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Abstract

The purpose of this study was to determine whether the breathing action in front crawl (FC) sprint swimming affects the ipsilateral upper limb kinematics relative to a non-breathing stroke cycle (SC). Ten male competitive swimmers performed two 25m FC sprints: one breathing to their preferred side (Br) and one not breathing (NBr). Both swim trials were performed through a 6.75m^3 calibrated space and recorded by six gen-locked JVC KY32 CCD cameras. A paired t-test was used to assess statistical differences between the trials, with a confidence level of $p<0.05$ accepted as significant. Swimmers were slower (3%) when breathing. Within the entry phase, swimmers had a slower COM horizontal velocity (3.3%), less shoulder flexion (8%), abduction (33%) and roll (4%) when breathing. The pull phase was longer in duration (14%) swimmers had a shallower hand path (11%), less shoulder abduction (11%), a slower hand vertical acceleration (30%) and slower centre of mass (COM) horizontal velocity (3%) when breathing. In the push phase, swimmers had a smaller elbow range of motion (ROM) (38%), faster backwards hand speed (25%) and faster hand vertical acceleration (33%) when breathing. Swimmers rolled their shoulders more (12%) in the recovery phase when breathing. This study confirms that swim performance is compromised by the inclusion of taking a breath in sprint FC swimming. It was proposed that swimmers aim to orient their ipsilateral shoulder into a stronger position by stretching and rolling the shoulders more in the entry phase whilst preparing to take a breath. Swimmers should focus on lengthening the push phase by extending the elbow more and not accelerating the hand too quickly upwards when preparing to inhale.

Key words: Freestyle swimming; three-dimensional; breath-holding; ipsilateral, technique.

Introduction

Researchers have often recommended that swimmers limit the number of breaths taken during a race due to the possible adverse effects that the front crawl breathing action may have on stroke mechanics and hydrodynamic drag (Di Prampero et al., 1974; Pendergast et al., 1977; Town and Vaness, 1990; Cardelli et al., 1999; Formosa et al., 2014). However the literature does not conclusively support the premise that breathing in front crawl swimming has a negative effect on swim performance. Some studies have reported reduced swim velocity and/or stroke frequency as a result of breathing compared to not breathing (Pedersen and Kjendlie, 2006; Psycharakis and McCabe, 2011), whereas other researchers have reported no differences (Castro et al., 2006; Vezos et al., 2007; Seifert et al., 2008). The disparity within the literature may be attributed to methodological issues such as whether the centre of mass (COM) or hip joint was utilised to quantify the above variables, which mathematical approach was implemented, and the range of swim speeds assessed within these studies. Nevertheless, as breathing is a fundamental skill within front crawl swimming, it is imperative to further assess what effect it may have on a swimmer’s sprint performance.

As the arms contribute to propulsion more than the legs in front crawl swimming (Di Prampero et al., 1974; Watkins and Gordon, 1983), this study will focus on examining the effect breathing has on various key upper limb kinematic variables linked to swim performance. Shoulder and hip roll rotations have been strongly related to front crawl swim performance (Payton et al., 1999; Castro et al., 2002; Psycharakis and Sanders, 2010). Swimming at a 200m pace, Payton et al. (1999) reported that swimmers rolled their shoulders 9degs more during a breathing trial compared to a non-breathing trial. More recently Psycharakis and McCabe (2011) found that although the total magnitude of shoulder and hip roll angles did not differ between breathing conditions, male sprinters rolled their shoulders and hips to the breathing side significantly more (9.5° or 18.8%) relative to the non-breathing side. Previous studies have tended to examine shoulder and hip roll angles in terms of the total magnitudes within the SC. The aim of this study will be to investigate shoulder and hip roll angles within the integral phases of the SC in order to provide a more comprehensive insight as to how these parameters may, or may not, be influenced by the breathing action.

The motion of the shoulders, in terms of flexion/extension, abduction/adduction internal/external rotation and elevation have been associated with determining upper limb propulsion. However, shoulder kinematics are more commonly discussed within aquatic literature in relation to injury and rarely with respect to swim performance within an ecological environment. Consequently, it is unknown whether incorporating a breath within the SC causes alterations of the shoulder movements and thus influences the swimmer’s overall performance.

The shoulder motion has often been linked to the hand-path throughout the underwater stroke cycle (SC) which consists of horizontal, vertical and lateral motions in order to achieve forward propulsion of the body (Schleihauf et al., 1983; Deschodt et al., 1996a; Deschodt et al., 1999). To date, only two studies have investigated the influence the breathing action has on hand-path trajectory. Payton et al. (1999) reported that the front crawl breathing action did not interfere with the underwater hand-path, in terms of maximum depth and width when elite male swimmers swam at a 200m pace. However Vezos et al. (2007) found that the breathing action caused significant modifications in hand-path when investigating a group of female front crawl sprinters at a submaximal pace. Vezos et al. (2007) speculated that the discrepancies with Payton et al. (1999) were due to anthropometric differences associated with opposing genders sampled, yet did not consider the differing swim pace. Because Payton et al. (1999) analysed swimmers at a 200m pace, it is unknown whether male swimmers adjust their hand-path between breathing and non-breathing conditions when swimming at a sprint pace. Such knowledge is beneficial in terms of how the breathing action may, or may not, alter a swimmer’s hand-path when maximally swimming, thus ultimately influencing their forward propulsion and performance.

The elbow angle magnitude during the underwater phase of the SC has been proposed to influence the hand-path trajectory (Hay et al., 1993) whilst also affecting the propulsive actions of the upper limbs (Cappaert, 1998; Haffner and Cappaert, 1998). Payton et al. (1999) is the only study to examine the elbow angle between breathing and non-breathing conditions, reporting that the breathing action did not influence the elbow angle range of motion (ROM) during the pull phase (breathing: 44 ± 15°; non-breathing: 45 ± 14°). Therefore, with the exception of only the pull phase, no study has examined the elbow angle magnitudes throughout the underwater SC between breathing conditions when front crawl sprinting, which could affect the capability of the upper limbs to generate propulsion.

