Kraissl's lines, however performed when the skin is relaxed) (Borges & Alexander, 1962). The aforementioned are a select few of many guidelines currently available to surgeons, when performing surgical incisions (Seo et al., 2013). However, with further information as to skin strain properties surgeons may be better informed when selecting incision location and direction. This is of particular interest across the breast surface as recent studies have reported an increase in breast augmentation surgery (Mahmood et al., 2013), and an increase in mastectomy rates in those with breast cancer or benign breast lump removal (Albornoz et al., 2013). Surgical incisions performed in areas of high skin strain, when gravity loaded, may cause stretching of scars and increased healing times as well as increased incidence of scar repair / removal.

The biomechanical properties of the skin vary directionally, regionally, and between individuals (Clark *et al.,* 1996, Finlay 1970). At low strains the collagen fibres are loosely interwoven and there is little resistance to deformation. At increasing strains the collagen fibres align in the direction of loading and begin to resist extension, until eventually failure occurs (Daly 1982). Skin failure studies are typically conducted on porcine or cadaver skin samples rather than *in vivo* (Winter 2006; Gallagher *et al.,* 2012), and results have shown that skin resistance and skin failure can occur at a range of different strain values. The onset of skin resistance has been reported to occur at strains between 16% and 48% (Stark 1977), with skin failure occurring at strains between 16% (Lim *et al.*, 2011) and 126% (Gallagher *et al.,* 2012; Ní Annaidh *et al.*, 2012). The wide-ranging results presented for the different stages of skin extension may be due to differences in skin sampling techniques, sample preservation procedures, and strain measurement systems. For the purpose of this study strain limits were defined as 30% for skin resistance and 60% for skin failure based on the representative strain values for human skin reported by Silver *et al.,* (2001).

When evaluating the risk of strain-induced damage to the breast skin it is imperative that measurements of strain are taken from the unloaded (neutral) position of the breast. However, the continuous deforming effect of gravity on the breast makes it difficult to identify the neutral breast position from which to take measurements of strain (Gao & Desai 2010). Previously reported strain measurements taken from the gravity-loaded breast position have produced the counter-intuitive result that larger-breasted women experienced less breast strain than their smaller-breasted counterparts (Scurr *et al.,* 2009). Subsequent studies have considered the effect of gravity, but have only included two markers to measure breast strain (one on the nipple and one on the torso) (Haake & Scurr 2011, Haake *et al.,* 2012). The use of a single marker pair to represent the breast means that the reported strain values may not represent the strain on any particular breast structure, making it difficult to apply the appropriate strain failure limits to assess damage. Despite the limitations associated with the two-marker method, Haake *et al.*, (2012) reported static gravity-induced breast strains up to 80%, which indicate that gravity may induce considerable static strains on the breast skin.

This study uses a novel approach for assessing breast skin strain from the neutral (unloaded) position using a marker array over the breast surface. The method used the buoyant force of the fluid to counteract the effect of gravity on the breast. As breast mass-density can vary between women, a single fluid may not completely counteract the effect of gravity across different participants. Instead, the boundaries of the neutral breast position may be identified by immersing the breast and body in two fluids with densities above (water) and below (soybean oil) the range of reported breast mass-densities (Sanchez *et al.*, 2016). The mid-point between these two immersion conditions may then be used to identify a more accurate neutral breast position than could be achieved using either fluid in isolation (Mills *et al.*, 2016).

The second novel aspect of this study was the implementation of a marker array on the breast skin. Although an array has been implemented in previous research assessing the effect of gravity on the breast (Rajagopal 2007), there have been no attempts to calculate skin strain. Application of a marker array over the breast skin provides a better representation of the breast's curved surface, which enables measurements of strain to better replicate the strain experienced by the breast skin. This is important for evaluating the risk of skin damage caused by excessive strain (above 60%). Strain data obtained using an array also permits the evaluation of skin strain in different regions of the breast, which may enable identification of breast regions that are most susceptible to excessive levels of skin strain.

Measurements of strain on the breast skin could be used to assess the risk of damage associated gravitational loading and also act as a starting point from which to subsequently help inform the selection of incision locations during breast surgery. The aim of this study was to quantify static skin strain over the breast surface and to estimate the risk of skin damage caused by gravitational loading.

2.0 Methods

Following institutional ethical approval (SFEC 2013-001), a convenience sample of 14 females gave written informed consent to take part in this study. All participants were aged between 20 and 27 years, were nulliparous, had not exposed their breasts to UV radiation within the last three months, and had not undergone surgical procedures on their breasts. These criteria were imposed in an attempt to ensure the participants' breast skin was elastic and would return to its neutral position when supported by the buoyant forces from water and soybean oil (Gambichler *et al.*, 2006, Fujimura *et al.*, 2007, Smalls *et al.*, 2006, Fisher *et al.*, 1997). Participants had their bra size assessed by a trained bra fitter using best-fit criteria (McGhee & Steele 2010), and were assigned a participant number in ascending bra cross-grading size.

Retro-reflective markers (12 mm diameter flat markers) were applied to the participants' suprasternal notch, xiphoid process, right and left anterior-inferior aspect of the 10^{th} ribs, and left nipple using hypoallergenic tape, based on the torso marker set described by Scurr et al. (Scurr *et al.*, 2011). Participants also had a retro-reflective marker array applied to their left breast (6 mm diameter flat markers) (Figure 1), which was based on the rectangular segmentation of the breast described by Rajagopal *et al.,* (2008). The total mass of the markers on the breast was 0.17 g, and was assessed using a Mettler PC400 balance (Mettler Toledo, Switzerland).

