How Do Asymmetries Affect Swimming Performance?

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Abstract

This paper, the third in a series of four papers reviewing asymmetry in swimming, addressed the question 'how do asymmetries affect performance?' In view of a paucity of directly related research papers on this topic the question was addressed with a combination of rationale based on mechanical principles and extant literature. 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 asymmetries affect performance is reviewed and discussed.

There is a paucity of literature relating directly to the issue of how asymmetries might affect performance of swimmers. In particular, studies involving controlled interventions with pre and post quantification of asymmetries and performance are extremely scarce. Thus, in this review we rely on scientific rationale in combination with extant literature to hypothesize how asymmetries might affect performance, thereby providing a foundation underpinning future studies. 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.

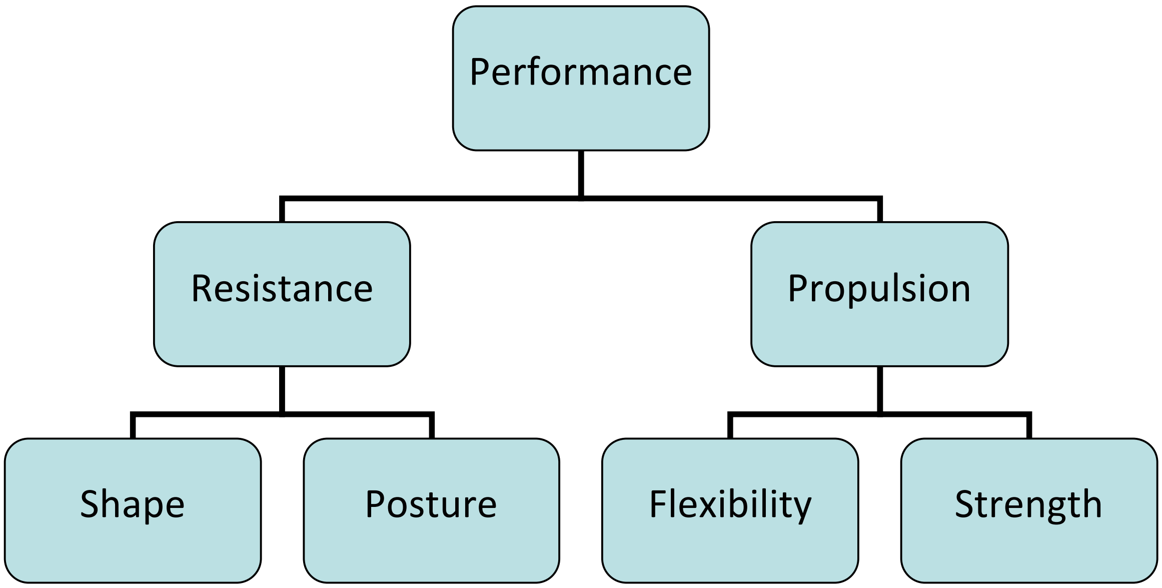

Figure 1: Model of main factors affecting performance in swimming.

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. Thus, 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. Logical assessment and hypothesizing regarding how asymmetries might affect performance 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 dissipation of energy as waves following the work done to raise the body against gravity, 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).

In 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 applies lower pressure from behind the body than the pressure of water pushing against the leading surfaces 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. Thus, 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). By transducing resistive forces of mannequins having a typical male and typical female shape in a flume at incrementally varying depths, Pease (2012) 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 mannequin 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.

Understanding the effect of shape asymmetries on resistance is even more complex and represents a virtually untapped area of research. 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 bilaterally and muscle imbalances both bilaterally and antero-posteriorly. Further, technique differences affecting the instantaneous body shapes adopted throughout the strokes may influence body shape either independently of those factors or through a cause and effect relationship.

Knowledge regarding the effect of the instantaneous asymmetric body shapes is severely lacking at this time. Again, CFD analysis in combination with empirical data obtained from actual swimming in which instantaneous postures are clearly defined and used as input to validated CFD programs offers promise in addressing the effect of shapes adopted during swimming. At this time, some insights may be gained from studies of the effect of asymmetries of objects on resistive drag. For example, deliberate asymmetries in hulls of sailing boats and winged keels of yachts offer an advantage in producing lift at the expense of some disruption to the flow conditions that influence resistive drag (Morabito, 2011).