The pull and push phases are regarded as propulsive and the entry and recovery phases are regarded non-propulsive (Chollet et al., 2000). Payton et al. (1999) noted that male swimmers had a longer duration of the underwater phase during the breathing trials (1.11 ± 0.15s) vs. non-breathing trials (1.05 ± 0.12s) but did not comment whether this observed difference was significant. Vezos et al. (2007) found similar results within a female sprint group (breathing: 1.25 ± 0.17s vs. breath-holding: 1.16 ± 0.15s; $p<0.05$), but added that the longer duration within breathing trials was the result of a prolonged entry phase compared to the non-breathing trials. Payton et al. (1999) did not report the durations of the discrete phases between breathing conditions. Thus, it is important to explore whether the breathing action affects the duration of the propulsive and/or non-propulsive stroke phases in front crawl sprint swimming as ultimately any changes are likely to affect swim performance.

The velocity of the swimmer's COM has become a valuable tool as it indicates when and to what extent phases of the SC are effective in propelling the body forwards (Maglishco et al., 1989; Alves et al., 1994). To date, no study has investigated the COM velocity magnitude within the integral phases of the SC in relation to breathing vs. non-breathing conditions. The literature further indicates that the COM velocity is strongly influenced by swimmers accelerating their hands (Schleihauf, 1984), yet no study has examined these characteristics between breathing conditions within a male sprinting population.

In summary, it is unclear to what extent breathing affects performance in terms of, shoulder/hip roll, shoulder kinematics, hand-path, elbow angle magnitudes, stroke phase durations, COM velocity profile, hand velocity and acceleration throughout the SC. The purpose of this study was to investigate whether the breathing action in front crawl sprint swimming affects the ipsilateral upper limb kinematics (same side as breathing side) relative to a non-breathing stroke cycle and to assess any changes in swimming performance. The rationale to analyse the ipsilateral hand was to compare datasets in relation to previous studies and its action may be constrained by the breathing rotation whereas there is no a priori reason to expect that the hand motion on the non-breathing side would be affected.

Materials and Methods

Participants

Ten male front crawl swimmers (age: 18.4 ± 2.6 years; mass: 72.9 ± 10.2 kg; height: 182.7 ± 7.9 cm) volunteered to participate in this study. These athletes competed at a national/international level and registered a personal best time of 25.31 ± 0.98s (long course) for 50m front crawl sprint. The test procedures were approved by the University Ethics Committee and all swimmers provided written informed consent.

Testing Procedure

Following an individualised warm-up each participant swam two randomised maximal 25m front crawl sprints: one 25m sprint breathing once to their preferred side (Br) and one 25m sprint with no breathing (NBr) throughout the 25m.

The testing set-up was similar to Psycharakis et al. (2010) with all swim trials performed through a 6.75m^3 pre-calibrated volume (orthogonal axes: 4.5m [X- horizontal], 1.5m [Y- vertical], 1.0m [Z-medio-lateral]). Based on previous accuracy and reliability calculations for this frame (Psycharakis et al., 2005), 20 control points were used for calibration. Reconstruction errors were calculated following 10 repeated digitisations by the same operator (20 control points and 10 different points representing the ‘markers’), which were found as low in all three directions (2.4mm-4.5mm absolute errors; 3.3mm-5.2mm root mean square errors; 0.1%-0.5% of the calibrated space). Six gen-locked JVC KY32 CCD cameras (four below and two above water) sampling at a frequency of 50 fields per second and a shutter speed of 1/120s were positioned similar to Psycharakis et al. (2010) so that all cameras captured the swimmer throughout the pre-calibrated space.

To enable subsequent calculation of the whole body COM using the 'eZone' method (Deffeyes and Sanders, 2005) each swimmer had 19 markers applied to the following anatomical landmarks: vertex of the head, the right and left of the: 3rd distal phalanx tip (hand), wrist axis, elbow axis, shoulder axis, hip axis, knee axis, ankle axis, 5th metatarsophalangeal joint, and the tip of 1st phalanx (big toe).

Data Processing

One SC, defined as the period between the instant of hand entry to the instant of entry of the same hand, was selected for analysis. Whilst the full stroke cycle was digitised, only the pulling arm on the same side that the swimmer took the breath was analysed (ipsilateral upper limb to breathing side), representing the first hand entry of the SC. The Ariel Performance Analysis System (APAS-2000 Ariel Dynamics, San Diego, CA) software was used to manually digitise the 19 anatomical landmarks from all camera views. Incorporating the direct linear transformation (DLT) algorithms in APAS, 3-dimensional coordinates of the anatomical landmarks were obtained and smoothed using a Fourier series transform (Bloomfield, 1976) retaining six harmonics.

The average X swimming velocity (V_{av}) was calculated by dividing the swimmer's mean COM X displacement by the time to complete one SC. The COM X velocity ($m \cdot s^{-1}$) was obtained by differentiating the COM displacement using the first central difference formula. Stroke frequency (SF) was the inverse of the time (seconds) to complete one SC which was then multiplied by 60 to yield units of strokes per minute. Stroke length (SL) was the X displacement of the COM during one SC.

Shoulder and hip roll angles were each determined as the angle between the unit vector of the line joining the shoulders and hips respectively, projected onto the yz plane (i.e. the plane perpendicular to the swimming direction) and the horizontal. Computationally, this is: arc-tangent (S_z/S_y) and arc-tangent (H_z/H_y); where S_z and S_y are the z and y components of the shoulder unit vector and H_z and H_y are the z and y components of the hip unit vector.

To assess the orientation of the shoulder to elbow joint, the longitudinal axis of the segment was expressed with respect to an internal frame of reference. The internal frame of reference consisted of the X_{int} being the unit vector in the direction of the vector joining the midpoint of the shoulder axes to the midpoint of the hip axes; the Y_{int} axis being the unit vector formed by the cross product of X_{int} and the unit vector in the direction of the vector joining the shoulder joints and Z_{int} the unit vector formed as the cross product of X_{int} and Y_{int}. A Cardan angle to each of the reference axes was then quantified as the arc-cosine of the dot product of the arm unit vector and the reference axis unit vector. Flexion and extension of the shoulder was indicated by the Cardan angle between the arm segment and the X_{int} axis. The angle was adjusted by subtracting 90 degrees so that 0 degrees corresponded to the transition between the pull and the push, the angle at entry was close to -90 degrees and approached 90 degrees of flexion at exit. Abduction refers to the angle of the arm axis to the Z axis with correction so that alignment with the Z_{int} axis is 90 degrees of abduction and -90 degrees represents 90 degrees of adduction.