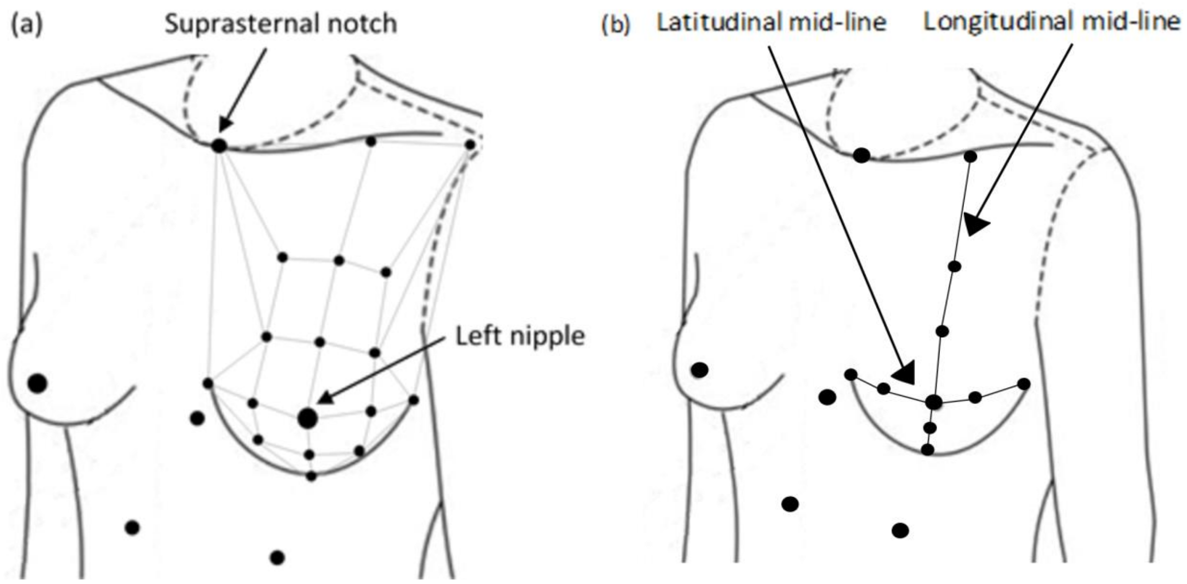


Figure 1: (a) Torso marker set, breast marker array, and inter-marker pairings (grey lines) used to calculate skin strain; and (b) longitudinal and latitudinal breast mid-lines.

The neutral position of the breast was obtained using immersion in both water and soybean oil. Three synchronised underwater cameras (25 Hz, VB5C6 Submersible Colour Camera, Videcon PLC) were attached to the inside of a D-shaped tank. The tank was first filled with water, and all participants were tested, then the tank was emptied, cleaned and filled with soybean oil. The cameras were calibrated before testing each participant using a custom-made 36-point calibration frame. A 16 order DLT was used to correct for image distortion caused by the fluids. In each fluid, participants sat on an adjustable stool so that their suprasternal notch marker was submerged. Participants remained stationary in an upright position with their arms by their sides while the static positions of the breast markers were recorded for three 1 s trials in each fluid. Participants also had their static gravity-loaded breast positions recorded in six 1 s trials (three before each fluid immersion) using a calibrated optoelectronic camera system (200 Hz, Oqus, Qualisys, Sweden).

The 3D co-ordinates of the torso and breast markers in the two immersion conditions were identified and reconstructed using SIMI software (version 8.5.5, Tracksys Ltd), and the gravity-loaded marker co-ordinates were identified using Qualisys Track Manager (QTM) (Qualisys, Sweden). The mean reconstruction errors for the SIMI and QTM software were 0.7 mm and 0.4 mm, respectively. All co-ordinate data were then exported to Visual 3D (v4.96.4, C-motion) for further analysis. Within Visual 3D, a torso segment was created for each participant using the suprasternal notch marker and the two rib markers to define the proximal and distal segment ends respectively (Mills *et al.*, 2014). The torso segment origin was defined at the proximal end of the segment and the xiphoid process marker was added to aid segment tracking. The 3D marker co-ordinate data were filtered using a generalised cross-validatory quintic spline and the position of each breast marker was calculated relative to the torso segment in each condition (water, soybean oil, and gravity-loaded). A total of 35 inter-marker distances were calculated for each participant, in each condition, using the resultant separation between the breast marker pairings shown in Figure 1.

The neutral (unloaded) inter-marker separation (L_0) was defined as the mean of the water and soybean oil conditions. Strain was calculated using,

Equation 1: $$\text{Strain} = 100\,.\left(\frac{(L - L_O)}{L_O}\right) = 100\,.\left(\frac{(\Delta L)}{L_O}\right)$$

where L was defined as the mean inter-marker separation calculated from the six gravity-loaded static trials. The risk of breast skin damage caused by static gravity-induced strain was estimated by comparing the static skin strain values for each participant to the strain limits reported by Silver (2001) (30% representing skin resistance and 60% representing the onset of skin failure).

To evaluate the potential improvement in skin strain estimation using a breast marker array, and for comparison to previously published data, strain was also calculated using the two-marker method described by Haake and Scurr (2011). For this analysis, strain was calculated using Equation 1 where the neutral and loaded breast lengths were defined as the superior-inferior displacement of the left nipple from the suprasternal notch in the neutral (L_0) and gravity-loaded (L) conditions respectively (Figure 1) (Haake & Scurr 2011).

3.0 Results

In the neutral position the breast shape was conical or hemispherical, with the breast bulk distributed symmetrically behind the nipple (Figure 2). Gravitational loading caused the breast bulk to fall inferiorly, leading to flattening of the upper breast and distortion of the lower breast to form the typically observed tear-drop breast shape (Figure 2). This breast deformation led to a posterior and inferior displacement of the nipple (Figure 2), with most participants also experiencing a small lateral shift of the breast bulk in the gravity-loaded condition, particularly below the nipple (Figure 3). Example gravity-induced skin strains resulting from deformation of the breast mid-lines are shown for Participant 11 (breast size 32DD) in Figure 4. These strain data reflect the changes in breast shape, with the inferior and lateral displacement of the breast causing positive strain (tension) to occur on the upper and medial skin segments, and negative strain (compression) to occur on the lower and lateral segments of the breast skin (Figure 4).