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. Thus, in the quest to minimize resistance, posture becomes a critical consideration.

Posture

As stressed above, a swimmer's 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, abduction, and outward rotation of the hips, as well as flexion of the knees and dorsi-flexion of the ankles prior to the backward push. The postures adopted during this process are not optimal for minimizing 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 torque tending to rotate the body than females due to less adipose tissue in the lower limbs, and larger lung volumes. The torques produced by the leg kick help to overcome the 'sinking legs' problem but at some additional energetic cost.

Asymmetries Affecting Propulsion

It is very common among elite swimmers for forces to differ bilaterally 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

Bilateral differences in strength can have at least three adverse effects with respect to performance. The first is the effect on rotational balance. If the pull is stronger on one side than the other there are rotational torques that are unbalanced. 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 that produces resultant forces acting close to the midline of the body (the line from head to feet through the center of mass) is important.

Thus, in front crawl, as long as the pull on both sides produces small rotational effects, the fact that the magnitude of the forces differ bilaterally may not affect resistance. This is not the case in backstroke. In backstroke the anatomical limitations mean that the hand path creates forces with lines of action that are not close to the midline and, as a consequence, the rotational effects are large. Therefore, bilateral differences in torques emanating from strength imbalance in the pull must be compensated by torques produced by the kicking actions, which in turn can lead to asymmetries in kicking that affect lower limb alignment and resistance.

In the 'symmetrical' strokes bilateral differences in the magnitude of the forces produced during the pull also cause rotations of the body causing misalignment and increased resistance. Our analyses of asymmetries in technique among breaststroke and butterfly swimmers have indicated 'yawing' rotation, that is, a rotation about a vertical axis that misaligns the body, linked to differences in force applied by the right and left sides. In turn that is linked to differences in shoulder flexion/extension and internal/external rotation strength known from tests on a Biodex dynamometer.

To avoid this yawing effect, the difference in force can be compensated by differences in hand path to change the relative distance of the force line of action from the axis of rotation. 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. Consequently the swimmer can become '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 disqualified repeatedly. Physical examination revealed strength asymmetries in shoulders and hips with concomitant postural asymmetries and asymmetrical muscle tightness. Encouragingly, therapeutic interventions resulted in improved muscle balance, improved movement patterns, and race performance.

The second effect related to bilateral strength difference 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 torques to maintain good alignment, a swimmer that 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 would be when both sides 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 dominant 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 effect relates to fatigue. In the attempt to maintain speed, the strong side applies greater force to compensate for the reduced force of the weaker side. The weaker side also fatigues more quickly than it would otherwise because it is trying to maintain a force contribution that is equivalent to the strong side. In both cases the muscles are working with a force output that is closer to their peak capacity than if the load was being shared evenly.

In addition to the decreased magnitudes of forces, 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 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 the kick. If the fatigue levels are different bilaterally 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 bilaterally in simulated front crawl swims on a swim bench, that the difference increased with fatigue, and that bilateral differences were less for bilateral than unilateral breathers. The findings of these studies emphasize the link between bilateral imbalances in force production and technique.

Flexibility

Like strength, flexibility affects performance in several ways and there are several interacting influences. Some are related to resistance and some to propulsion. With respect to resistance, flexibility affects the postures that can be adopted and the techniques employed 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 requires flexibility in addition to appropriate body roll.

In terms of propulsion, flexibility affects the positions of limbs and joints sought to maximize the forces applied and 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.

Swimmers may be constrained also 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 training 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 short. 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 exactly through the body's natural pivot point, that is the instantaneous center of mass, torques are produced that rotate the body and tend to disrupt its alignment. Any disruption to the optimal streamlined alignment of the body increases resistance. Skilled swimmers learn to maintain good alignment by two main mechanisms:

1. They learn to produce forces with lines of action that propel them forward but also act close to the center of mass to minimize the rotational effects. Hence, although the hand scribes a curved path to push against 'still water', 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. This minimizes 'yaw' rotation around the vertical axis.

