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THE MOVEMENT OF THE TRUNK AND BREAST DURING FRONT CRAWL AND BREASTSTROKE SWIMMING

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Abstract

Breast displacement has been investigated in various activities to inform bra design, with the goal of minimising movement, however, breast motion during swimming has yet to be considered. The aim was to investigate trunk and breast kinematics whilst wearing varying levels of breast support during two swimming strokes. Six larger-breasted females swam front crawl and breaststroke (in a swimming flume), in three breast support conditions while three video cameras recorded the motion of the trunk and right breast. Trunk and relative breast kinematics were calculated. Greater breast displacement occurred mediolaterally in the swimsuit condition (7.8 ±1.5 cm) during front crawl and superioinferiorly in the bare-breasted condition (3.7 ±1.6 cm) during breaststroke, with the sports bra significantly reducing breast displacements. During front crawl, the greatest trunk roll occurred in the sports bra condition (43.1 ±8.3°) and during breaststroke greater trunk extension occurred in the swimsuit condition (55.4 ±5.0°); however no differences were found in trunk kinematics between the three breast support conditions. Results suggest that the swimsuit was ineffective as a means of additional support for larger-breasted women during swimming; incorporating design features of sports bras into swimsuits may improve the breast support provided.

Keywords: kinematics, water, stroke, swimsuit, bra

1. Introduction

Previous research has investigated breast displacement in different designs of bras during a range of exercise modalities on land, including treadmill walking and running (McGhee, Steele & Power, 2007; Scurr, White & Hedger, 2009; Scurr, White & Hedger, 2010) and jumping (Bridgman, Scurr, White, Hedger & Galbraith, 2010), and found that increases in breast support caused decreases in breast displacement. Understanding the motion of the breast during exercise has helped to inform sports bra design (Zhou, Yu & Ng, 2012a, 2012b) with the goal of minimising breast motion and consequent pain.

The motion of the trunk has been referred to as the driving force for the motion of the breasts (Haake & Scurr, 2010), and due to the lack of internal support within the breasts (Page & Steele, 1999), it is recommended that breast motion is restrained via external breast support devices. There is no published research on the motion of the breasts during swimming, despite swimming being the most popular sport in England with over 2.9 million people swimming at least once a week (Sport England, 2013). The effectiveness of a swimsuit as a form of external breast support has also yet to be investigated and understanding breast motion during swimming may yield insights into the mechanisms underpinning trunk and breast motion as well as recommendations for swimsuit design.

The exercise environment during swimming is unique as the body is horizontal/semi-horizontal (Pendergast & Lundgren, 2009) and the increased density of water compared with air subjects the body to increased hydrostatic force (Pendergast & Lundgren, 2009). This increased hydrostatic compression elicits a number of physiological changes (Pendergast & Lundgren, 2009), not all of which are beneficial (Agostoni, Gurtner, Torri & Rahn, 1966; Robertson, Engle & Bradley, 1978). However, one such change that increases the work of breathing may actually be beneficial for breast support. The hydrostatic force of the water pushing the rib cage inwards creates a chest strapping effect (Robertson et al., 1978). It is not known whether this provides a form of natural breast support during swimming (similar to that of a sports bra on land) and whether breast support garments can provide additional support in water.

Breast motion in front crawl may be influenced by the angular motion of the trunk about its longitudinal axis, commonly referred to as trunk roll (Councilman, 1968; Lui, Hay & Andrews, 1993; Payton, Hay & Mullineaux, 1997; Psycharakis & Sanders, 2010). The magnitude of trunk roll can vary depending upon several factors such as breathing, with swimmers rolling further when taking a breath (66°) than when breath holding (57°) whilst swimming at 1.8 m/s (Payton, Barlett, Baltzopoulos & Coombs, 1999); or swim speed, with body roll changing from 72° at 1.3 m/s to 42° at 1.6 m/s (Yanai, 2004). If changes in breast support during front crawl swimming can influence breast motion (as reported on land), due to possible changes in longitudinal axis moment of inertia caused by the additional compressive effect of the garment, this may subsequently influence the magnitude of trunk roll. Breast motion in breaststroke swimming may also be driven by the motion of the trunk in the sagittal plane with less trunk extension (Colman, Persyn, Daly & Stijnen, 1998) and less undulation being associated with reduced breast motion. Trunk extension has been reported as high as 63° but this may result in a higher hydrodynamic resistance slowing the velocity of the swimmer (Colman, Persyn, Daly & Stijnen, 1998) and possibly altering breast motion.

People who experience pain when exercising on land are often advised to swim or exercise in water (Ariyoshi et al., 1999; Westby, 2001). Therefore, swimming represents a suitable form of exercise for larger breasted women who experience breast pain when exercising on land, but without appropriate breast support these women may experience pain due to the movement of the breasts that may be influenced by trunk motion or vice versa. It is yet to be investigated whether changes in breast support can impact upon trunk or breast motion during swimming. Understanding how trunk and breast kinematics differ across breast support conditions may yield insights into the underpinning mechanisms as well as recommendations for swimsuit design for the larger breasted female population. The aim of this study was to investigate the trunk and breast kinematics whilst wearing varying levels of breast support during front crawl and breast stroke swimming. The first hypothesis stated that there will be a significant decrease in breast displacement within each stroke as breast support changed from bare-breasted to the swimsuit to the sports bra. The second hypothesis stated that there will be a significant increase in trunk kinematics within each swimming stroke as breast support changed from bare-breasted to the swimsuit to the sports bra. The third hypothesis stated that there will be a significant positive relationship between trunk roll and mediolateral breast displacement, in the front crawl, with women who exhibit greater trunk roll also experiencing greater mediolateral breast displacement. Finally, the fourth hypothesis stated that there will be a significant positive relationship between trunk extension and superioinferior breast displacement, in the breaststroke, with women who exhibit greater trunk extension also experiencing greater superioinferior breast displacement.