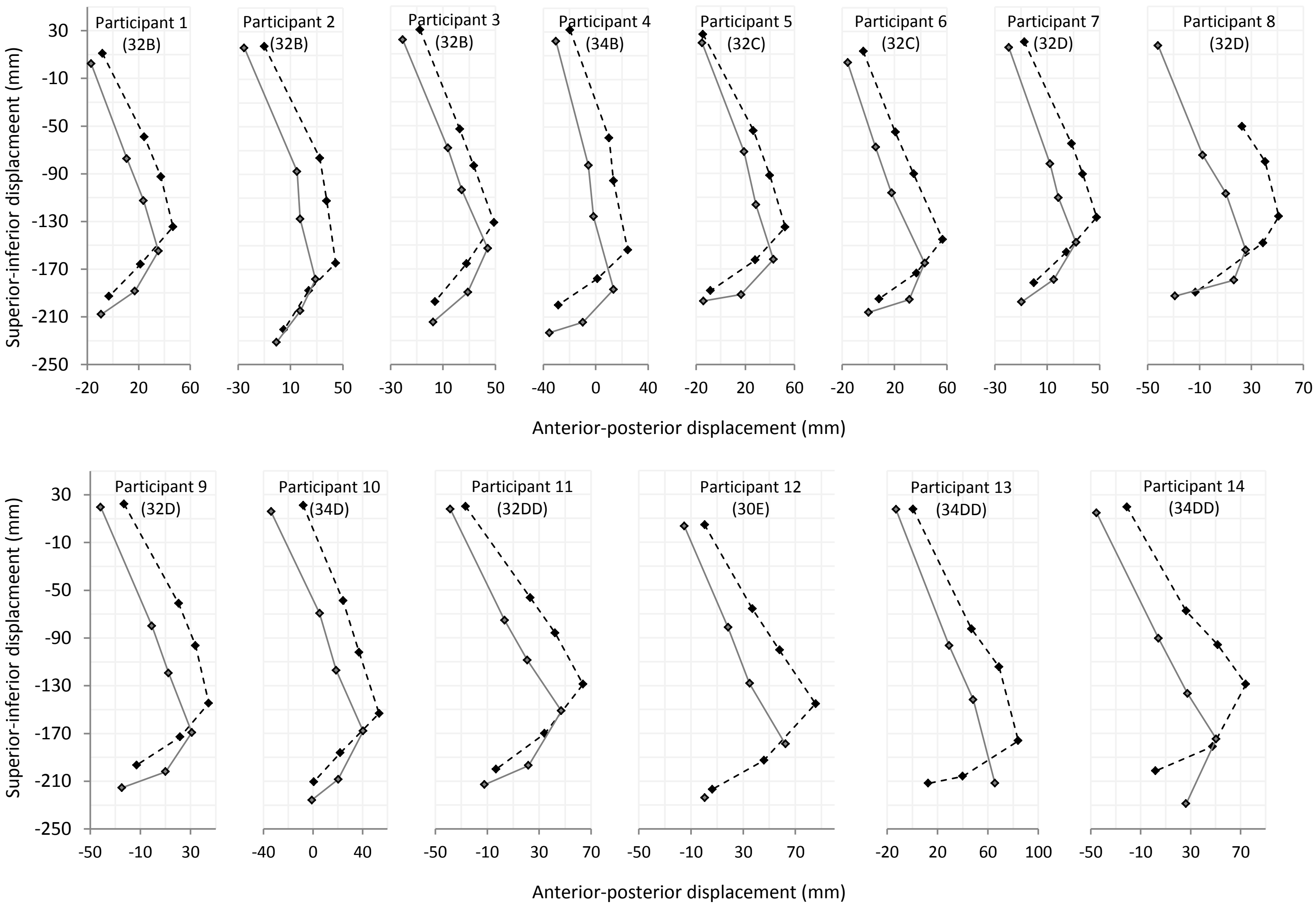

Participant 1 (32B)
Participant 2 (32B)
Participant 3 (32B)
Participant 4 (34B)
Participant 5 (32C)
Participant 6 (32C)
Participant 7 (32D)
Participant 8 (32D)
Participant 9 (32D)
Participant 10 (34D)
Participant 11 (32DD)
Participant 12 (30E)
Participant 13 (34DD)
Participant 14 (34DD)
Superior-inferior displacmeent (mm)
Anterior-posterior displacement (mm)

Figure 2: Position of the markers along the longitudinal breast mid-line in the neutral (dashed) and gravity-loaded (grey) conditions, in the sagittal plane.

