J. Swimming Research, Vol. 21:1 (2013)

Coaching Applications

How Do Asymmetries Affect Swimming Performance?

Ross H. Sanders

Centre for Aquatics Research and Education, ISPEHS, The University of Edinburgh; Exercise and Sport Science, Faculty of Health Sciences, The University of Sydney

Abstract

This paper, the third in a series of four papers reviewing asymmetry in swimming, addressed the question 'how do asymmetries affect performance?'. The paper is in three sections: the effect of asymmetries in body shape and posture on resistance; the effect of strength and flexibility on propulsion, and specific effects of asymmetries during the propulsive actions, breathing, recovery and entry.

Introduction

Four general questions need to be addressed with regard to asymmetries in swimming.

1. What are the likely causes of the asymmetries?
2. How can asymmetries be identified and measured?
3. How do asymmetries affect performance?
4. What interventions can be administered to correct asymmetries in swimming?

Sanders, Thow and Fairweather (2011) and Sanders et al (2012) reviewed literature relating to the first and second question respectively. In this paper the issue of how the observed asymmetries affect performance is reviewed and discussed.

While there are many possible ways in which swimming performance could be affected by asymmetries, very little research relates directly to this topic. Thus, in this paper some ideas are put forward based on our understanding of swimming mechanics. In doing so it must be recognized that asymmetry is not necessarily associated with a decrease in performance. For example, an early study of breaststroke swimmers (Czabanski and Koszcyc, 1979) revealed that technique asymmetry is very common and does not necessarily reduce performance.

When considering what variables might affect performance, reference to a model (Figure 1) is useful. Asymmetries can affect both resistance and propulsion which, together with physiological capacity of the swimmer, are the key determinants of performance. Asymmetries affect resistance primarily through their effect on shape and posture. Asymmetries affecting propulsion include uneven contributions by right and left upper and lower limbs due to strength and flexibility imbalances.

Shape, posture, strength, and flexibility must be considered for each of the strokes and the contributions to the stroke including propulsive actions including the arm pull and leg kick, breathing, and recovery and entry.

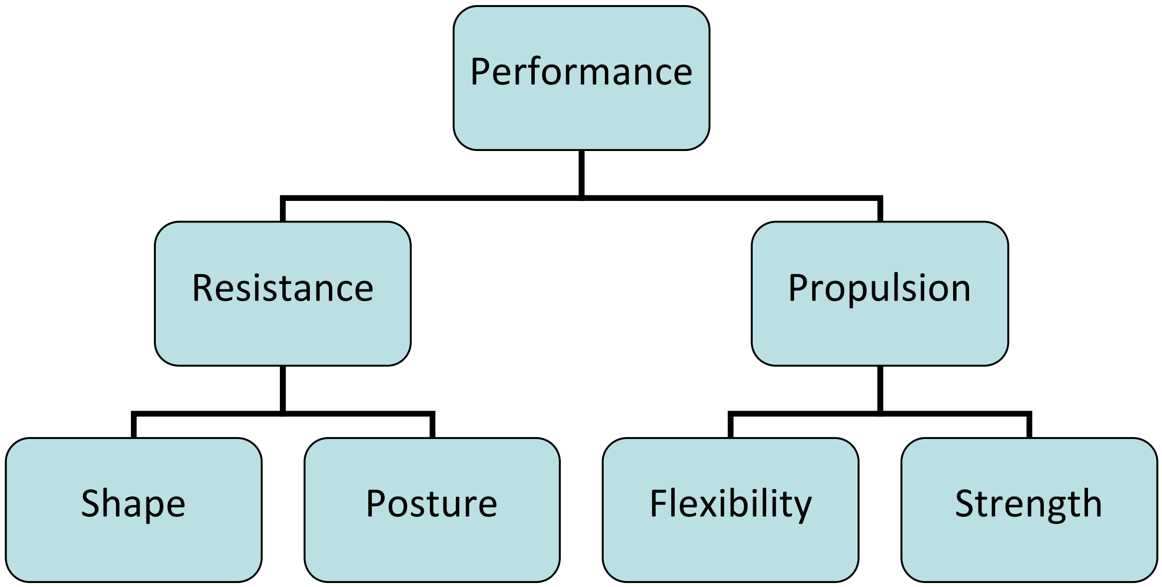

Figure 1: Model of main factors affecting performance in swimming.

Asymmetries Affecting Resistance

Shape

Most sources of information relating to the effect of the shape of objects moving through fluid media are limited to objects of regular, symmetrical, and unchanging shape. In contrast the human body is not regular, and constantly changes shape during swimming. Even individuals who are predominantly symmetrical when in a static standing posture have asymmetrical shapes when swimming, except perhaps during a passive glide after entry in starts, following the push form the wall in turns, or following the kick in breaststroke.