The Y and X motion of the hand was represented by the displacement (m) of the 3rd distal phalanx (with respect to a pool-fixed Cartesian reference system). Similar to Vezos et al. (2007) the underwater pull length (X) was defined as the backward displacement of the hand from its most forward position to its most backward position. The lateral motion of the hand, with respect to the swimmer's COM, was calculated as the absolute Z displacement (m) of the 3rd distal phalanx.

The elbow angle was determined as the arc-cosine of the dot product of the upper and lower arm unit vectors and was quantified at four instants throughout the underwater SC in accordance with McCabe et al. (2011). The first instant ('first back') was defined as the moment the finger began to move horizontally backward. The second instant ('shoulder x') as the moment the finger was vertically aligned with the shoulder. The third instant ('end back') was defined as the moment the finger stopped moving horizontally backwards and the fourth instant (‘re-entry’) when the hand entered the water. On identification of these four instants the corresponding time was noted and the elbow angles calculated accordingly. This process also allowed the identification of the stroke phases: entry phase - period between hand entry to ‘first back’ position; pull phase - period between ‘first back’ to ‘shoulder x’; push phase - time between ‘shoulder x’ and ‘end back’; recovery phase - period from ‘end back’ to ‘re-entry’. The stroke phase durations were expressed as a percentage of the SC (%SC).

Hand velocity was calculated in the X and Y axis (with respect to an external reference point) throughout the underwater SC. Hand speed was quantified as the resultant of the X, Y and Z hand velocity components. Since acceleration is the second derivative of position, the X and Y acceleration of the hand was obtained by double differentiating positional data of the hand throughout the underwater SC.

Errors due to manual digitisation were assessed through 10 repeated digitisations of a SC by the same operator. The standard deviation (SD) and coefficient of variation (CV) showed small and acceptable errors for all variables (CV: 0.22 to 4.92%).

Statistical Analysis

The assumption of normality was verified through the Shapiro–Wilk test. A paired t-test was used to assess statistical differences between breathing conditions, with a confidence level of $p<0.05$ accepted as significant, using the Statistical Package for Social Sciences (SPSS) version 22.0. Taking into account the increased possibility of type 1 or type 2 errors (large number of variables tested), effect size (d) calculations (mean difference between the conditions relative to the pooled standard deviation) were performed across all variables using Cohen’s (1992) criteria for interpreting the results.

Results

Race Parameters

Swim velocity was significantly greater during the NBr (1.82 ± 0.08m·s^{-1}) compared to Br (1.77 ± 0.07m·s^{-1}) trials ($t(9)=2.78$; p=0.02; d=0.67). There were no significant differences between conditions for SL (NBr: 1.98 ± 0.14m; Br: 1.96 ± 0.18m; $t(9)=0.52$; d=0.12) and SF (NBr: 55.2 ± 4.1 cycles·min^{-1}; Br: 54.6 ± 4.5 cycles·min^{-1}; $t(9)=0.63$; d=0.14).

Shoulder and Hip Roll

Figure 1 illustrates the finding that average shoulder roll angle was 4 degs (11%) greater within the entry phase of the NBr trial compared to Br trial (p=0.03; d=1.04). The magnitude of maximum shoulder roll was found to be 12% (7.6degs) greater during the recovery phase of the Br vs. NBr trial (p=0.02; d=0.97) (Table 1). Shoulder and hip roll magnitudes at all other instances did not differ between breathing conditions (Table 1).

Shoulder Angle

Within the entry phase, it was found that the shoulder was flexed 6degs (8%) more during the NBr vs. Br trial (p=0.01; d=1.14) (Table 1). Figure 2 illustrates that the shoulder abducts further within both the entry (7degs; 33%) and pull (7degs; 11%) phases during the NBr compared to the Br trial (Table 1). There were no other significant differences between breathing conditions in relation to shoulder flexion/extension and abduction/adduction (Table 1).

Hand Path

Maximum depth (Y) of the ipsilateral hand was found to be significantly greater by 0.04m (6%) during NBr vs. Br trial. Figure 3 illustrates the ipsilateral hand travelled deeper during the NBr vs. Br trial mostly during the pull phase (0.07m, 11%). Neither the X or Z average hand displacements throughout the SC differed significantly between breathing conditions (Table 1).

Stroke Phase Durations

The durations of the entry and recovery phases were not significantly different between Br and NBr (Figure 4). The difference in duration of the pull and push phases between the two breathing conditions was significant with a large effect size (*t*(9)=2.85; p=0.02; d>0.80). Figure 4 illustrates that during the breathing trial, swimmers spent 14% longer in the pull phase and 16% less time in the push phase compared to when they did not breathe.

Elbow angle

The elbow extension angle at the 'end back' position was 11.4° (8%) greater during the NBr than Br trial (p=0.02; d=0.76) (Table 1). It was also found that the elbow ROM within the push phase had a 17.3° (38%) greater extension during the NBr trial compared to the Br trial (p=0.02; d=0.99). The magnitudes of elbow angle at all other specified instants throughout the SC were not significantly different between breathing conditions (Table 1).

Hand Speed & Acceleration

Table 1 indicates that X hand velocity during the push phase was 0.5m·s^{-1} (25%) faster during the Br vs. NBr trial (p=0.01; d=1.51). Y acceleration of the hand was found as 4.8m·s^{-2} (30%) faster within the pull phase when NBr compared to Br (p=0.04; d=1.21). In contrast, within the push phase, the Y hand acceleration was approx 7.8m·s^{-2} (33%) faster during the breathing trial (p=0.03; d=0.96). Differences between breathing conditions in relation to the X hand acceleration during the pull and push phases approached significance (p=0.06) with large effect sizes (d>0.80).