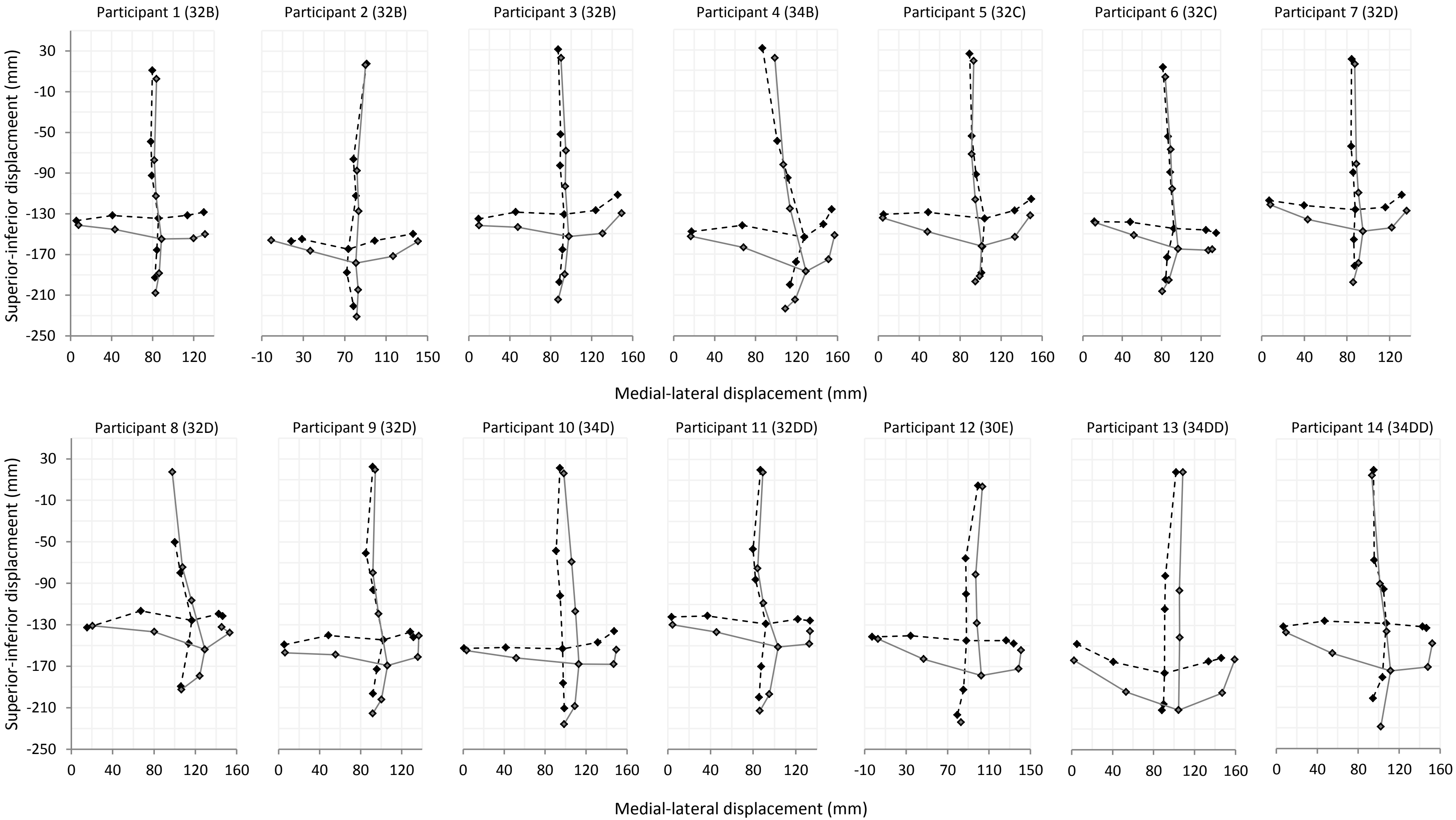

Participant 1 (32B)
Participant 2 (32B)
Participant 3 (32B)
Participant 4 (34B)
Participant 5 (32C)
Participant 6 (32C)
Participant 7 (32D)
Participant 8 (32D)
Participant 9 (32D)
Participant 10 (34D)
Participant 11 (32DD)
Participant 12 (30E)
Participant 13 (34DD)
Participant 14 (34DD)
Superior-inferior displacmeent (mm)
Medial-lateral displacement (mm)

Figure 3: Position of the markers along the longitudinal and latitudinal breast mid-lines in the neutral (dashed) and gravity-loaded (grey) conditions, in the frontal plane.

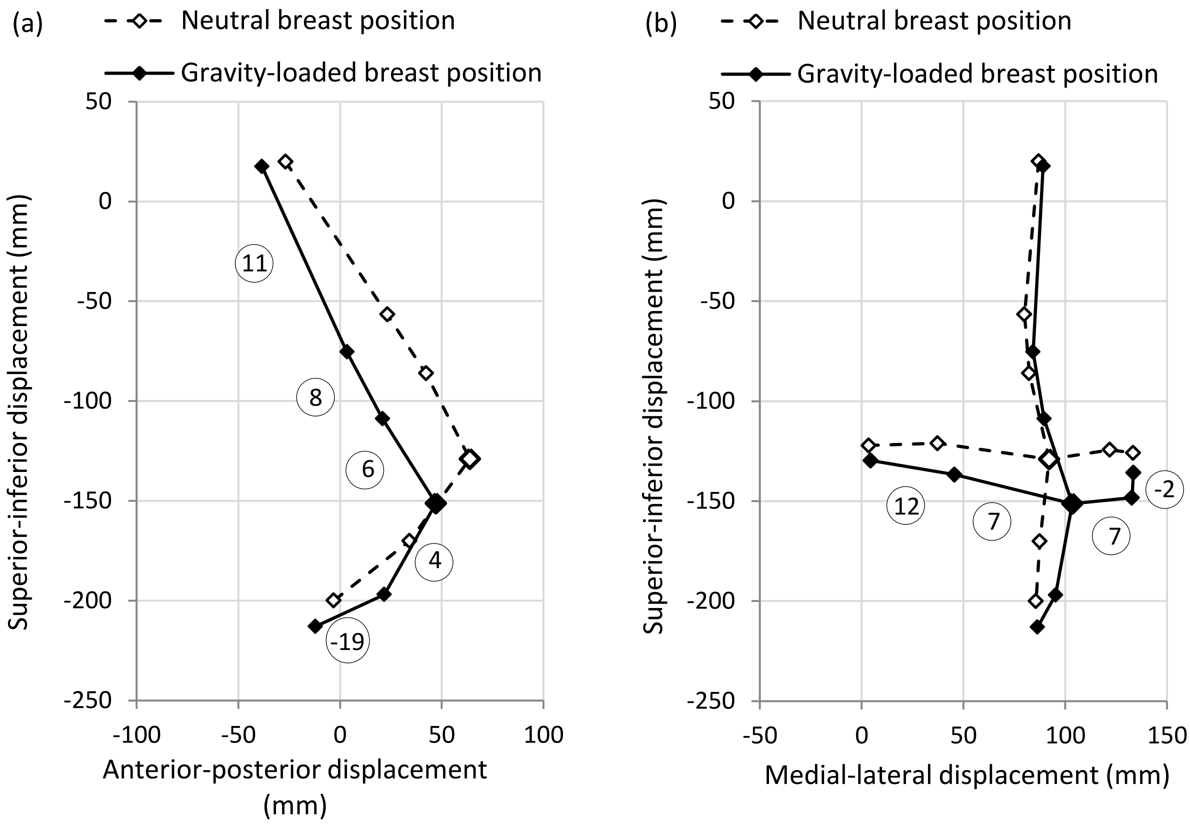
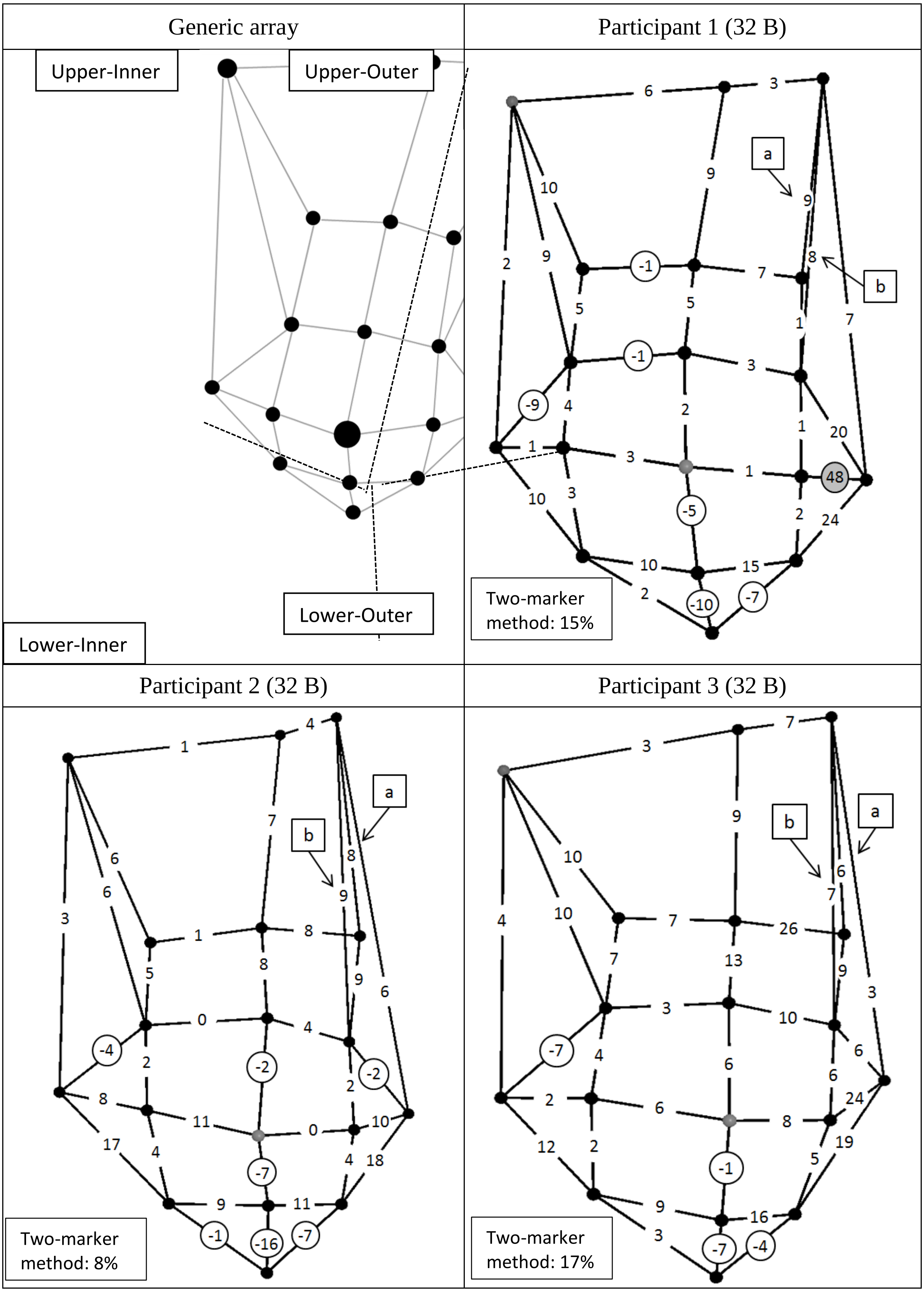