While the advantages and disadvantages of particular body shapes, and how these are influenced by the competitive stroke and race distance, are recognized (Carter and Ackland, 1994; Kjendlie and Stallman, 2011), the effect of asymmetries is less well understood. It demands a consideration of the contributions to resistance to motion of a body in a fluid. Three main contributions are recognized. These are the contribution of wave drag associated with raising and lowering the body, the contribution of pressure drag (also called 'form drag') due to the differences in pressure between the leading and trailing surfaces of the body, and surface drag (also called 'skin friction') due to the friction between the fluid molecules and the surface of the object (Toussaint, 2011; Ungerechts and Arellano, 2011).

When considering the effect of shape on swimming performance most emphasis has been placed on the effect of pressure drag recognizing that it is much greater than surface drag for irregular bodies such as human swimmers moving at competition speeds. The non streamlined shapes of human swimmers, in contrast to those of marine animals and marine vessels, cause the flow to 'separate' from the surface of the body and become turbulent along almost its entire length. Turbulent flow is lower pressure than the pressure of water pushing against the leading surfaces of the swimmer and therefore creates drag. Pressure drag is minimized with symmetrical 'teardrop' shapes, i.e., shapes in which the leading edge is narrow and rounded reaching a maximum width at approximately one third of the object's length and then tapering to a point. This shape is abundant in marine animals and vessels made by man to minimize resistance.

Consequently, swimmers possessing shapes that minimize the disruption to the flow and the level of turbulence and that taper along the length of the body have a natural advantage. Typically, successful swimmers have tapered bodies with broad chests and shoulders and slender hips. Disruptions to the smoothly contoured and tapered lines of flow increase turbulence of volumes of water. Because turbulent water applies lower pressure to the body than water flowing in gently contoured lines (laminar flow) the body is pushed towards the low pressure areas by the higher pressure water. For example, a volume of turbulent water behind the buttocks forms due to the water having to change its course as it flows over them. The pressure is greater in front than behind the body creating a net force opposing forward motion.

There has been considerable speculation with regard to the explanation of the improved performance when wearing specially designed and custom fitted swimsuits such as the Speedo LZR. A recent comparison of the LZR and normal swimsuits for both males and females (Machtsiras, 2012) has provided evidence that the elasticized support of the customized suits reduces drag when gliding well below the water surface by improving the shape of the swimmer so that the contours change more gradually thereby reducing the turbulence.

However, while the shape characteristics have an important and somewhat predictable effect on pressure drag, the situation is complicated by the effect of wave drag. The swimmer spends most time during a race swimming at the surface in the interface between air and water. In this situation wave drag is the dominant resistive force at competitive paces (Pease, 2012). Pease found that the male shape, being more smoothly tapered and slender in the hips, had less drag than the more 'hour glass' female shape at depths in which wave drag has a relatively small influence. However, near the surface the indented waist of the female was advantageous due to its beneficial influence on the magnitude of wave drag. The mechanism for this phenomenon is unclear at this time but application of the rapidly evolving science of Computational Fluid Dynamics (CFD) promises a scientific explanation in the near future.

Shape asymmetries occur continuously in mid-pool swimming in front and back crawl due to the alternating nature of the stroke. Compounding those effects for all strokes are the effects of morphological, strength, and flexibility differences between right and left sides and muscle imbalances both between sides and between the front and back of the swimmer's body.

For any given shape, the resistive drag is determined by the cross sectional area, density of the fluid, and the speed of the swimmer. The resistance is particularly sensitive to speed for both pressure drag, being related to approximately the square of the speed (Vorontsov and Rumyantsev, 2000), and wave drag which increases exponentially as 'hull speed', which occurs when the bow wave length is equal to the length of the swimmer, is approached (Kolmogorov and Duplishcheva, 1992). Given that the swimmer seeks to go as fast as possible the only variable over which there is some level of control is the cross sectional area. This applies to the body as a whole as well as the limbs.

Within the constraints of anthropometric endowment, control of body shape is closely linked to the postures adopted and in the quest to minimize resistance, posture becomes a critical consideration.