COM Horizontal Velocity

During both the entry and pull phases, swimmers' COM X velocity was 0.6m·s^{-1} (3.3-3.4%) faster during the NBr vs. Br trial (p<0.02; d≥0.70; Table 1). There was no difference between conditions in relation to the COM X velocity within the push or recovery phases.

Discussion

When incorporating a breath into the SC, swimmers were overall slower. For the entry phase, swimmers had a slower COM horizontal velocity, less shoulder flexion, abduction and roll during the breathing trial. The pull phase was longer in duration, swimmers had a shallower hand path, less shoulder abduction, a slower hand vertical acceleration and slower COM horizontal velocity when breathing. The push phase was shorter in duration, swimmers had a smaller range of elbow extension, faster hand horizontal velocity and greater hand vertical acceleration when breathing. Finally, in the recovery phase, swimmers displayed greater maximum shoulder roll in the breathing trial.

The finding that incorporating a breath into the front crawl SC resulted in a 0.05m·s^{-1} decrement in swim velocity compared to not taking a breath is in agreement with Pedersen and Kjendlie, 2006but in contrast to Vezos et al. (2007), who reported no difference in swim velocity between breathing conditions within a female sprint population. The discrepancy between studies is perhaps due to findings that elite male swimmers experience significantly higher net drag forces than their female counterparts (26% vs. 16%) during breathing compared to non-breathing trials at a maximal pace (Formosa et al., 2014). The authors suggested that female participants demonstrated similar swimming technique regardless of the breathing condition compared to male swimmers (which contributed to the increased drag force), recommending further investigation in relation to kinematic changes between breathing conditions which will be explored within this discussion. While the changes in both SL and SF did not reach statistical significance, their combined effect meant that swim velocity between conditions was significantly different. Moreover, since SL did not differ between breathing conditions, it is estimated that the breathing action in front crawl sprinting results in a loss of 0.02s per SC. Interestingly, Pedersen and Kjendlie (2006) reported a loss of 0.03s within the SC when breathing. These studies affirm that incorporating a breath into the front crawl SC costs time. Therefore with such fine margins defining success, it is recommended that 50m/100m sprinters limit the number of breaths taken.

Entry Phase

Weldon & Richardson (2001) suggested that shoulder abduction and increased body roll enhances shoulder joint stability and net humeral joint reactive force. Consequently, the finding that swimmers rolled (4%) and abducted (33%) the ipsilateral shoulder more within the entry phase of the non-breathing trial, suggests that the shoulder is in a more stable and perhaps stronger position whilst breath-holding. Increased shoulder roll and abduction have also been linked to greater muscle activation from the supraspinatus and anterior/middle deltoids (Pink et al., 1991). As the ipsilateral shoulder within the NBr trial abducts further from the swimmer's COM, it creates a longer moment arm; combined with a greater muscle recruitment may provide an increased potential to produce greater torque and thus propulsion. It is recommended that kinetic and EMG analyses are combined in future studies to confirm the above assumption. As shoulder strength and swim speed are directly related (Weldon & Richardson, 2001), it is therefore possible that the actions of the shoulder between breathing conditions may have contributed to the finding that the COM X velocity was 3.3% faster during the entry phase of the NBr trial compared to the Br trial. To test this assumption, the researchers conducted a post-hoc analysis investigating the changes in COM X velocity within the entry phase. It was found that COM X velocity increased during the entry phase, but equally for both the breathing ($0.09 \pm 0.16 \text{m·s}^{-1}$) and non-breathing cycles ($0.09 \pm 0.26 \text{m·s}^{-1}$), with the difference between breathing conditions not significant ($p=0.99$). Therefore, it is unlikely that differences of shoulder kinematics within this phase during the non-breathing SC were beneficial in terms generating propulsion.

Pull Phase

The finding that the COM X velocity was greater during the pull phase of the NBr trial compared to the Br trial was further explored to minimise any possible 'knock-on' effect from the preceding entry phase, since COM X velocity was higher at the beginning of the pull phase within the NBr vs. Br trial. It was found that COM X velocity decreased during the pull phase within both breathing ($-0.16 \pm 0.16 \text{m·s}^{-1}$) and non-breathing cycles ($-0.10 \pm 0.10 \text{m·s}^{-1}$), with the difference between breathing conditions not significant ($p=0.49$). Therefore, it is unlikely that the kinematic differences (described below) during the non-breathing SC were more beneficial in terms of generating higher propulsion.

Within the pull phase, the ipsilateral shoulder was further abducted from the COM (11%) and the hand trajectory was deeper (11%) when not breathing, yet the duration of this phase was shorter by 14% compared to the breathing trial. Lerda and Cardelli (2003) reported that stroke phase durations are associated with the accelerative actions of the upper limbs, which was confirmed in this study by the ipsilateral hand accelerating faster in the vertical direction (30%) and horizontal direction (35%) within this phase when not incorporating a breath into the SC. It seems that the actions of the ipsilateral hand travelling deeper, yet accelerating faster can account for the shorter duration of the pull phase within the NBr vs. Br trial. It is assumed that any reduction in its duration would not be beneficial in terms of production of impulse. Therefore it is questionable whether this action contributed to the faster non-breathing vs. breathing trial.

Push Phase

This study reported that all swimmers reduced elbow extension by 8% at the end back position and the elbow extension ROM during the push phase by 38% when Br compared to the NBr trial. Deschodt et al. (1996b) reported that a greater elbow displacement throughout the underwater SC was strongly linked to swim performance, thus it is suggested that the greater elbow extension within the push phase during the NBr trial may have contributed to this trial being faster than the Br trial. The reduced elbow extension range during the push phase may have also contributed to the 16% shorter duration when Br vs. NBr. As discussed previously, findings that the ipsilateral hand vertically accelerated 33% faster and 25% faster horizontal hand velocity within the push phase of the Br vs. NBr trial is also a contributing factor to the reduced phase duration. Whereas these factors may all account/contribute towards a shorter push phase duration within the breathing trial, they do not appear to influence the propulsive output as observed via the post hoc analysis that the change in COM X velocity within the push phase between breathing conditions (NBr: 0.10±0.06$m\cdot s^{-1}$; Br: 0.14±0.10$m\cdot s^{-1}$; p=0.57) was not significantly different.