Figure 4: Static deformation of the breast mid-lines in the (b) sagittal plane and (a) frontal plane (Participant 11, 32DD). The numbers indicate the strain on the segments shown.

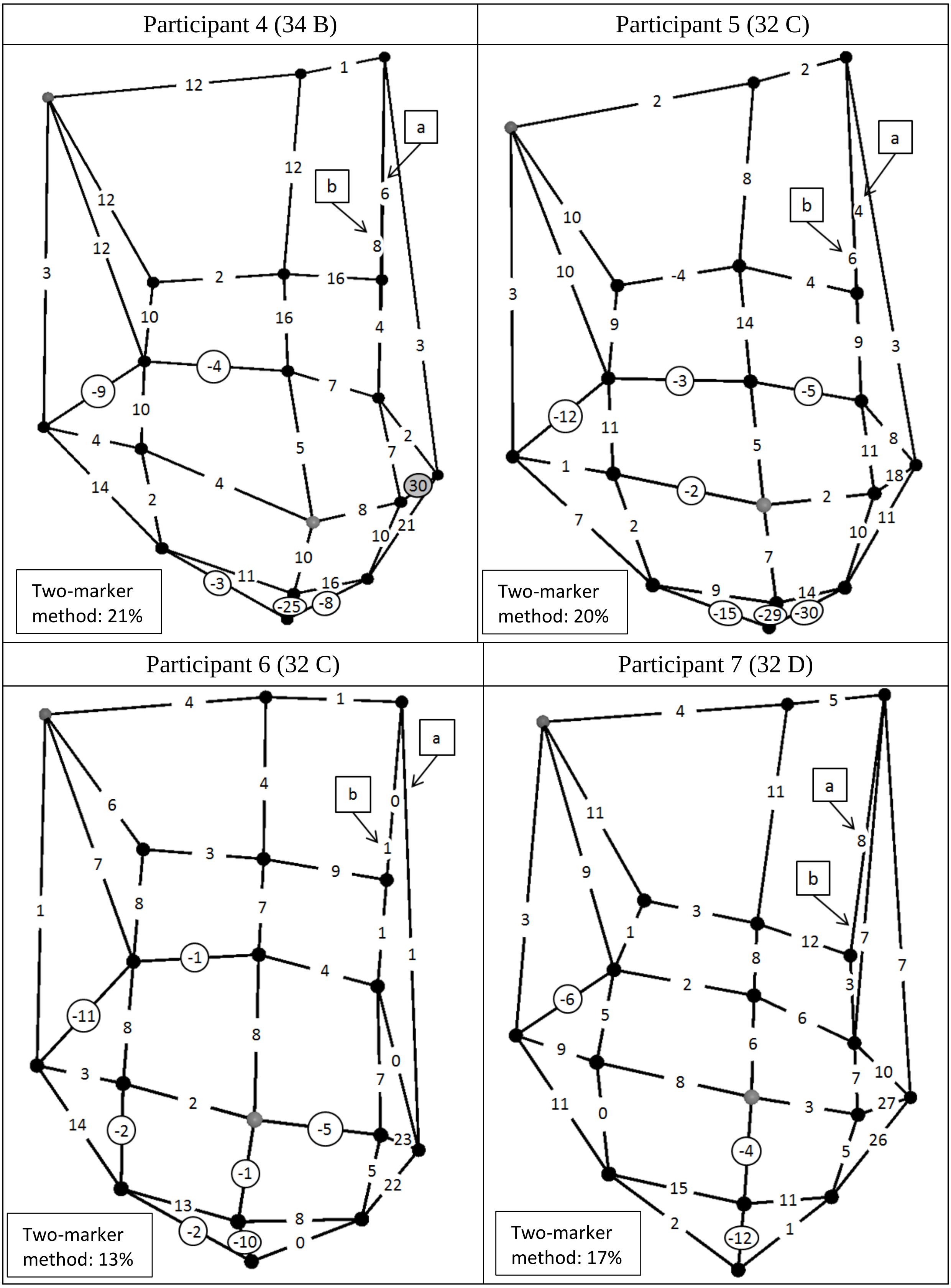
Skin strains across the surface of the breast are shown for each participant in Figure 5 and peak skin strain ranged from 14 to 75% across participants. Errors in the calculated strain values were estimated using the quotient rule (Taylor 1982), and the mean maximum error in the static strain data was 3%. One participant (Participant 14) experienced potentially damaging gravity-induced skin strain (75%), and four participants (Participants 1, 4, 12 and 13) experienced skin strains above 30% (skin resistance zone) (Figure 5). Participant-specific strain data demonstrate that the highest longitudinal breast strains generally occurred in the second row of skin segments on the upper region of the breast (Figure 5). In the latitudinal direction contrasting results were observed for smaller- and larger-breasted participants. With the exception of two participants (Participants 2 and 8), peak latitudinal skin strains occurred on the medial side of the breast for participants with a breast size of 34D or smaller, but on the lateral side of the breast for the larger-breasted (34DD or greater) participants (Figure 5).