Posture

As stressed above, the shape changes continuously during the stroke cycle of all strokes due to the arm actions including the pull and recovery, the leg actions, the actions associated with breathing, and with deliberate undulations of the whole body, particularly in butterfly and breaststroke. The swimmer's overall aim is to maintain a shape that minimizes resistance while still positioning the body and its limbs to generate propulsion in an energetically efficient manner. This requires 'tradeoffs' to optimize the combination of resistance and propulsion to maximize speed at a sustainable energetic cost. For example, positioning the feet to push on the water to generate propulsion in breaststroke demands that there is some flexion of the hips and knees and ankles prior to the backward push. The postures adopted during this process cause additional resistive drag but are necessary to position the feet for a powerful propulsive kick.

The angle of the body when viewed from the side has always been keenly observed for all strokes with general recognition of the 'sinking legs' problem creating an inclined body that increases resistance and reduces swimming speed (Strzala and Krezalek, 2010). The problem is related to the gravity force being further to the rear than the buoyancy force due to the legs being denser than the chest area. Generally, males have a stronger tendency to rotate the body than females due to less adipose tissue in the lower limbs, and larger lung volumes. The leg kick helps to overcome the 'sinking legs' problem but at some additional effort.

Asymmetries Affecting Propulsion

It is very common among elite swimmers for propulsion to differ between right and left sides in terms of magnitude, duration, and pattern (Havriluk, 2003, 2007; Barbosa and Junior, 2011; Formosa et al., 2011). Two of the main causes are related to strength differences and flexibility.

Strength

Differences in strength between right and left sides can reduce performance in several ways. The first is the effect on rotational balance. If the pull is stronger on one side than the other the body tends to rotate causing misalignment and therefore increased resistance. In front crawl there are alternating rotational effects regardless of whether there are asymmetries in strength because the arms are operating alternately rather than simultaneously. This explains why development of a technique in which the propelling limbs are close to the midline of the body (the line from head to feet) is important.

In front crawl this can be achieved readily. However, in backstroke the anatomical limitations mean that the hand path is away from the midline and the rotational effects are large. Therefore to avoid large misalignments that cause resistance the rotation can be countered by the kicking actions which in turn can lead to asymmetries in kicking that affect lower limb alignment and resistance.

In the 'symmetrical' strokes differences in the forces produced by the right and left lower limbs during the pull cause misalignment and increased resistance. In our analyses of asymmetries in technique among breaststroke swimmers and butterfly swimmers we have observed a 'yawing' rotation, that is, a rotation about a vertical axis that misaligns the body. To avoid this yawing effect, the difference in force can be compensated by differences in hand path. However, this then introduces technique asymmetries which become habit and may reinforce the strength differences so that one side must always produce more force than the other. Therefore, the swimmer becomes 'locked in' to having asymmetrical strength and asymmetrical technique to compensate for the strength asymmetries.

These interactive effects between strength asymmetries and performance are exemplified in a case study (Carson, 1999) of an 11 year old competitive swimmer whose breaststroke technique was so asymmetrical in its movement pattern that he was being repeatedly disqualified. Physical examination revealed strength asymmetries in shoulders and hips reflected in postural asymmetries and asymmetrical muscle tightness. Encouragingly, therapeutic interventions resulted in improved muscle balance, improved movement patterns, and race performance.

The second effect on performance related to strength differences between right and left sides is that the weaker side contributes less to propulsion than the stronger side. Therefore, other things being equal, and assuming that the swimmers are effective in balancing rotational effects to maintain good alignment, a swimmer who has even strength will swim faster than a swimmer who is weak on one side.

Further, to compensate for the weak side, the strong side has to work harder to maintain speed. This applies to both the alternating strokes and the symmetrical strokes. In the alternating strokes the body loses speed during the pull of the weak side and the strong side must then regain the lost speed as well as increase speed beyond the average speed to allow for the forthcoming loss during the pull of the weaker side. In the symmetrical strokes the combined force is less than the combined propulsive force when both sides can make an equal contribution.

Tourney-Chollet et al (2009) found that the duration of force application from catch to release in front crawl was greater for the stronger shoulder (51.7% of the stroke cycle) than the non-dominant shoulder (48.4%). In addition to showing that strength asymmetries affect the contribution to propulsion that study also highlighted that strength differences affect timing of phases and coordination. Similarly, Barden et al (2011) showed that timing asymmetries become apparent at high intensities and suggested that this was due to bilateral differences in strength.

The third influence of strength asymmetries on performance relates to fatigue. The strong side fatigues more quickly than it would otherwise because it is trying to compensate for the reduced force of the weaker side so that speed is maintained. The weaker side also fatigues more quickly than it would otherwise because it is trying to maintain a force equivalent to the strong side. In both cases the muscles are working closer to their peak capacity than if the load was being shared evenly.