2. Methods

Six large breasted females (34F, 34F, 30G, 34G, 36FF and 34HH) were recruited for this study (age: 29 ± 7 years; mass: 78.9 ± 14.9 kg; height: 1.66 ± 0.05 m). Larger breasted women were selected as Lorentzen & Lawson (1987) identified that controlling breast displacement was of most importance in this size range. Participants were pre-menopausal, physically active, had not experienced any surgical procedures to the breasts, and were not pregnant or breast feeding within the last year. All participants were competent, recreational swimmers as determined by a qualified swimming instructor. Following institutional ethical approval and prior to testing each participant gave written informed consent and completed a health history questionnaire and had their blood pressure checked to ensure it was within the institutional guidelines. Participants' bra size was established by a trained bra fitter and fitted in the sports bra used for testing (using the fit criteria as set out by White & Scurr (2012)). Participant's swimsuits were sized according to the manufacturer's guidelines.

Two swimming trials (front crawl and breaststroke) were completed by each participant. For both swimming trials the participants were filmed using three synchronised underwater cameras (VB5C6 Submersible Colour Camera, Videcon PLC) sampling at 25 Hz with a resolution of 720 by 576 pixels. The three camera views were synchronised using an event synchronisation (light flash) viewed in all cameras. During the swimming trials the three cameras were placed on the base of a swimming flume (600-T, SwimEx Inc., USA), with one to each side and one in the centre (Figure 1a). The activity volume was calibrated using a 17-point three-dimensional calibration frame (Sputnik Calibration Frame, Simi Reality Motion Systems) which covered a volume of 1.3 m (anterioposterior, x) by 1.0 m (mediolateral, y) by 0.8 m (vertical, z) and was submerged in the water.

Following calibration, water refraction and lens distortion error were corrected for in Simi Motion Analysis software (Version 5.5) using 12 DLT parameters (Bader, 2011). The underwater filming reconstruction accuracy was assessed using a board covered with markers with 0.1 m separations arranged in a 10 x10 grid. Sixteen of these markers were digitised in Simi and the reconstructed distances between the markers were compared to the known distances; the average error for the underwater filming was 3 mm in all planes.

Custom made, fibreoptic markers were adhered to the skin using hypoallergenic waterproof tape (under clothing). Markers were attached to landmarks at the sternal notch, the right nipple and the left and right anterior inferior aspect of the 10th ribs (Scurr et al., 2009; 2010; White et al., 2009). Before data were collected the participants conducted a five minute warm-up to familiarise themselves with the experimental set up and swimming flume environment. The testing consisted of front crawl swimming at 1.08 (± 0.1) $m.s^{-1}$ and breaststroke swimming at 0.94 (± 0.1) $m.s^{-1}$ (water temperature: 30.5°C ± 1°C), a pilot study with these participants classed both swimming speeds as “comfortable”. On entering the swimming flume, the participants began to swim; once they achieved a consistent stroke pattern (as assessed by a qualified swimming instructor) marker positions were captured during two complete non-breathing (front crawl) and breathing (breaststroke) stroke cycles. Each swimming stroke was performed in three breast support conditions; bare-breasted, swimsuit (71% Polyamide, 29% Elastane), the best-selling swimsuit for recreational swimmers in the UK and a sports bra (45% Polyester, 44% Polyamide and 11% Elastane), the 2008 best-selling branded sports bra in the UK.

Digital video footage of the swimming trials were uploaded to Simi and following calibration of the synchronised footage, anatomical markers were manually digitised for each participant, during each stroke and trial in each breast support condition. Following 3D reconstruction, marker coordinate data were exported into Microsoft Excel. A trunk reference segment was constructed using the markers on the suprasternal notch and left and right ribs, this was used to convert the motion of the right nipple from the global coordinate system to a local, relative coordinate system enabling independent relative motion of the right nipple to be determined (Scurr et al. 2010). The local coordinate system identified x as anterioposterior, y as mediolateral and z as superioinferior, regardless of the prone position (Figure 1b). Relative breast coordinates were filtered using a 2nd order low-pass Butterworth filter (cut-off frequency of 8 Hz). This cut-off frequency was determined using a customised MatLab programme which enabled the power spectrum and residual analysis of the signal to be analysed (Winter, 1990). Multiplanar relative breast displacement was calculated by subtracting minima positional coordinates from maxima coordinates during each swimming stroke (adapted from gait assessment; Scurr et al. 2010).

***** Insert figure 1 here*****

The maximum angle of trunk roll (in the global coordinate system) during each front crawl stroke was calculated using the trunk reference segment. The segment from the mid-point of the left and right rib (virtual mid rib) to the sternal notch was used to define the longitudinal axis of the trunk. The angle was measured from the mediolateral vector extending from the virtual mid rib to the right rib and the horizontal global plane (Figure 2a). Trunk roll was defined as the peak angle from the horizontal global plane during each swimming stroke (Psycharakis & Sanders, 2010). The maximum trunk extension (in the global coordinate system) during breaststroke was calculated as the angle between the trunk segment defined by the vector extending from the mid rib to the sternal notch relative to the horizontal global plane (water surface) (Colman, Persyn, Daly & Stijnen, 1998) during each swimming stroke (Figure 2b).