Comparison of individual static strain data revealed high between-participant variation in strain values across the breast skin, with differences of up to 74% in strain for the same marker pairing between individuals (Participants 1 and 6, and participant 14 in the upper outer breast, Figure 5). Furthermore, differences of up to 110% strain were observed across the breast skin of a single participant (Participant 14, Figure 5), highlighting the importance of implementing a marker array when calculating breast skin strain.

A comparison of the results obtained using the two-marker and breast array method (Figure 5) demonstrates that the two-marker method produced static strain values of the same order of magnitude as those presented previously (Haake *et al.*, 2012, Haake and Scurr 2011), and that these values could be used to approximate the longitudinal strain on the upper breast mid-line (Figure 5). However, the two-marker method consistently underestimated the peak static strain on the breast skin (by up to 59%) assessed using a marker array, as these peak strains typically occurred on the upper-outer breast regions.

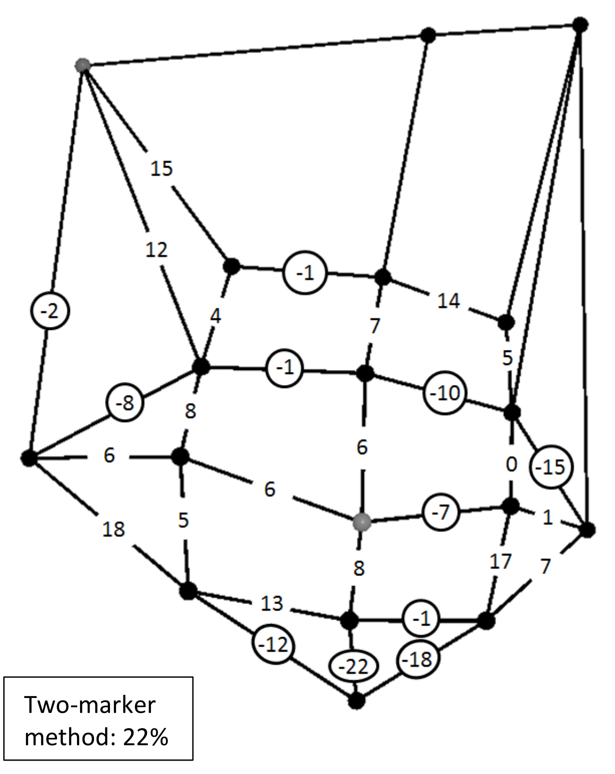


Generic array
Participant 1 (32 B)
Upper-Inner
Upper-Outer
Lower-Outer
Lower-Inner
a
b
Two-marker method: 15%
Participant 2 (32 B)
Participant 3 (32 B)
Two-marker method: 8%
Two-marker method: 17%

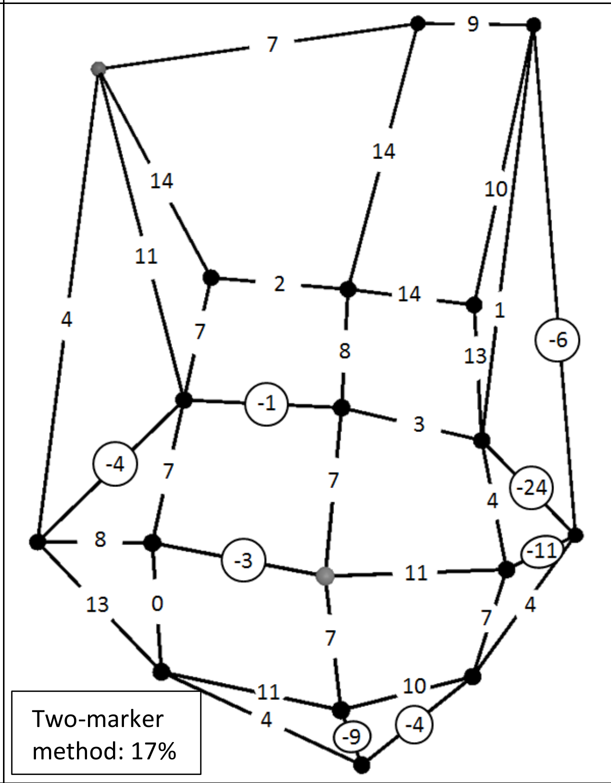


Participant 4 (34 B)
a
b
Two-marker method: 21%
Participant 5 (32 C)
a
b
Two-marker method: 20%
Participant 6 (32 C)
a
b
Two-marker method: 13%
Participant 7 (32 D)
a
b
Two-marker method: 17%