In addition to the magnitudes of forces produced, fatigue affects the technique and the swimmer becomes unable to maintain good technique and streamlining (Aujouannet et al. (2006; Conceicao et al, 2010; Thow, 2010). For example, Thow (2010) found that in front crawl swimming there are significant differences in technique kick between fatigued and non-fatigued states including maximum shoulder roll, time of the pull phase, knee angle at the end of the leg downbeat and upbeat phases, angle of the elbow at the end of the arm upsweep phase, and the maximum depth of the foot during leg. If the fatigue levels are different between right and left sides it could be expected that technique asymmetries that further affect performance would emerge during the fatigue process. Suito et al (2008) showed that the relative contributions of internal rotation and adduction to the 100m front crawl are affected by fatigue. Potts et al. (2002) found that power output differed between sides in simulated front crawl swims on a swim bench, that the difference increased with fatigue, and that differences were less for bilateral than unilateral breathers.

Flexibility

Like strength, flexibility affects performance in several ways. Some are related to resistance and some to propulsion. With respect to resistance, flexibility affects the postures that can be adopted and the techniques developed to minimize resistance. In butterfly, a 'clean' hand exit without having to raise the body high out of the water depends strongly on shoulder flexibility. A high elbow recovery in front crawl that minimizes the misaligning rotational effects associated with arm recovery requires flexibility in addition to appropriate body roll.

Flexibility also affects the positions of limbs and joints sought to apply large forces and increase their duration of application. For example, shoulder flexibility in conjunction with body roll is vital in backstroke to enable a strong and early catch. Structure of the skeleton and its joints imposes limits to flexibility. However it is possible to modify various soft tissues that affect flexibility including ligaments, tendons and muscle fibers.

The role of ligaments is to stabilize the joint to maintain functionality and avoid injuries such as dislocations. However, ligaments that are too short and hold the joint together too strongly can limit the flexibility required for efficient swimming. Thus, regular stretching of the joint can enable the swimmer to adopt the positions desirable for applying strong forces throughout the stroke and to enable good streamlining.

However, swimmers may be constrained by the properties of the muscles rather than joint mobility. Inappropriate strength ratios of shoulder and hip flexors and extensors, and internal and external rotators, can cause postural changes that affect streamlining. For example, breaststroke swimmers may have strong hip flexors and relatively weak hip extensors. Therefore, they naturally have some flexion in the glide phase that causes resistance and attainment of a strong position for the kick might also be inhibited.

Another important factor is the natural resting length of the muscle. When a muscle is in a lengthened position, for example at entry in backstroke, the overlap of the contractile units, the actin and myosin filaments within each fiber, is very small and the force that be generated is correspondingly small (Hunter, 1994). This makes it difficult to apply propulsive forces at the beginning of the pull. By increasing the resting length of the muscle and tendon unit through flexibility work the actin-myosin overlap at the equivalent extended joint position increases. This enables the production of strong forces in this position. In practical terms, this means that the catch can be made earlier and more strongly in the backstroke pull, than when the resting length of the muscle is shorter. The same principle applies in all strokes where the muscles are expected to apply strong forces despite the joint being in extreme positions.

Specific Effects of Asymmetries during the Propulsive Actions, Breathing, Recovery and Entry

Propulsive Actions

The pull in front crawl is inevitably asymmetrical because the arms are pulling at different times. This means that the force created by one hand is not offset and balanced by the forces created by the other. Unless the line of action of the force is close to the midline of the body the body rotates and its alignment is disrupted. Any disruption to the optimal streamlined alignment of the body increases resistance. Skilled swimmers learn to maintain good alignment by fine-tuning the path of the lower limbs. Although the hand scribes a curved path to make use of both lift and drag forces, and to use the joint lever system effectively, the pull is characterized by commencing in line with the body, that is, the hand is entered and then commences its pull close to the 'midline' or longitudinal axis of the body and then continues on a path close to that axis. Swimmers also learn to offset the rotational effects by refining their kicking actions. Thus, in the process of becoming skilled, total body coordination emerges in a way that minimizes disruptions to alignment and thereby minimizes resistance.

Among swimmers, differences in technique represent different 'solutions' to the problem of balancing the interacting actions to maintain good alignment. There is no one 'correct' technique and each swimmer optimizes their technique taking into account their own morphology, joint structure, flexibility, muscle characteristics, and external influences such as coaching and role models that they have copied.

Morphological asymmetry adds another layer of complexity for swimmers attempting to develop a technique that balances the torques to maintain good alignment. An interesting example comes from the work of Osborough (2012). His study of single arm amputee swimmers revealed that the swimmers adopted one of three hand path patterns to maintain good alignment when swimming with an asymmetrical body structure.