Recovery Phase

Finally within the recovery phase the finding that maximum shoulder roll was 12% (7.6degs) greater during the Br vs NBr trial is unsurprising and most likely as a consequence to facilitate the breathing action. Payton et al. (1999) reported a similar increase in body roll (9degs) during breathing trials when male swimmers swam at a 200m pace. Since the difference in COM X velocity during the recovery phase did not differ between conditions (NBr:-0.02±0.12m·s^{-1} vs. Br: -0.20±0.35 m·s^{-1}; $p=0.21$) it is suggested that the greater turning motion of the shoulders did not cause considerable resistance to affect swim performance.

Conclusion

Taking a breath in sprint front crawl swimming resulted in a decrement in performance compared to not taking a breath. Overall, as swimmers prepare to incorporate a breath into the stroke cycle, the ipsilateral shoulder remains closer to the COM during both the entry and pull phases thus potentially reducing the magnitude of torque applied compared to the faster non-breathing trial. Swimmers should ‘stretch’ and roll the shoulders more within the entry phase of a breathing trial as this should bring the arm into a position to apply more force. Most kinematic differences between breathing conditions occurred within the push phase. Swimmers are advised to focus on lengthening the push phase by extending the elbow more and not accelerating the hand too quickly upwards when preparing to inhale. Not all the kinematic changes found between breathing conditions could account for the differences in swim performance, therefore it is suggested that the combined effect of other contributing factors such as the activities of the opposite upper limb and/or leg kick should be considered to assess the overall impact and constraint of breathing.

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Conflict of Interest Statement

None

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Table 1. Data and statistical comparisons of the differences between non-breathing (NBr) and breathing (Br) conditions for the following variables: upper limb displacement, elbow angle magnitudes, hand speed, and hand acceleration on the ipsilateral (breathing) side and COM velocity.

Variables	*NBr*	*Br*	*t- Value*	*P-Value*	*Effect Size*
Maximum Hand Y Depth (m)	-0.67 ± 0.06	-0.63 ± 0.06	2.41	0.04*	0.78†
Av. Hand Y Depth (m)	-0.40 ± 0.06	-0.36 ± 0.05	2.87	0.02*	0.89†
Av. Hand Y Depth- Entry (m)	-0.21 ± 0.06	-0.17 ± 0.07	1.85	0.10	0.61
Av. Hand Y Depth- Pull (m)	-0.62 ± 0.06	-0.55 ± 0.08	2.55	0.03*	0.99†
Av. Hand Y Depth- Push (m)	-0.37 ± 0.07	-0.34 ± 0.11	0.78	0.45	0.33
Av. Hand Z Width- Entry (m)	0.23 ± 0.06	0.20 ± 0.07	1.33	0.22	0.46
Av. Hand Z Width- Pull (m)	0.36 ± 0.13	0.36 ± 0.13	0.10	0.93	0.00
Av. Hand Z Width- Push (m)	0.15 ± 0.06	0.17 ± 0.07	0.58	0.58	0.31
Av. Hand X– Entry (m)	-0.51 ± 0.17	-0.53 ± 0.24	0.42	0.68i	0.10
Av. Hand X – Pull (m)	0.25 ± 0.05	0.28 ± 0.11	0.73	0.49	0.35
Av. Hand X – Push (m)	0.29 ± 0.05	0.25 ± 0.08	1.25	0.24	0.60
Av. Total Hand X Pull Length (m)	0.55 ± 0.06	0.53 ± 0.08	0.64	0.54	0.28
Elbow Angle: 1st Back (degs)	147.6 ± 8.4	151.7 ± 11.4	0.99	0.35	0.41
Elbow Angle: Shoulder X (degs)	105.4 ± 7.3	111.2 ± 8.3	1.60	0.14	0.74
Elbow Angle: End Back (degs)	151.2 ± 11.7	139.8 ± 17.7	2.96	0.02*	0.76†
Elbow Angle: Range of Pull (degs)	42.2 ± 9.8	40.5 ± 13.8	0.27	0.79	0.14
Elbow Angle: Range of Push (degs)	45.8 ± 15.4	28.5 ± 19.2	2.88	0.02*	0.99†
Av. Shoulder flex/ext – Entry (degs)	-65.79 ± 4.62	-71.76 ± 5.22	4.46	0.01*	1.14†
Av. Shoulder flex/ext – Pull (degs)	-2.90 ± 10.00	-2.91 ± 13.64	0.01	0.99	0.01
Av. Shoulder flex/ext – Push (degs)	65.22 ± 3.70	63.25 ± 9.82	0.59	0.57	0.27
Max Shoulder Flexion (degs)	-80.37 ± 7.20	-82.06 ± 4.41	1.08	0.31	0.28
Max Shoulder Extension (degs)	78.23 ± 2.47	78.23 ± 7.28	0.01	0.99	0.01
Av. Shoulder Abd –Entry (degs)	21.14 ± 6.46	14.14 ± 6.07	3.89	0.01*	1.12†