***** Insert figure 2 here*****

Multiplanar breast displacement and trunk motion were statistically analysed using PASW software (Version 18). All data were checked for normality using the Shapiro-Wilk tests and were parametric if $P > 0.05$. Repeated Measures ANOVAs were used when the data were normally distributed and a Friedman test was used for non-parametric data. Within each stroke the independent variable of breast support had three factors; bare-breasted, swimsuit and sports bra and the dependant variables were breast displacement (in each direction) or trunk motion (peak roll or extension). ANOVAs were followed by post-hoc analysis in the form of multiple paired samples T-tests with a Bonferroni adjustment ($P < 0.017$). Effect sizes (parametric: Cohen's d or non-parametric: r) and 95% confidence intervals (CI) are reported, where appropriate, to provide an indication of the magnitude of the result. A large effect size was defined as $d > 0.8$, moderate as between 0.8 and 0.5, and a small effect size defined as < 0.5 (Field, 2009). Either Pearson's or Spearman's correlations assessed relationships between breast displacement and trunk motion. Correlation coefficients (r_S) of 0.1 to 0.29 defined a weak relationship, 0.3 to 0.49 a moderate relationship and 0.5 to 1 a strong relationship (Cohen, 1988).

3. Results

3.1 Qualitative overview of trunk and breast motion during front crawl swimming

Trunk roll exhibits a double peak with the first peak occurring after approximately 30% of the stroke and the second at 75%. Mediolateral breast displacement follows a similar temporal pattern with breast displacement firstly peaking medially and then laterally. These temporal characteristics are present within each breast support condition with a decrease in the magnitude of breast displacement as breast support changed from bare-breasted to the swimsuit to the sports bra (Figure 3). Anterioposterior breast displacement first peaks anteriorly and then posteriorly with a similar timing as trunk roll in the bare-breasted support condition, however, the timing becomes out of phase with the trunk as breast support changed from the swimsuit to the sports bra. The magnitude of superioinferior breast displacement represents the smallest of the three components and its temporal characteristics change with support condition. During the swimsuit and sports bra support condition breast displacement peaks superiorly at approximately 50% to 60% of the stroke cycle and inferiorly at approximately 90% of the stroke cycle (Figure 3).

***** Insert figure 3 here*****

3.2 Qualitative overview of trunk and breast motion during breaststroke swimming

Trunk extension exhibits a single peak occurring after approximately 55 to 60% of the stroke cycle. Bare-breasted anterioposterior breast displacement also exhibits a single peak (similar to trunk extension), however this posterior peak in breast displacement occurs at approximately 80% of the stroke cycle. This temporal pattern is also present within each support condition (Figure 4). Superioinferior breast displacement peaks inferiorly at approximately 70% through the stroke cycle within the bare-breasted support condition, however this peak is not evident within the swimsuit and sports bra support conditions. The magnitude of mediolateral breast displacement represents the smallest of the three components and its temporal characteristics change with support condition. During the bare-breasted support condition breast displacement peaks medially (25%), laterally (50%) then medially again (75%) during the stroke. This may reflect the movement of the arms toward the centre of the body during the middle phase of the stroke ‘pushing’ the breast together. This temporal pattern is not evident in the swimsuit and sports bra support conditions (Figure 4).

***** Insert figure 4 here*****

3.3 Front crawl and breast motion

The greatest mean breast displacement occurred mediolaterally in the swimsuit condition (7.8 ± 1.5 cm) and the least mean breast displacement occurred in the superioinferior direction (3.3 ± 1.3 cm) whilst wearing the sports bra (Figure 5). A significant difference was found between breast displacements in the three support conditions during front crawl swimming ($F_{(2, 10)} = 21.25$, $P < 0.001$), with no interaction effect seen with the direction of displacement (superioinferior, mediolateral, anterioposterior) ($F_{(2, 10)} = 2.12$, $P = 0.07$). Post-hoc analysis revealed that the sports bra condition significantly reduced breast displacement when compared to both the bare-breasted ($t = 3.466$, $P < 0.001$, $d = 1.15$, 95% CI [0.63, 2.59]) and swimsuit ($t = 3.498$, $P < 0.001$, $d = 1.03$, 95% CI [0.62, 2.51]) conditions, but no difference was found between the bare-breasted and swimsuit conditions ($t = 0.107$, $P = 0.916$, $d = 0.04$, 95% CI [-0.99, 1.10]).

***** Insert figure 5 here*****

3.4 Breaststroke and breast motion

During breaststroke swimming the greatest breast displacement occurred superioinferiorly in the bare-breasted condition (3.7 ± 1.6 cm) and the least breast displacement occurred in the mediolateral direction (1.4 ± 0.8 cm) whilst wearing the sports bra (Figure 6). A significant difference was found in breast displacement across breast support conditions ($\chi^2_{(2)} = 12.25$, $P = 0.002$). Post-hoc analysis revealed that this difference lay between the bare-breasted and sports bra conditions (Z = -2.60, *P* = 0.009, r = 1.06) with the sports bra decreasing amount of breast displacement compared to bare-breasted, but there was no difference between the bare-breasted and swimsuit (Z = -3.37, *P* = 0.02, r = 1.38) or the swimsuit and sports bra (Z = -2.23, *P* = 0.03, r = 0.91) conditions.