Balancing rotational effects in backstroke is more difficult than in front crawl because the backstroke pull is necessarily well outside the midline due to the body's structural limitations. Backstroke swimmers require good flexibility to enter the hand in line with the midline to achieve a streamlined posture. The width of the pull with respect to the midline can be minimized by using considerable body roll and flexing the elbow. Even so, the alignment of the body tends to be disrupted more in backstroke than in front crawl manifest in lateral motions of the hips and bowing of the body. Oblique kicking of the feet as the body rolls is important to reduce these effects. The importance of the kick becomes evident among those with disabilities that affect the ability to kick. These backstroke swimmers have much more bowing as well as swaying of the legs from side to side in response to the rotational effects of the arm pull.

Among able bodied backstroke swimmers limitations in shoulder flexibility or asymmetries between the shoulders in strength or flexibility would add to the problem of maintaining good alignment throughout the stroke cycle. Strength and flexibility asymmetries are common and are reflected in the force profiles produced by the hands during the pull phases (Havriluk, 2003; 2007).

In butterfly and breaststroke yaw effects should be balanced throughout the stroke provided the pull and kick are symmetrical in both magnitude of force and the distance of the line of action of the force from the midline. Therefore, good alignment of the longitudinal axis of the body can be maintained throughout the stroke. However, our studies of elite swimmers have revealed that swimmers have considerable asymmetries in strength and flexibility that affect their alignment. For example, a yawing action of one of our breaststroke swimmers is linked to the upper limbs on the right side being stronger than the left in flexion and internal rotation. Consequently, the pull is performed more quickly by the right upper limbs than the left so that the propulsive force on that side is greater than on the left side. Thus, the unbalanced torques cause yaw rotation that affects alignment and increases resistance. The imbalance in strength of this swimmer is due to a combination of right hand natural dominance and a history of injuries to the left shoulder and left intercostal muscles.

Streamlining can also be affected by antero-posterior (front and back of the body) muscle imbalances. For example, one of the elite breaststroke swimmers does not fully extend the hips following the kick. This means that, rather than being in the slipstream of the trunk, the thighs add to the cross sectional area of the body and therefore increase the resistance experienced. Tests conducted by physiotherapists at the sportscotland Institute have indicated a lack of hip and lumbar extensor flexibility in this swimmer.

Breathing

In front crawl, the breathing action disrupts the alignment of the body to varying extents among swimmers. It is known that swimmers are faster when sprinting without breathing than when the breathing action is incorporated into the stroke (Castro and Guimares, 2000; Pedersen and Kjendlie, 2006). Logically, the difference in speed would be due to a combination of increased resistance associated with disruption of body shape and alignment and a reduction in propulsion due to reduced ability to use the optimal joint lever system and maintain timing. However, the relative contributions to the resistive and propulsive effects have not been quantified.

Breathing changes the temporal structure of front crawl so that the duration of the phases of the stroke are asymmetrical (Vezos et al, 2007; Seifert et al., 2008) and the three-dimensional paths of the limbs, and body roll, differ between sides (Vezos et al. 2007; Psycharakis and Sanders, 2008). Thus, disruptions to alignment are inevitable due to breathing.

Consequently swimmers seek to breathe in a manner that minimizes disruption to alignment and the characteristics of technique. However, while the breathing action itself can be disruptive to posture and alignment, the problem can be exacerbated by habituation, that is breathing more on one side than the other during practice and in competition. Studies have shown (Seifert et al., 2008)) that swimmers who have a definite preferred breathing side are more likely to have technique asymmetries than swimmers who are habitual bilateral breathers. For example, Psycharakis et al (2008) have shown that swimmers roll more to their preferred breathing side even when swimming without breathing. Also, among swimmers who don't breathe bilaterally routinely in practice, there is a tendency to align the head towards the breathing side even when not breathing. In addition to the head itself being out of alignment, the posture of the whole body, for example the spinal curvature, can be influenced by the head positioning.

In butterfly and breaststroke the head must be raised to breathe. This results in dynamically changing posture and body orientation to the flow when observed from the side. Seifert, Chollet and Sanders (2010) have shown that butterfly cycles incorporating breathing differ from non-breathing cycles in timing of the phases and the interactive coordination between arms and legs. While it is logical to assume that the postural and timing changes would increase resistance by disrupting the flow and increasing cross sectional area, other factors must be considered. For example, the relatively recent trend in breaststroke towards raising the head and shoulders so that the upper body is at a steep angle to the flow would seem to be counter to the idea of minimizing cross section area and having the axis of the body aligned with the flow. However, there is a 'tradeoff' of several other factors:

1. When the upper body is angled upwards during the 'undulating' style, the angle between the upper body and thighs during the recovery of the legs is less than when the upper body is level as in the 'flat' style of breaststroke. This may mean that the flow from the upper body along the thighs is less disrupted than in the flat style (Seifert et al., 2011).