Av. Shoulder Abd - Pull (degs)	59.72 ± 5.94	52.90 ± 5.41	3.30	0.01*	1.20†
Av. Shoulder Abd – Push (degs)	14.03 ± 3.54	16.75 ± 9.57	0.91	0.39	0.38
Hand X Speed – Entry (m·s^{-1})	1.47 ± 0.26	1.50 ± 0.36	0.31	0.76	0.10
Hand X Speed – Pull (m·s^{-1})	1.27 ± 0.17	1.34 ± 0.30	0.80	0.44	0.29
Hand X Speed – Push (m·s^{-1})	1.54 ± 0.26	2.04 ± 0.39	3.50	0.01*	1.51†
Hand Y Speed – Entry (m·s^{-1})	1.48 ± 0.41	1.35 ± 0.42	1.69	0.12	0.31
Hand Y Speed – Pull (m·s^{-1})	1.22 ± 0.14	1.17 ± 0.21	0.46	0.65	0.28
Hand Y Speed – Push (m·s^{-1})	2.56 ± 0.38	2.89 ± 0.91	1.15	0.28	0.47
Res. Hand Speed – Entry (m·s^{-1})	2.33 ± 0.14	2.34 ± 0.17	0.23	0.82	0.06
Res. Hand Speed – Pull (m·s^{-1})	2.52 ± 1.03	2.19 ± 0.18	1.01	0.34	0.45
Res. Hand Speed – Push (m·s^{-1})	3.57 ± 0.80	3.32 ± 0.46	0.88	0.40	0.38
Res. Hand Speed – Recovery (m·s^{-1})	6.25 ± 1.34	6.76 ± 0.60	1.25	0.24	0.49
Hand X accel. – Entry (m·s^{-2})	-7.62 ± 1.95	-7.25 ± 2.22	0.37	0.72	0.18
Hand X accel. - Pull (m·s^{-2})	-4.73 ± 2.60	-7.29 ± 3.5	2.12	0.06	0.83†
Hand X accel. - Push (m·s^{-2})	13.87 ± 5.59	20.09 ± 8.67	2.11	0.06	0.85†
Hand X accel. - Recovery (m·s^{-2})	-7.95 ± 9.27	-6.64 ± 12.35	0.44	0.67	0.12
Hand Y accel. - Entry (m·s^{-2})	-3.54 ± 1.87	-3.61 ± 2.64	0.13	0.89	0.03
Hand Y accel. - Pull (m·s^{-2})	16.37 ± 4.54	11.54 ± 4.06	2.40	0.04*	1.12†
Hand Y accel. - Push (m·s^{-2})	15.86 ± 5.56	23.66 ±10.11	2.52	0.03*	0.96†
Hand Y accel.- Recovery (m·s^{-2})	-14.43 ± 4.15	14.38 ± 6.18	0.03	0.97	0.01
COM X velocity – Entry (m·s^{-1})	1.84 ± 0.09	1.78 ± 0.08	2.94	0.02*	0.70
COM X Velocity – Pull (m·s^{-1})	1.79 ± 0.08	1.73 ± 0.08	3.21	0.01*	0.75†
COM X Velocity – Push (m·s^{-1})	1.82 ± 0.10	1.85 ± 0.11	0.68	0.51	0.27
COM X Velocity – Recovery (m·s^{-1})	1.81 ± 0.08	1.76 ± 0.09	2.19	0.06	0.59
Av. Shoulder roll – Entry (degs)	36.67 ± 3.74	32.81 ± 3.69	2.68	0.03*	1.04†
Av. Shoulder roll – Pull (degs)	35.81 ± 8.73	35.62 ± 5.52	0.09	0.93	0.03
Av. Shoulder roll – Push (degs)	32.38 ± 6.93	35.67 ± 9.13	0.80	0.44	0.41

Av. Shoulder roll – Recovery (degs)	41.19 ± 4.70	45.95 ± 9.97	1.85	0.10	0.61
Max Shoulder roll – Entry (degs)	52.02 ± 7.15	52.07 ± 7.91	0.03	0.98	0.01
Max Shoulder roll – Pull (degs)	50.87 ± 6.48	48.92 ± 6.85	0.69	0.51	0.29
Max Shoulder roll – Push (degs)	50.19 ± 7.39	53.96 ± 8.87	0.90	0.39	0.46
Max Shoulder roll – Recovery (degs)	54.49 ± 5.10	62.06 ± 9.73	2.92	0.02*	0.97†
Av. Hip Roll – Entry (degs)	12.77 ± 4.57	12.70 ± 5.46	0.03	0.98	0.01
Av. Hip Roll – Pull (degs)	8.15 ± 3.85	10.83 ± 3.47	2.14	0.06	0.73
Av. Hip Roll – Push (degs)	11.20 ± 4.75	14.46 ± 6.97	1.46	0.18	0.55
Av. Hip Roll – Recovery (degs)	14.34 ± 3.32	18.39 ± 9.33	1.90	0.09	0.58
Max Hip Roll – Entry (degs)	20.49 ± 6.67	20.49 ± 5.09	0.01	0.99	0.01
Max Hip Roll – Pull (degs)	17.71 ± 7.51	19.40 ± 6.31	0.84	0.42	0.24
Max Hip Roll – Push (degs)	17.84 ± 5.05	21.18 ± 7.58	1.94	0.08	0.52
Max Hip Roll – Recovery (degs)	22.73 ± 3.99	28.74± 11.90	1.68	0.13	0.68

Data are expressed as mean (± SD), p value and effect size. * indicates a significant difference between conditions, † indicates a large effect size. X – Horizontal; Y – Vertical; Z – Mediolateral; Av. – Average; accel. – acceleration; Res. – resultant; Max – maximum.

Figure Legends

Figure 1: Average shoulder roll throughout the stroke cycle for both breathing conditions. As the hand entry was not always the same for each swimmer, the absolute shoulder roll angles are plotted. Peaks represent maximum shoulder rotation and troughs that the swimmer is neutral in the water (i.e. no shoulder rotation). Breathing (Br) trial: A - beginning of finger moving horizontally backward; B - finger vertically aligned with the shoulder; C - end of finger backwards movement; D – finger water. A→B = pull phase; B→C = push phase; C→D = recovery phase. Non-breathing (NBr) trial was defined similarly as Br with an added annotation (e.g. A') to distinguish between conditions.

Figure 2: Average ipsilateral shoulder abduction throughout the stroke cycle for both conditions. Increased magnitudes represent the shoulder abducting further away from the swimmer, whereas decreased magnitudes represent the shoulder moving towards the swimmer. Breathing (Br) trial: A - beginning of finger moving horizontally backward; B - finger vertically aligned with the shoulder; C - end of finger backwards movement; D – finger water. A→B = pull phase; B→C = push phase; C→D = recovery phase. Non-breathing (NBr) trial was defined similarly as Br with an added annotation (e.g. A') to distinguish between conditions.

Figure 3: Ipsilateral hand vertical displacement throughout the stroke cycle for both breathing conditions. Breathing (Br) trial: A - beginning of finger moving horizontally backward; B - finger vertically aligned with the shoulder; C - end of finger backwards movement; D – finger water. A→B = pull phase; B→C = push phase; C→D = recovery phase. Non-breathing (NBr) trial was defined similarly as Br with an added annotation (e.g. A') to distinguish between conditions.