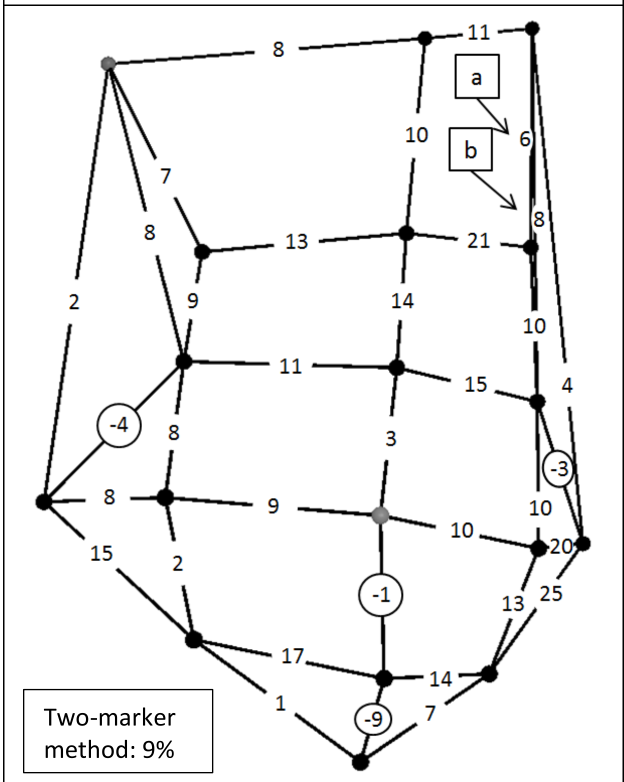
Participant 8 (32 D)



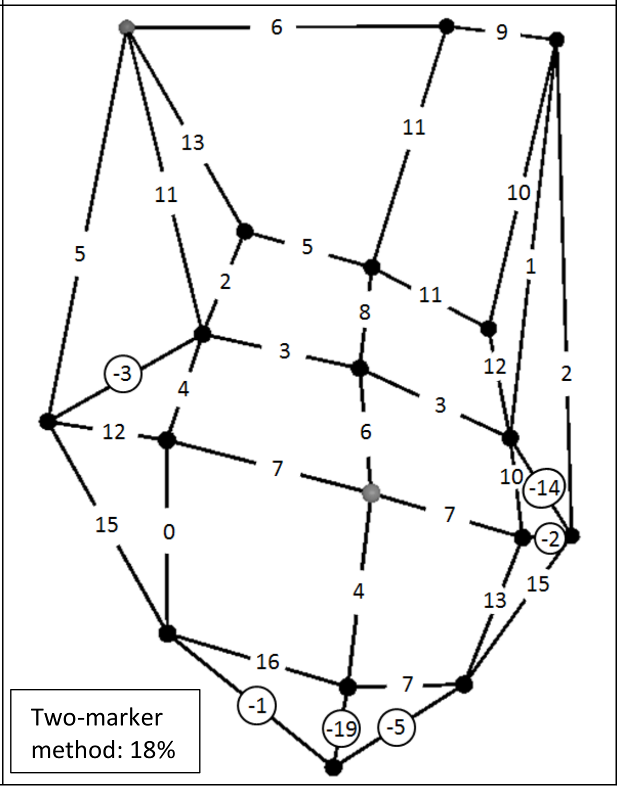
Participant 9 (32 D)



Participant 10 (34 D)



Participant 11 (32 DD)



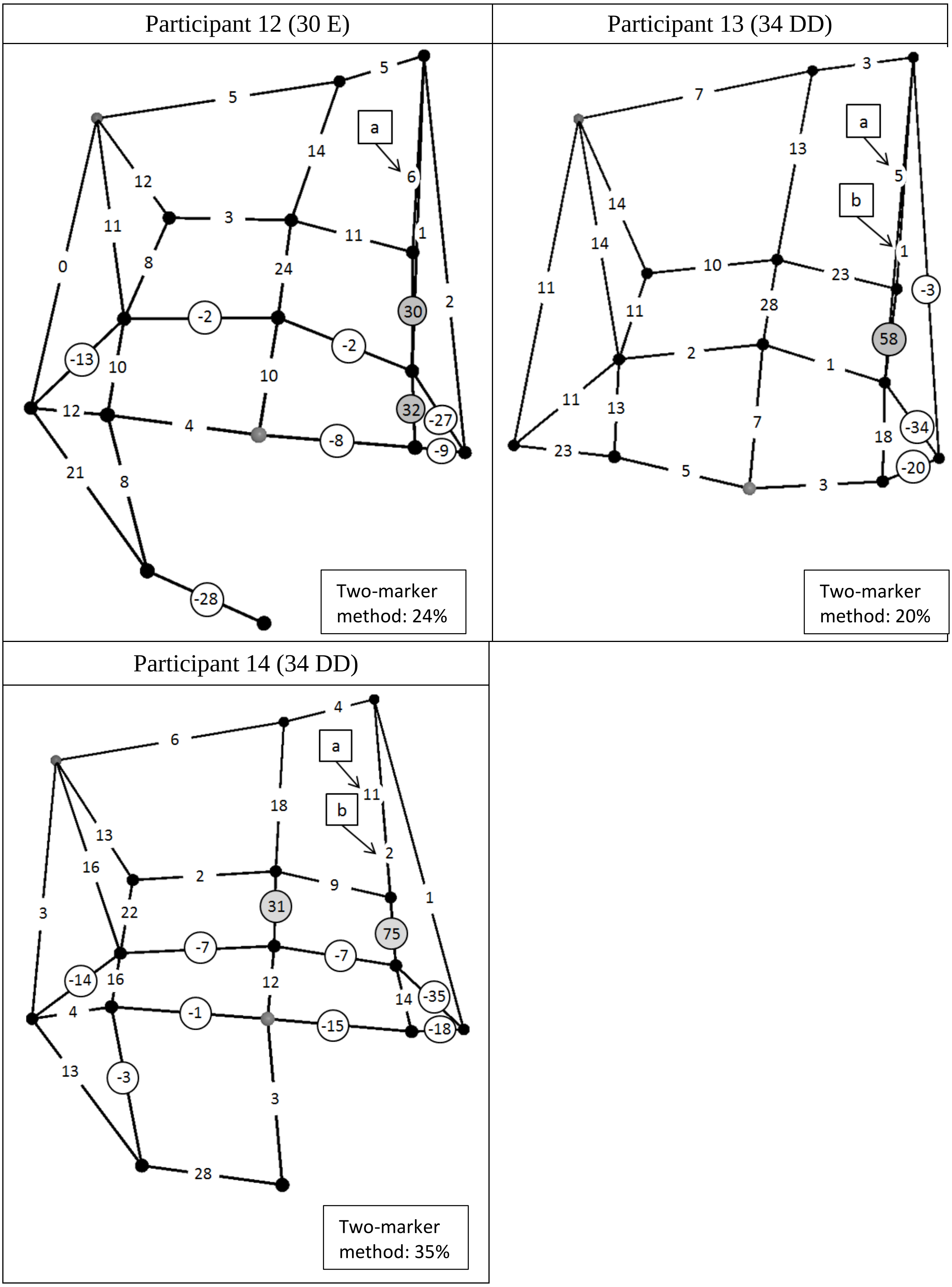


Figure 5: Static left breast skin strain for 14 participants with breast sizes ranging from 32 to 34 under band and B to E cup size. The grey marker represents the nipple. Strains above the