2. The high upper body action means that part of the upper body and arms are out of the water for part of the stroke cycle and this may reduce resistance during that part of the cycle.

3. The subsequent lunge of the upper body into the water sets up an oscillation which may contribute to an energy saving body wave that transfers energy along the body to contribute to propulsive actions (Sanders, 1995; 2011). There is a possibility that the body wave itself might contribute to propulsion as in the body waves of marine animals, or, at least reduce resistance due to its positive effect on fluid flow.

In butterfly there is strong evidence (Sanders, 1995; 2011) that a body wave travelling caudally saves energy by reusing the energy associated with raising the upper body to contribute to the kick. The body waves travelling from hips to ankles are faster than the swimmer's forward velocity thereby contributing to propulsion in a fish-like manner. The implication for both breaststroke and butterfly is that good antero-posterior muscle balance and flexibility are required so that these actions can be performed optimally to derive the associated benefits.

Recovery and Entry

The recovery may influence resistance in several ways. First, to commence recovery the hands must stop pushing back relative to the water and commence moving forward. Thus, in front and back crawl and butterfly swimming there is a period of transition between the pull and recovery in which the upper limbs are in the water but have ceased to be propulsive and cause resistance until they are clear of the water.

In front and back crawl these resistive forces act outside the midline of the body thereby producing rotation that affects alignment. The distance of the recovery from the midline, and hence the rotation effect, is influenced by the body roll. Well timed body roll assists in a 'clean' exit to minimize resistance as well as to minimize the width of the recovery.

In butterfly, provided the recovery is symmetrical, the alignment should not be affected in the transition between the pull and recovery. However, asymmetries are evident among many swimmers and may be apparent in the time of release and exit of the hands from the water as well as differences in the resistance during the transition from pull to exit. The same applies to breaststroke. However, even among breaststroke swimmers with a high trunk action and 'overwater recovery' the period during which the upper limbs are creating resistance is considerable. Also, breaststroke swimmers may not be entirely symmetrical when recovering and entering the upper limbs. Therefore body alignment may be affected as well as the flow lines of the water around the upper limbs as they recover.

Second, there are reaction effects to the action of swinging the arms outwards during recovery. Disruption to alignment of the body is minimized among skilled front crawl swimmers by minimizing the 'width' of the recovery by having a 'high recovery'. Traditionally, swimmers have been taught to have a 'high elbow' with the hands below the elbow. The ability to keep the upper limbs close to the midline of the body is assisted by well-timed body roll. Thus, in addition to enabling a 'cleaner' exit body roll can reduce the yaw rotation of the body. Further, yaw rotation can be offset by an oblique kicking action to maintain alignment along the length of the body. The oblique kick is also assisted by body roll as the roll inclines the lower limbs so that the kick is performed in an oblique rather than vertical plane.

These strategies can reduce the effect of the recovery of the arms in front crawl. However, asymmetries in the arm recovery and body roll can set up 'wobbles' and misalignments that can disturb the flow and increase resistance. Such asymmetries may be related to the breathing action as discussed above. It is common even among elite swimmers to observe asymmetries in the width of the recovery, the amount of elbow flexion, the amount of body roll, and in the oblique orientation of the kick.

What about the effect of body roll itself? Wouldn't that disrupt the flow and increase resistance. Therefore, wouldn't it be better to stay as 'flat' as possible rather than roll the body through a large angle? There is a lack of direct evidence regarding the effect of body roll on the fluid flow. However, it is thought that body roll is beneficial in a direct way by reducing drag in addition to the advantages it offers in assisting exit, recovery, and entry both in terms of minimizing resistance and in placing the body in stronger positions to make the catch, and perform the pull.

In backstroke, the final downward motion of the hand following the pull helps to roll the body to assist the subsequent exit of the hand. The body roll produced also assists the entry and subsequent catch of the other hand. Following exit the recovery of skilled swimmers is then confined to the midline to minimize the 'wobbles' that increase resistance.

During entry, front crawl and back crawl swimmers seek to enter the hand close to the midline of the body. This improves the streamlining and minimizes the cross sectional area exposed to the flow. In both strokes this is facilitated by body roll towards the side of the entering limbs. Insufficient body roll tends to cause the body to bow as the swimmers push the upper limbs forward. Shoulder flexibility helps to minimize poor alignment at entry, particularly in back crawl where the position of the shoulder is more limited by the swimmer's joint structure. Asymmetries in shoulder flexibility can produce differences in body alignment and induce differences in shoulder roll as the swimmer attempts to maintain good alignment at entry. Also, flexibility issues can be both cause and effect of shoulder injuries.