Figure 4: Stroke phase durations for non-breathing (NBr) and breathing (Br) trials. Mean stroke phase duration data are indicated. Bars represent standard deviation. * Significant at $p<0.05$.

Figure 1

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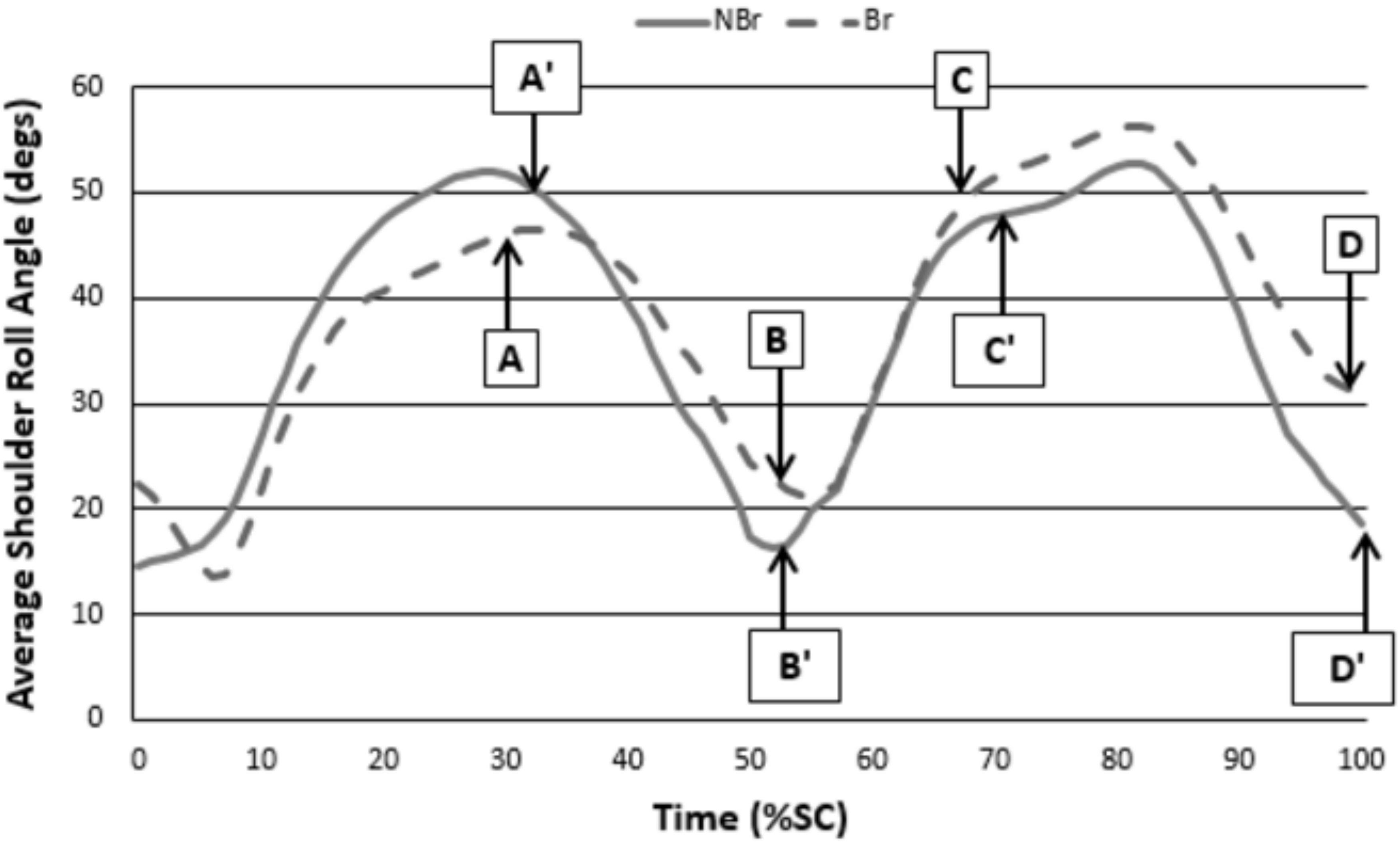