***** Insert figure 6 here*****

3.5 Front crawl and trunk roll

During front crawl swimming visual inspection of the data showed the greatest trunk roll occurred in the sports bra condition (43.1 ± 8.3°), followed by the bare-breasted condition (42.1 ± 5.7°), with the least trunk roll occurring in the swimsuit condition (39.3 ± 4.2°), however no significant differences were found in trunk roll between the three support conditions ($\chi^2_{(2)} = 1.33$, $P = 0.513$). It was noted that some participants showed an increase in trunk roll with changes in support and others showed a decrease in trunk roll with changes in support (Figure 7).

***** Insert figure 7 here*****

3.6 Breaststroke and trunk extension

The greatest trunk extension occurred in the swimsuit condition (55.4 ± 5.0°), followed by the sports bra condition (54.5 ± 2.9°), with the least trunk extension occurring in the swimsuit condition (52.4 ± 5.4°), however no significant differences were found in trunk extension between the three support conditions ($F_{(2, 10)} = 0.759$, *P* = 0.493). It was noted that trunk extension was individual with changes in breast support resulting in both increases and decreases in trunk extension across participants (Figure 8).

***** Insert figure 8 here*****

3.7 Relationships between trunk and breast motion

Strong negative relationships were found between trunk roll and anterioposterior breast displacement ($r_s = -.527$, $P = 0.025$) and superioinferior breast displacement ($r_s = -.583$, $P = 0.011$). This suggests that more trunk roll results in less anterioposterior and superioinferior breast displacement during front crawl swimming. No significant relationships were found between breast displacement and trunk extension during breaststroke swimming.

4 Discussion

Understanding how trunk and breast kinematics differ across breast support conditions may yield insights into design recommendations for swim specific sportswear. The aim of this study was to investigate the differences in trunk and breast kinematics whilst wearing varying levels of breast support during front crawl and breast stroke swimming. One key finding of this study was that the level of breast support affects the magnitude of breast motion with the sports bra reducing breast displacement compared to the other breast support conditions. Interestingly, there was no significant difference in breast displacement between the swimsuit and the bare-breasted condition suggesting that the swimsuit offers minimal support to the breasts during front crawl swimming. A similar result was also found during breaststroke swimming with the sports bra reducing the magnitude of breast displacement when compared to the swimsuit and bare-breasted conditions. These findings reject the first hypothesis as there was no significant decrease in breast displacement within each stroke as breast support changed from bare-breasted to the swimsuit to the sports bra.

The majority of previous literature has investigated breast displacements on land during running and jumping and have reported that the unsupported breasts displace up to 15 cm (Scurr et al., 2011) and 18.7 cm (Bridgman, Scurr, White, Hedger & Galbraith, 2010) respectively. However, during swimming the maximum breast displacement was 7.6 cm for larger breasted women, which may reflect the differences in the activities, such as the global trunk orientation and possibly the hydrostatic compression of the water (Lomax & McConnell, 2003) acting as a form of support to the breasts. The compression effect of the water may reduce breast displacement similar to that of a compression bra (White et al., 2009). As the support provided by the swimsuit resulted in no differences in breast displacement between the swimsuit and bare-breasted conditions, one may conclude that the natural chest strapping effect of hydrostatic compression (Robertson et al., 1978) was not enhanced by the addition of the swimsuit. Thus, the swimsuit was ineffective as an additional means of support for the breasts during swimming. However, as the sports bra was able to reduce breast displacement during both swimming strokes, aspects of its design could help to inform improvements in swimsuit design for larger breasted women. Swimsuits that incorporate elements of sports bra design such as adjustable straps and structured seams (Zhou, Yu & Ng, 2012b) may help to minimise breast displacements especially during front crawl (since the greatest amount of breast displacement occurred during this stroke), and also during breaststroke swimming.

A further notable finding of this study was that trunk motion (trunk roll in front crawl and trunk extension in breaststroke), the previously reported driving force for the breasts on land, was not significantly different across breast support conditions, rejecting the second hypothesis. When examining the magnitudes of trunk roll during front crawl swimming it was evident that the majority of participants rolled less than previously published data (42 to 72°) but did achieve the coaching recommendation of 30 to 40° of trunk roll (Maglischo, 1993). There were also no changes in trunk extension with levels of breast support, however, it was noted from visual inspection of the video that, during breaststroke swimming, water became trapped in the upper section of the swimsuit (and also, to a lesser extent, the sports bra) possibly influencing trunk extension. These results suggest that increasing the amount of breast support does not reduce the moment of inertia about the rotational axis of the trunk or alter the form drag also reducing the resistance to rotation. It may be possible that the water exerts a stronger effect on trunk motion than that of the breast support condition. It may also be possible that the hydrostatic pressure alone provided by the water was sufficient to support the breasts, therefore allowing the participants to maintain similar trunk motion.