Given that symmetry is expected in butterfly and breaststroke one would anticipate that resistive forces would be balanced during recovery. However, from our observations of elite swimmers, asymmetries are common. For example, many swimmers tend to lean to one side so that one side is lower than the other. This means there is different flow on one side than the other and differences in the surface area striking the water on each side. This may occur in breaststroke when swimmers have a high upper body action and an upper limb recovery that is partially above the water. Similarly, in butterfly, as the arms sweep inward during entry, one hand and forearm may strike the water before the other. With respect to the breaststroke kick, underwater footage of elite breaststroke swimmers has revealed that it is common for one side to be lower than the other due to the lean to one side and that both the kick and recovery vary in width with respect to the midline. These differences affect the fluid flow as well as the balance of rotational effects, thereby affecting alignment.

References

1. Aujouannet, Y.A., Bonifazi, M., Hintzy, F., Vuillerme, N., and Rouard, A.H. (2006). Effects of a high-intensity swim test on kinematic parameters in high-level athletes. *Applied Physiology Nutrition Metabolism*, **31**, 150-158.

2. Barbosa, A.C., and Junior, O.A. (2011). Effects of different hand paddle sizes on bilateral propulsive force difference in front crawl swimming. *Serbian Journal of Sport Sciences*, **5(3)**, 91-97.

3. Barden, J.M., Kell, R.T. and Dylan, K. (2011) The effect of critical speed and exercise intensity on stroke phase duration and bilateral asymmetry in 200-m front crawl swimming. *Journal of Sport Sciences*, **29(5)**, 517-526.

4. Carson, P.A. (1999). Case Report: The rehabilitation of a competitive swimmer with an asymmetrical movement pattern. *Manual Therapy*, **4(2)**, 110-106.

5. Carter, J.E.L., and Ackland, T.R. (1994). *Kinanthropometry in aquatic sports. A study of world class athletes*. Champaign, Il: Human Kinetics.

6. Castro, F., and Guimares, A.C. (2006). Front crawl kinematic: breathing and pace acute effects. *Portuguese Journal of Sport Sciences*, **6**, 26-28.

7. Czabanski, B., and Koszcyc, T. (1979). Relationship of stroke asymmetry and speed of breastroke swimming. *Swimming III* (pp.148-152).

8. Conceicao, A., Silva, A., Palma, S., Silva, H., Gamboa, H., and Louro, H. (2010). Electromyography in front crawl technique – case study. *The Open Sports Science Journal*, **3**, 67-69.

9. Formosa, D.P., Mason, B.R., and Burkett, B. (2011). The force-time profiles of elite front crawl swimmers. *Journal of Sports Sciences*, **29(8)**, 811-819.

10. Havriluk, R. (2003). Analysis of swimming performance using advanced technology. *Coaches Information Service.*
11. http://www.coachesinfo.com/index.php?option=com_content&view=article&id=10086:analysis-of-swimming-performance-using-advanced-technology&catid=41:swimming-assessment&Itemid=85.

12. Havriluk, R. (2007). Analysing hand force in swimming: bilateral symmetry. *American Swimming Magazine*, **1**, 34-38.

13. Hunter, G. (1994). Muscle Physiology. In T. R. Baechle (Ed.) *Essentials of Strength Training and Conditioning* (pp.3-11). Champaign, Il., Human Kinetics.

14. Kjendlie, P.L. and Stallman, R. (2011). Morphology and swimming performance. In L. Seifert, D. Chollet., and I. Mujika (Eds.) *World Book of Swimming: From Science to Performance* (pp. 203-222). New York: Nova Science Publishers.

15. Kolmogorov, S.V. and Duplishcheva, O.A. (1992). Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. *Journal of Biomechanics,* 25: 311-318.

16. Machtsiras, G. (2012). *Utilizing flow characteristics to increase performance in swimming*. Unpublished PhDThesis. The University of Edinburgh.

17. Osborough, C. (2102). Upper-arm kinematics of competitive unilate3ral arm amputees, during sprint and distance paced front crawl swimming. In G. Whyte et al. (Eds.) *Abstracts of the International Convention on Science, Education and Medicine in Sport* (FC93.4). Glasgow, U.K. www.ICSEMIS2012.com.