skin resistance limit (30%) are in grey circles, and negative strains (compression) are in white circles. Strains calculated using the two-marker method are also shown for each participant. Breast regions are identified on the generic array, and strain lines ‘a’ and ‘b’ are marked on the generic array, and subsequent participant arrays, to aid clarification of the strain line as these can superimpose over each other.

4.0 Discussion

Marker array data obtained within this study provided an opportunity to investigate the deforming and strain-inducing effects of gravity over the breast surface for the first time in breast research. The results demonstrate that gravity-induced breast deformation caused potentially damaging breast skin strain (up to 75%) for one participant (Participant 14), and that four further participants (Participants 1, 4, 12 and 13) experienced gravity-induced skin strains above 30% (skin resistance zone) (Figure 5). These peak strain values all occurred in the longitudinal direction in upper-outer region of the breast skin for the three largest-breasted participants, suggesting that this region of the breast skin may be particularly prone to damage in larger-breasted women. Excessive gravity-induced skin strain in the upper-outer region of the breast may lead to failure of the collagen fibres and a permanent extension of the skin in this breast region. This skin extension may allow the breast bulk to move inferiorly and laterally on the torso; a position change which has previously been associated with breast ptosis (Brown *et al.*,, 1999).

It was initially anticipated that the highest static strains would occur along the longitudinal breast lines for all participants as gravity was assumed to act predominantly in this direction in the static standing position. However, aside from the three largest breasted participants, peak static strain typically occurred in the latitudinal direction, either along the breast mid-line or in the lower regions of the breast. Interestingly, individual static strain data (Figure 5) demonstrated that the smaller-breasted participants experienced greater strain on the outer (lateral) breast regions and less strain on the inner (medial) breast regions, a trend which was reversed in their larger breasted counterparts (above size 34D). This new information could be combined with existing knowledge on the lines of natural tension in the skin (Jatoi *et al.,* 2006) to inform the selection of incision locations during breast surgery. There are multiple factors taken into consideration when selecting the incision location, such as surgeon visibility and control, and patient choice (Tebbetts & Adams, 2005). Interestingly, possible injury to neighbouring soft tissue is also a factor taken into consideration (Tebbetts & Adams, 2005), and results in the current study indicate that for smaller breasted women it may be preferential to select more medially positioned incision locations, whilst for larger breasted women it may be preferential to select more laterally positioned incision sites. Surgeons would thereby be selecting incision locations with reduced skin tension or strain.

In the longitudinal direction, strain data demonstrate that the greatest breast strain generally occurred in the second row of skin segments on the upper region of the breast (Figure 5). This may be explained by considering the hemispherical shape of the breast (Figure 2) and the underlying breast anatomy. Breast tissue typically extends from the second to the sixth or seventh rib in the superior-inferior direction (Macéa & Fregnani 2006). The breast is broadest at its contact point on the torso and is generally narrowest at the nipple (the apex of the breast). The most superior row of longitudinal skin segments may have predominantly overlaid the soft tissue of the torso rather than the breast, meaning that the second row of skin segments may have overlaid the broadest cross-section of the breast and experienced larger strains during gravitational breast loading.

The results of this study demonstrate diverse strain values across the breast skin, which could not be measured using the previously published two-marker method for estimating breast strain (Haake & Scurr 2011). Although the two-marker method could approximate the longitudinal strain on the upper breast mid-line, it was not appropriate for identifying peak skin strain or for estimating the risk of skin damage. For example, if the two-marker method alone had been implemented in this study then the potentially damaging skin strain (75%) experienced by Participant 14 would not have been identified (Figure 5). Consequently, the two-marker method is not recommended for assessing breast skin strain in future research. Furthermore, the magnitude of static skin strains observed within this study (up to 75% for Participant 14, Figure 3) demonstrate the importance of identifying the neutral breast position before calculating breast strain, particularly if assessing the risk of skin damage. Measuring skin strain from the gravity loaded position, as performed by Scurr in 2009, may lead to the omission of potentially damaging skin strain caused by static gravitational loading of the breast (Scurr *et al.,* 2009).

Peak skin strain values observed in this study were higher than anticipated. The implication that gravity alone could be causing permanent damage to the breast skin is surprising, and the lack of existing static breast strain data makes it is difficult to assess the credibility of these results. On one hand the prevalence of ptosis among mature women (Rinker *et al.,* 2010) , and the reports of markedly elongated breasts among tribal women who do not wear breast support (Morgan 1997, Gunkel & Handler 1969), suggest that the breast can experience damaging skin strains. However, it was acknowledged that the straight-line approximation method used to calculate strain within this study may have led to an over-estimation of breast skin strain. Although the marker array used to represent the breast surface was more detailed than those presented in previous breast strain studies, the inter-marker separations were too large to negate the possibility of skin curvature between markers in the neutral position (L_0). Consequently, some degree of inter-marker extension (ΔL) may have been caused by flattening of the breast surface.

5.0 Conclusion

This exploratory study provides a novel contribution to breast research by quantifying regional skin strain caused by external gravitational loading on the breast. The key outcome of this work was the observation of potentially damaging static skin strains (up to 75% peak strain) caused by gravitational loading. Particularly high skin strains were observed longitudinally in the upper-outer breast region for larger-breasted women. In the latitudinal direction, smaller-breasted participants experienced more strain on the outer (lateral) breast regions and less strain on the inner (medial) breast regions, a trend which was reversed in their larger breasted counterparts (above size 34D). These initial results suggest that to reduce tension on latitudinal surgical incisions the preference should be given to medial locations for smaller breasted women and lateral locations for larger breasted women. Finally, this study also demonstrated the importance of considering the deforming effect of gravity in breast research, and that a marker array is required to assess strain on the breast skin.

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