Although the greatest breast motion occurred in the mediolateral direction strong negative relationships were found between trunk roll and anterioposterior and superioinferior breast displacement during front crawl swimming, indicating that an increase in trunk roll will decrease breast displacement in these directions, rejecting hypothesis three. No significant relationships were found between trunk extension and superioinferior breast displacement, suggesting that women who exhibit greater trunk extension do not experience greater superioinferior breast displacement, rejecting hypothesis four. The relationship between trunk roll and breast displacement was an interesting and unexpected finding as it was anticipated that women who exhibit greater trunk roll would induce significantly greater mediolateral breast displacement. There may be several reasons for this; firstly, the flow velocity of the water in the flume may not be uniform with changes in water depth. This may mean that the flow velocity is greater nearer the surface and decreases with depth, therefore affecting the drag on the swimmer. With increased trunk roll the breast may be closer to the water's surface and exposed to higher flow velocities resulting in a 'pinning' effect on the breast, pushing it closer to the trunk, decreasing anterioposterior breast displacement and consequently minimising superioinferior displacement. Similarly, the breast being closer to the surface of the water may also cause an increase in wave drag (Vennell, Pease & Wilson, 2006). An increase in wave drag may also have a similar 'pinning' effect to that associated with an increase in flow velocity. Finally, flume construction may mean that the wave energy cannot be dissipated and is rebounded back off the side of the flume wall towards the swimmer. An increase in trunk roll may expose more of the trunk and breast to this rebound wave, again acting to 'push' or 'pin' the breast towards the trunk minimising breast anterioposterior and superioinferior displacement. It would be beneficial for a future study to examine any differences in breast motion during swimming both in the flume and pool environments and also to manipulate trunk roll from low to high to determine its effect on breast displacement using an intraparticipant design. However, as it was beyond the scope of the present study to do this, caution must be advised when interpreting the observed relationship between trunk roll and breast displacement.

3 Conclusion

This study found that greater breast displacements were present during front crawl swimming compared to breaststroke swimming and the level of breast support affected the magnitude of breast displacement in water. Sports bras offered significant breast displacement reductions, similar to published findings based on land, yet the swimsuit was ineffective as an additional means of support for the breasts during swimming. However, as the sports bra was able to reduce breast displacement during both swimming strokes, it is recommended that aspects of its design could help to inform improvements in swimsuit design for larger breasted women. Trunk motion (trunk roll in front crawl and trunk extension in breaststroke), the previously reported driving force for the breasts, were not significantly affected by changes in the level of breast support for larger breasted women, possibly suggesting that the water exerts a stronger effect on trunk motion than that of changes in breast support.

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Figure captions

Figure 1. (a) Camera locations on base of swimming flume (b) trunk local coordinate system (LCS) and swim flume global coordinate system (GCS) definition.

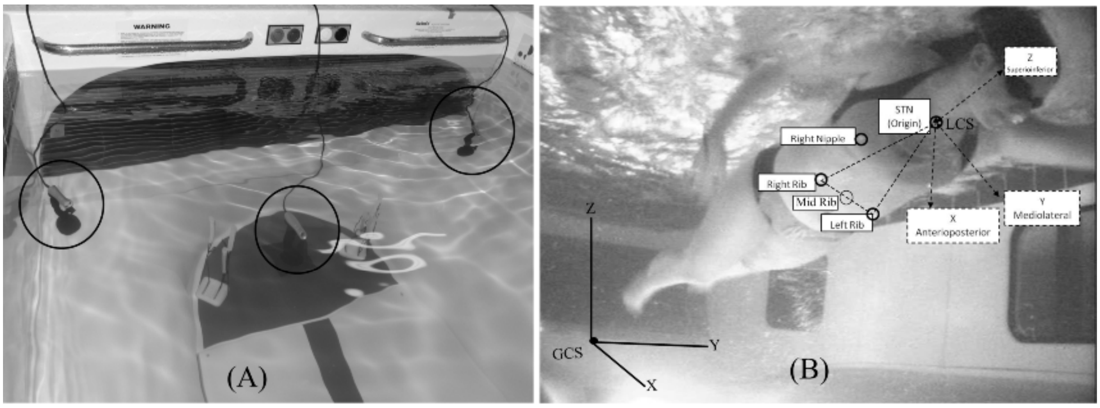

Figure 2. Angle definitions for (a) trunk roll during front crawl swimming, (b) trunk extension during breast stroke swimming.

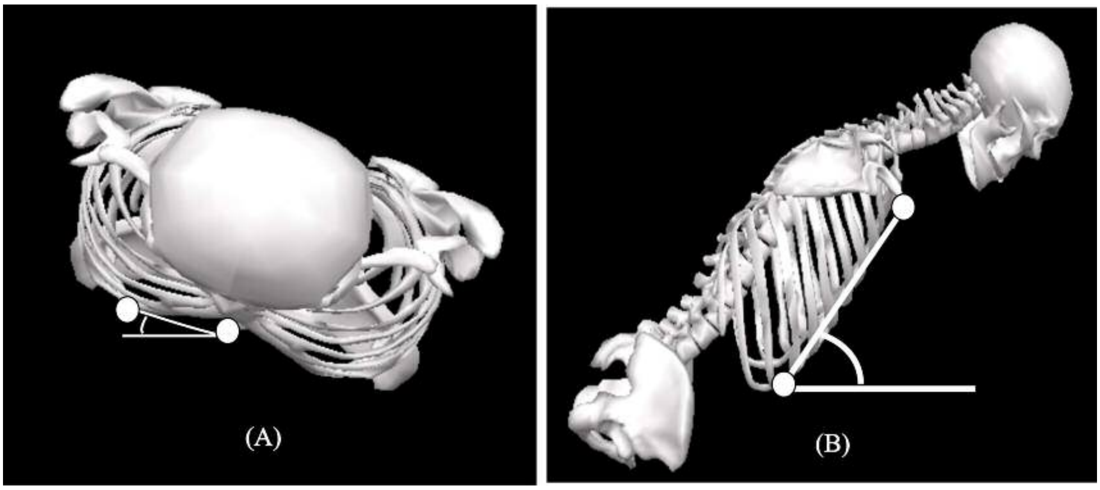

Figure 3. Trunk roll and multiplanar breast displacement (a) trunk roll, (b) anterioposterior, (c) mediolateral, (d) superioinferior, in three supports during average front crawl swimming strokes (solid line = bare-breasted, square dot = swimsuit; circular dot = sports bra), (n=6).