2. Torques produced by forces that are not through the center of mass of the body may be offset by torques produced by compensatory actions. Thus, a skilled front crawl swimmer maintains alignment by refining their actions so that the torques produced in reaction to the recovery of the non-pulling upper limbs are offset by the torques produced by the kicking actions and by the forces produced by the action of the pulling arm. 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 torques to maintain good alignment. There is no one ‘correct’ technique and each swimmer optimizes their technique unwittingly taking into account other factors such as their own ‘organismic constraints’ such as morphology, joint structure, flexibility, muscle characteristics, and external influences such as coaching and role models whose technique characteristics the swimmer may have copied.

While individuals find their own solutions to the problem of minimizing resistance, differences in the effectiveness of those solutions are often observable in the kinematics and the performance. However, there has been a paucity of quantitative research to establish clearly the relationships between the technique characteristics, their effectiveness in minimizing resistance, and their relationship to performance.

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 path of the affected arm varied widely and clustered towards one of three distinct paths. This indicates that the swimmers have adopted one of three possible general technique solutions to the problem of maintaining good alignment when swimming with an asymmetrical body structure that affects both propulsion and resistance.

In backstroke, balancing torques is more difficult 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 axis 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 and is manifest in lateral motions of the hips and bowing of the body. Kicking in oblique planes as the body rolls produces torques to compensate these effects. The importance of the kick in this role 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 torques produced by the pulling arm.

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, the torques about the vertical axis 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 center of mass of the body. 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 bilateral 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. The unbalanced torques cause yaw rotation that affects alignment and increases resistance. The imbalance is 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 muscle imbalances. For example, one of the elite breaststroke swimmers in our study did not fully extend the hips following the kick. This means that, rather than being in the slipstream of the trunk, the thighs added to the cross sectional area of the body and increased the resistance. 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 kinematics differ between sides in terms of spatial kinematics and body roll (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 spatial and temporal characteristics of technique.

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 spatial and temporal 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. Raising the upper body and arms out of the water for part of the stroke cycle 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 similar to that in butterfly swimming (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 relative to the body. 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. Indeed, they create resistance during this period until they are clear of the water. In front and back crawl these resistive forces act outside the midline of the body thereby producing torques that can affect alignment. The distance of the limbs from the midline, and hence the length of the lever arm that determines the torque acting to rotate the body and upset its alignment, is influenced by the body roll. Well timed body roll assists in a 'clean' exit to minimize resistance as well as to minimize the length of the lever arm.

In butterfly, provided the recovery is symmetrical in both spatial and temporal terms, the alignment should not be affected by these resistive forces in the transition between the pull and recovery. However, asymmetries are evident in many swimmers and may be manifest in temporal differences in the time of release and exit of the hands from the water as well as differences in the amount of 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, as noted previously, breaststroke swimmers may not be entirely symmetrical both in spatial and temporal terms 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. The angular acceleration about the vertical axis at the commencement of the recovery in front crawl produces a reaction torque that tends to swing the body about a vertical axis. Disruption to alignment of the body is minimized among skilled front crawl swimmers by the following strategies:

1. 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. This means that the mass of the upper limbs is close to the vertical plane aligned with the swimming direction and through the swimmer's center of mass. As a consequence, the rotational inertia is reduced and the torque in reaction to the angular acceleration of the upper limbs is reduced.

2. The ability to keep the upper limbs close to the vertical plane through the midline of the body is assisted by well-timed body roll. Thus, in addition to enabling a 'cleaner' exit and reduced torques prior to exit, body roll can reduce the reaction torques associated with the angular acceleration of the arms immediately after exit.

3. The reaction torque can be offset by an oblique kicking action that creates a balancing torque. Body roll assists greatly in positioning the lower limbs to enable oblique kicking.

While these strategies minimize the effect of the recovery of the arms in front crawl on alignment, bilateral 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 bilateral 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 paucity 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 and, as a consequence, assists the exit of the hand. Following exit the recovery of skilled backstroke swimmers is then confined to the vertical plane, thereby minimizing the torque associated with angular accelerations about a vertical axis during recovery.

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 constrained anatomically during hyper-extension when adducted towards the midline. Bilateral 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, both temporally and spatially, 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 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 torques bilaterally, thereby affecting alignment.

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