Figure 2

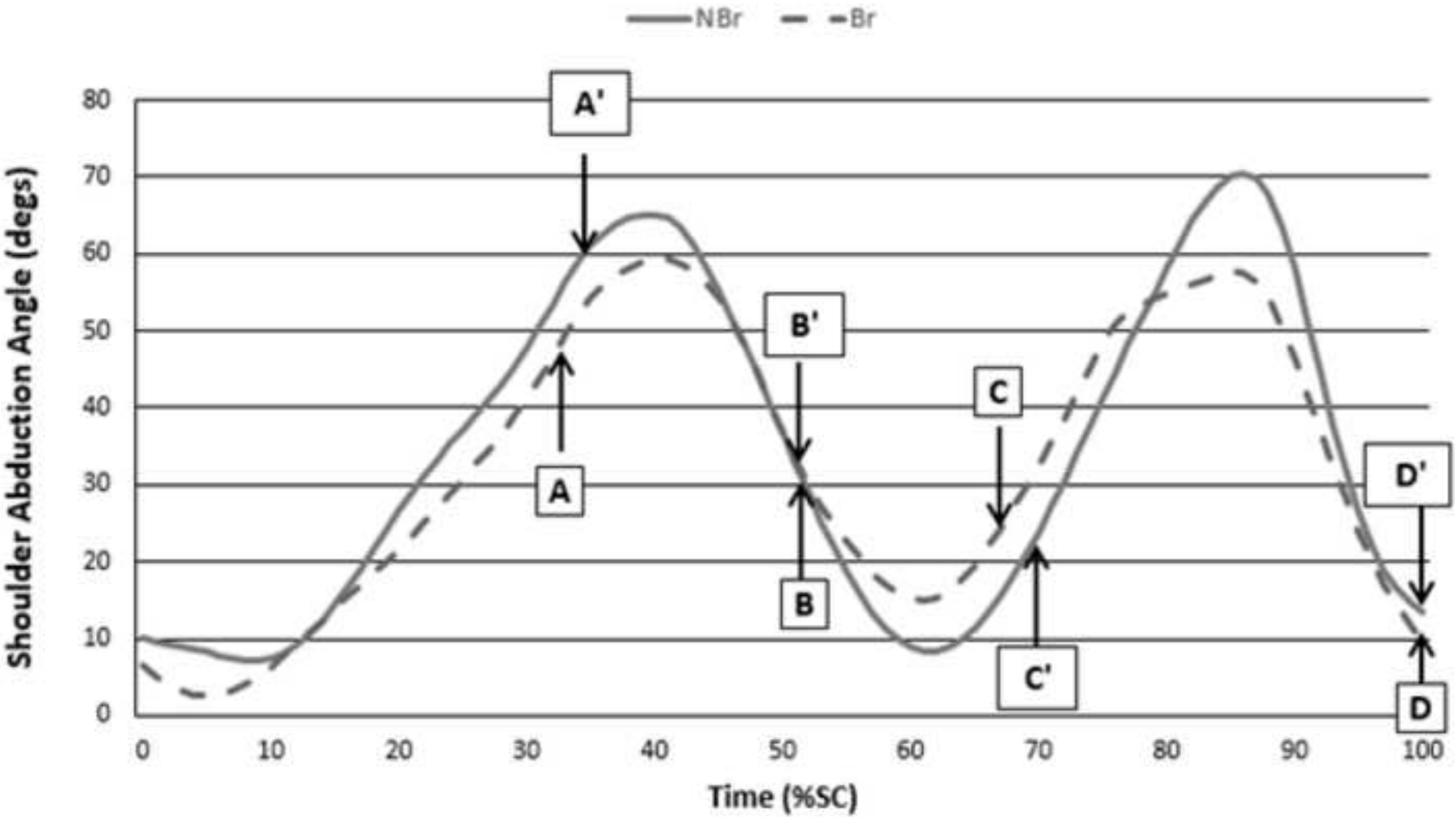
NBr
Br
Shoulder Abduction Angle (degs)
80
70
60
50
40
30
20
10
0
A'
A
B'
B
C
C'
D'
D
0
10
20
30
40
50
60
70
80
90
100
Time (%SC)

Figure 3

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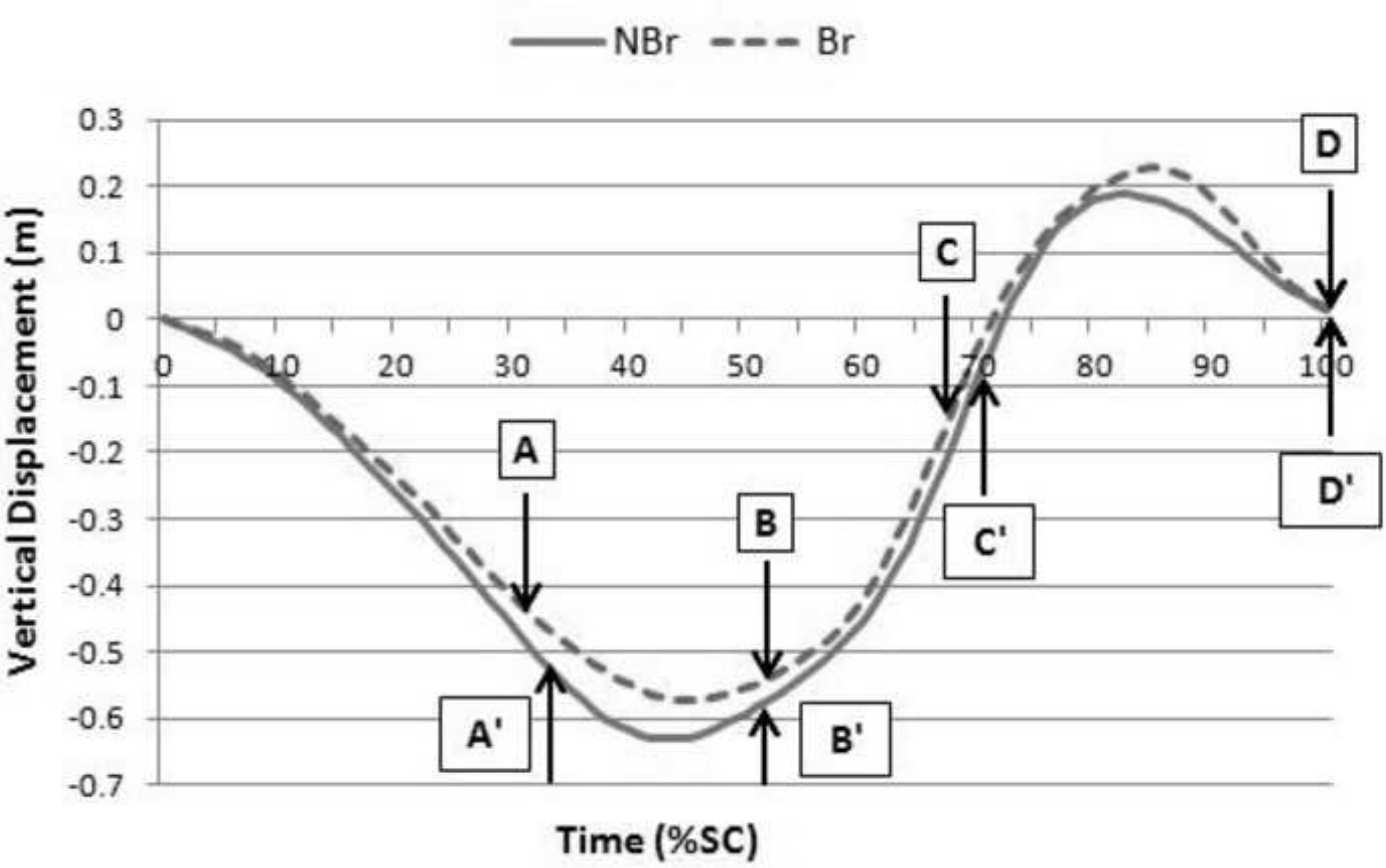

Figure 4

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