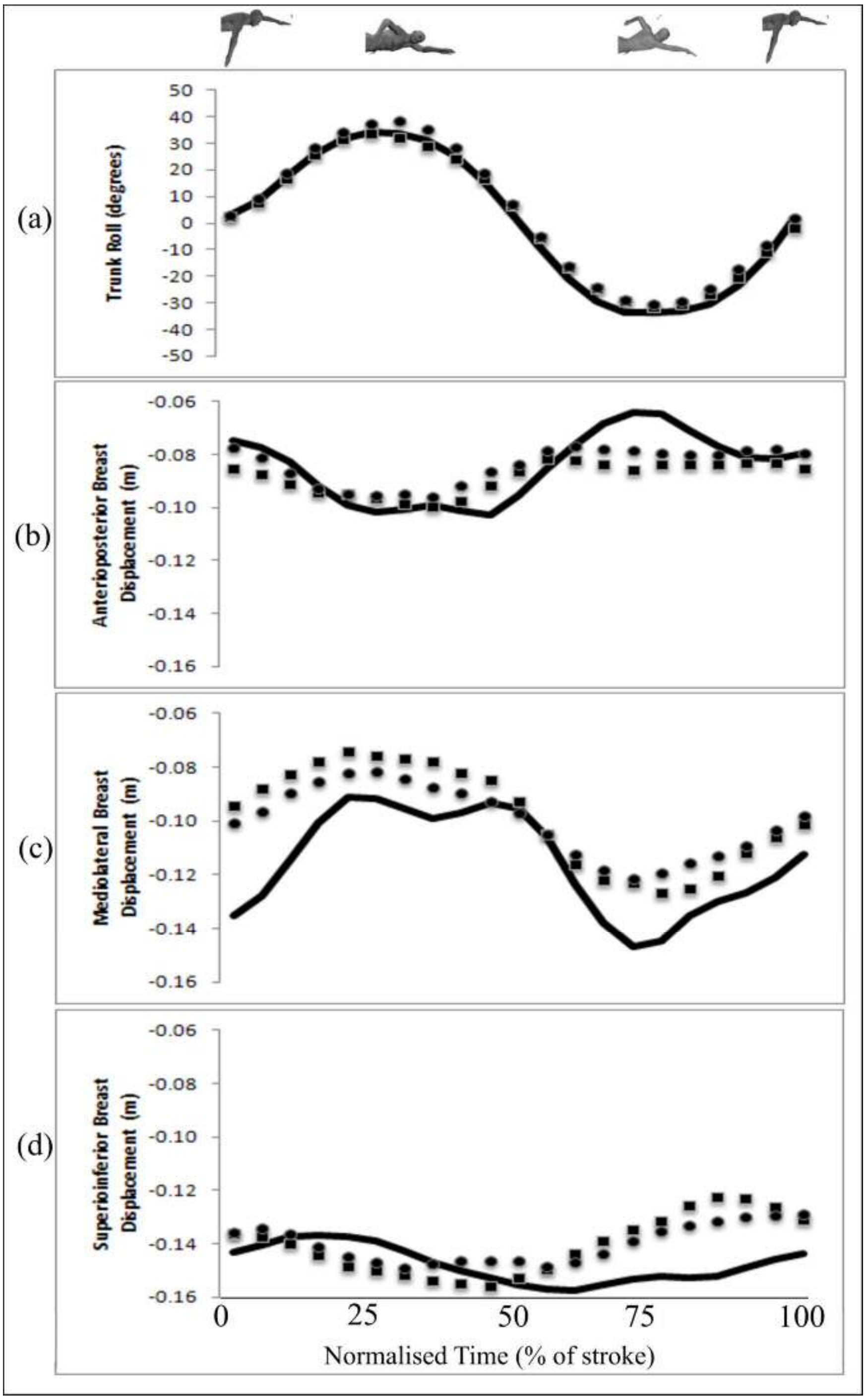

Figure 4. Trunk extension and multiplanar breast displacement (a) trunk extension, (b) anterioposterior, (c) mediolateral, (d) superioinferior, in three supports during average breaststroke swimming strokes (solid line = bare-breasted, square dot = swimsuit; circular dot = sports bra), (n=6).