18. Pease, D. (2012) Wave drag in human swimming. In L. Bradshaw, A. Burnett, P. Hume (Eds.) *Proceedings of the 30th International Conference on Biomechanics in Sports*. Melbourne, July, 2012. https://ojs.ub.uni-konstanz.de/cpa/article/view/5167.

19. Pedersen, T., and Kjendlie, P.L. (2006). The effect of the breathing action on velocity in front crawl sprinting. *Portuguese Journal of Sport Science*, **6**, 75-77.

20. Potts, A.D., Charlton, J.E., and Smith, H.M. (2002). Bilateral arm power imbalance in swim bench exercise to exhaustion. Journal of Sport Sciences, **20**, 975-979.

21. Psycharakis, S., and Sanders, R.H. (2008). Shoulder and hip roll changes during 200-m front-crawl swimming. Medicine and Science in Sports and Exercise, **40(12)**, 2129-2136.

22. Psycharakis, S., and Sanders, R.H. (2010). Body roll in swimming: A review. Journal of Sport Sciences, **28(3),** 229-236.

23. Sanders, R.H., Cappaert, J.M., and Devlin, R.K. (1995). Wave characteristics of butterfly swimming. *Journal of Biomechanics*, 28(1), 9-16.

24. Sanders, R.H. (2011). Rhythms in butterfly swimming. In L. Seifert, D. Chollet., and I. Mujika (Eds.) *World Book of Swimming: From Science to Performance* (pp. 191-202). New York: Nova Science Publishers,
25. Sanders, R.H., Thow, J., Alcock, A., Fairweather, M. Riach, I, and Mather, F. (2012). How can asymmetries in swimming be measured? *Journal of Swimming Science,* **19**, Spring, 2012. http://www.swimmingcoach.org/Journal/index.html.
26. Sanders, R.H., Thow, J., and Fairweather, M. (2011). Asymmetries in swimming: Where do they come from? *Journal of Swimming Science,* **18**, Fall 2011. http://www.swimmingcoach.org/Journal/index.html.

27. Seifert, L, Chehensse, A., Torney-Chollet, C, Lemaitre, F., and Chollet, D. (2008). Effect of breathing pattern on arm coordination symmetry in front crawl. *Journal of Strength and Conditioning Research*, **22(5)**, 1670-1676.

28. Seifert, L., Chollet, D., and Sanders, R. (2010). Does breathing disturb arm to leg coordination in butterfly. *International Journal of Sport Medicine*, **31**, 167-173.

29. Seifert, L., Leblanc, H., Chollet, D., Sanders, R., and Persyn, U. (2011). Breaststroke Kinematics. In L. Seifert, D. Chollet., and I. Mujika (Eds.) *World Book of Swimming: From Science to Performance* (pp.135-151). New York: Nova Science Publishers.

30. Strzala, M., and Krezalek, P. (2010). The body angle of attack in front crawl performance in young swimmers. *Human Movement*, **11(1)**, 23-28.

31. Suito, H., Ikegami, Y., Nunome, H., Sano, S., Shinkai, H., and Tsujimoto, N (2008). The effect of fatigue on the underwater arm stroke motion in the 100m front crawl. *Journal of Applied Biomechanics*, **24(4)**, 316-324.

32. Thow, J. (2010). *The development and validation of a battery of swimming technique measures associated with strength deficits among competitive front-crawl swimmers*. Unpublished Masters Thesis, The University of Edinburgh.

33. Tourney-Chollet, C., Seifert, L., and Chollet, D. (2009). Effect of force symmetry on coordination in crawl. *International Journal of Sports Medicine*, **30**, 182-187.

34. Toussaint, H. (2011). Biomechanics of drag and propulsion in front crawl swimming. In L. Seifert, D. Chollet., and I. Mujika (Eds.) *World Book of Swimming: From Science to Performance* (pp.3-20). New York: Nova Science Publishers.

35. Ungerechts, B, and Arellano, R. (2011). Hydrodynamics in swimming. In L. Seifert, D. Chollet, and I. Mujika (Eds.) *World Book of Swimming: From Science to Performance* (pp. 21-42). New York: Nova Science Publishers.

36. Vezos, N., Gougoulis, V., Aggeloussis, N., Kasimatis, P., Christofiridis, C., and Mavromatis, G. (2007). Underwater stroke kinematics during breathing and breath-holding front crawl swimming. *Journal of Sport Science and Medicine*, **6**, 58-62.

37. Vorontsov, A.R., and Rumyantsev, V.A. (2000). Resistive forces in swimming. In V. Zatsiorski (Ed.) *Biomechanics in Sport* (Vol1, pp.184-204). Oxford: Blackwell Science Ltd.