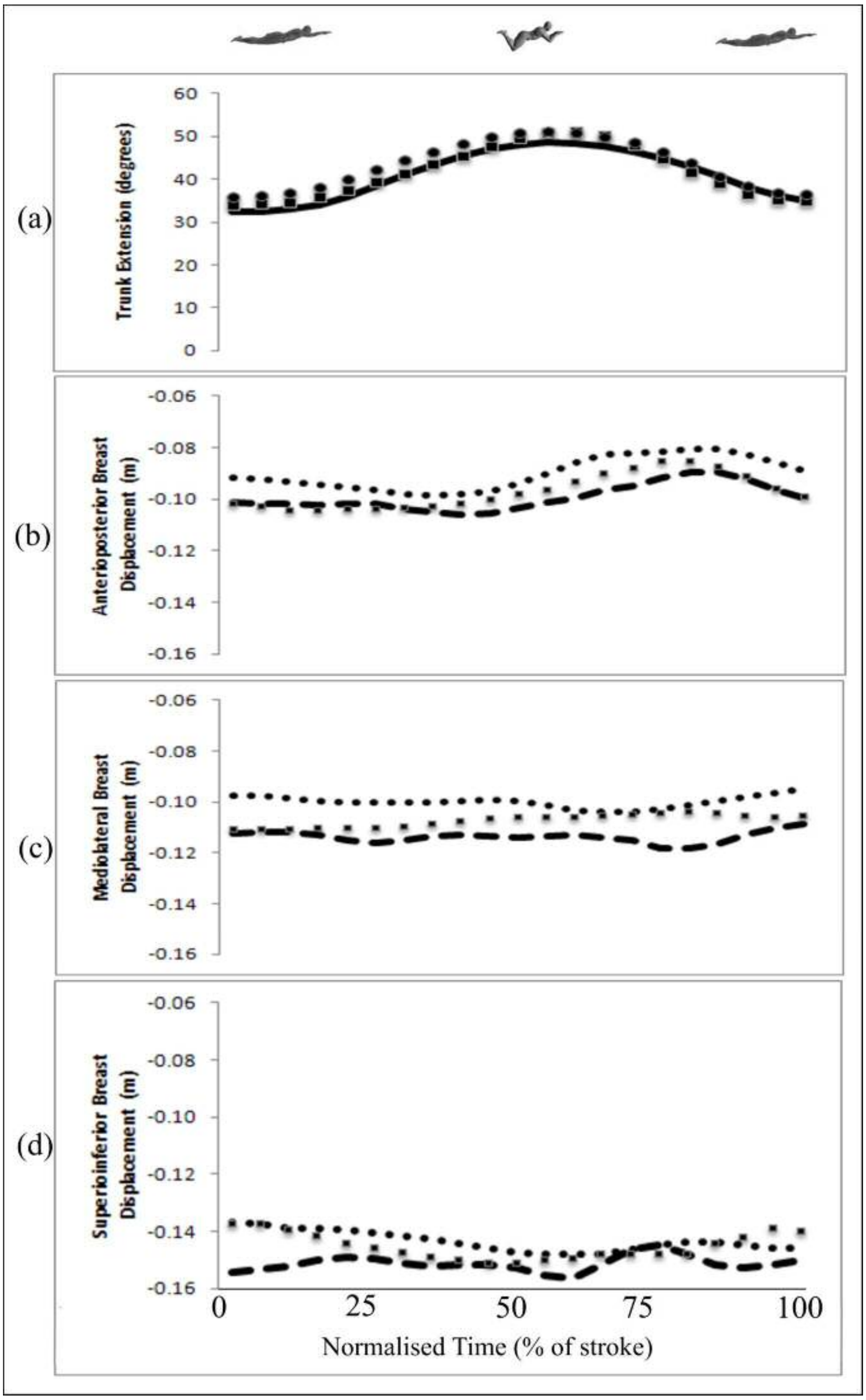

Figure 5. Breast displacement during front crawl swimming in three support conditions.

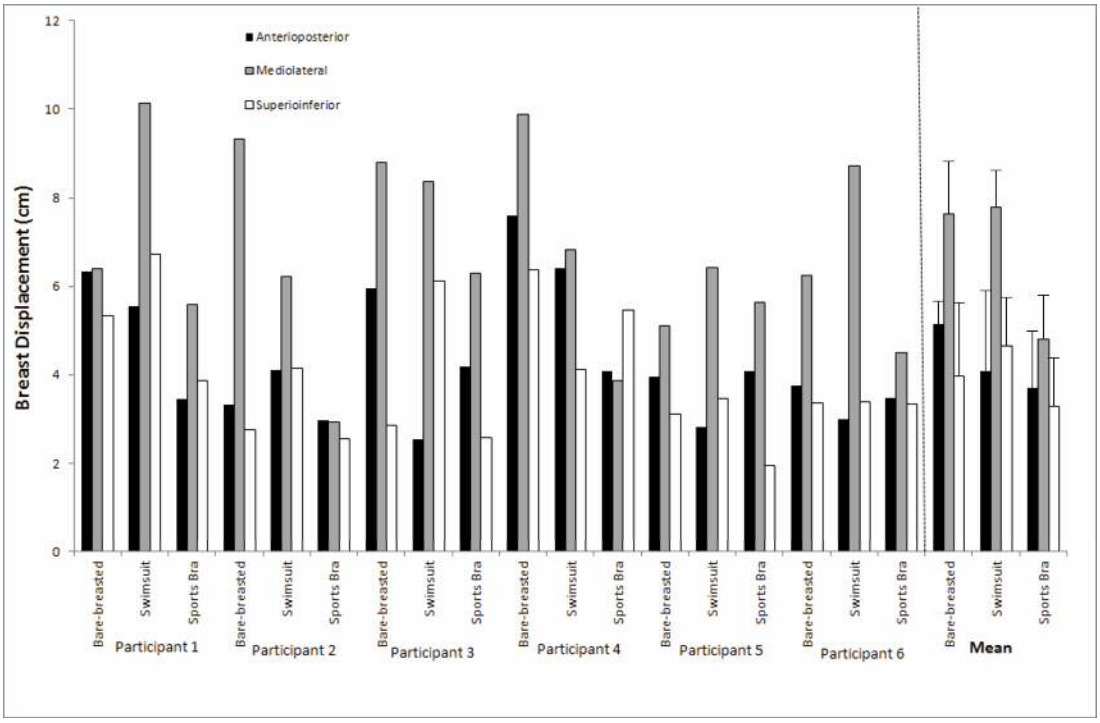

Figure 6. Breast displacement during breaststroke swimming in three support conditions.

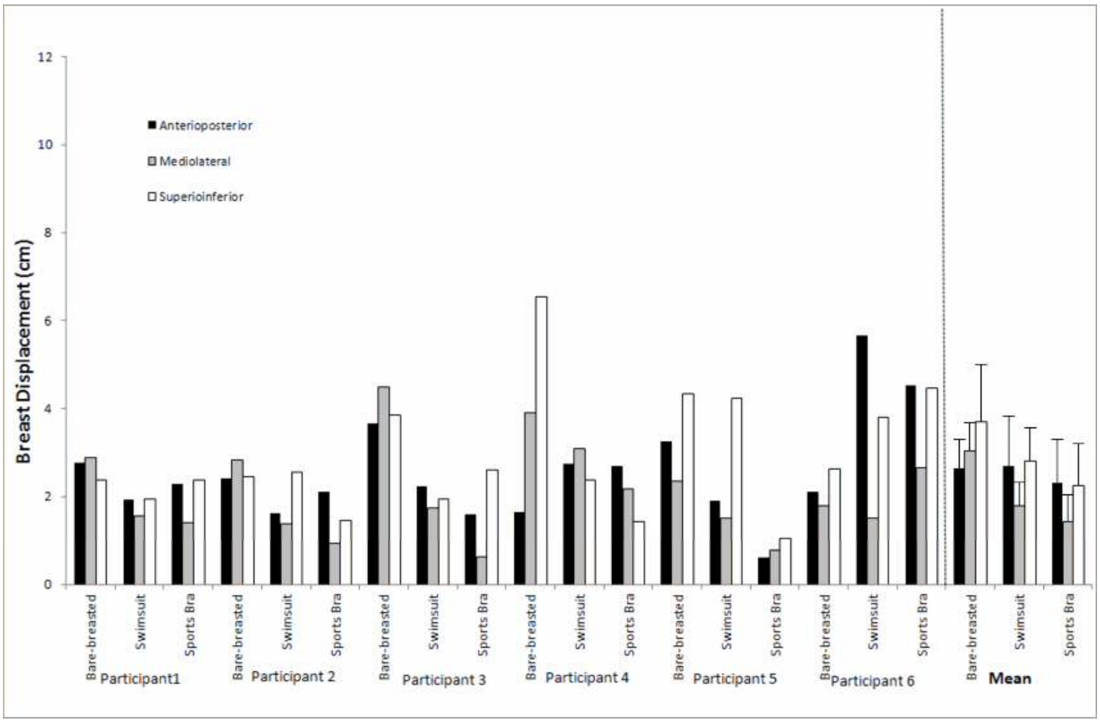

Figure 7. Trunk roll during front crawl swimming in three breast support conditions (averaged across two strokes).

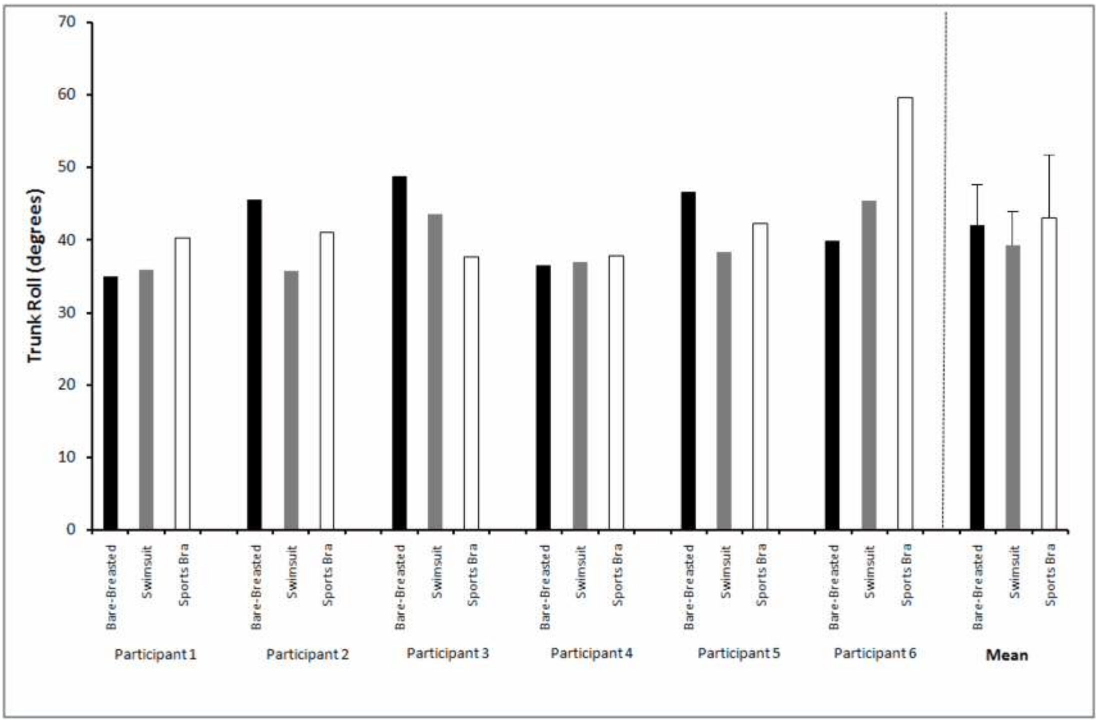

Figure 8. Trunk extension during breaststroke swimming in three breast support conditions (averaged across two strokes).