Body roll in swimming: A review
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Body roll in swimming: A review

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Abstract
In this article, we present a critical review of the swimming literature on body roll, for the purposes of summarizing and highlighting existing knowledge, identifying the gaps and limitations, and stimulating further research. The main research findings can be summarized as follows: swimmers roll their shoulders significantly more than their hips; swimmers increase hip roll but maintain shoulder roll when fatigued; faster swimmers roll their shoulders less than slower swimmers during a 200-m swim; roll asymmetries, temporal differences in shoulder roll and hip roll, and shoulder roll side dominance exist in front crawl swimming, but there is no evidence to suggest that they affect swimming performance; and buoyancy contributes strongly to generating body roll in front crawl swimming. Based on and stimulated by current knowledge, future research should focus on the following areas: calculation of body roll for female swimmers and for backstroke swimming; differences in body roll between breathing and non-breathing cycles; causes of body roll asymmetries and their relation to motor laterality; body roll analysis across a wide range of velocities and swimming distances; exploration of the association between body roll and the magnitude and direction of propulsive/resistive forces developed during the stroke cycle; and the influence of kicking actions on the generation of body roll.

Keywords: Biomechanics, shoulder roll, hip roll, front crawl

Introduction
Swimmers and coaches continually seek to optimize performance and reduce the risk of injury in training and competition through modification of technique. The evolution of approaches to biomechanical analysis in the last 50 years has allowed researchers to describe swimming technique more accurately as well as to advance our knowledge, enabling improved coaching practices to improve competitive performance and reduce the incidence of injuries. In these regards, the rolling motion of the trunk during front crawl and backstroke swimming has been of increasing interest in recent years.

It is well known that the alternation between left and right arm strokes in front crawl and backstroke is accompanied by angular motion of the trunk about its long axis, commonly known as body roll. Counsilman (1968) was one of the first authors to emphasize the potential importance of body roll in swimming. He suggested that body roll could make the recovery of the arm easier and permit a shorter radius of rotation of the recovery arm; place the strongest part of the arm pull more directly under the centre of mass; and place the hips in such a position that the feet can be thrust partially side-wards, thus cancelling the side-wards sway of the torso possibly created by the forward swing of the recovery arm. Other authors have suggested that body roll has functions such as facilitating the breathing action in front crawl swimming (Hay, Liu, & Andrews, 1993), increasing propulsion or decreasing the drag forces (Castro, Minghelli, Floss, & Guimaraes, 2003), and reducing the risk of developing shoulder injuries (Ciullo & Stevens, 1989; Penny & Smith, 1980; Weldon & Richardson, 2001).

For more than two decades after Counsilman’s suggestions, research publications relating to body roll and its influence on swimming performance were sparse. Since then, researchers have defined and examined body roll in two different ways. First, in some studies the roll of the whole trunk was calculated based on the assumption that the trunk rolls as a rigid segment while swimming. Researchers have estimated trunk roll with simulation methods (Hay et al., 1993; Payton Hay, & Mullineaux, 1997) or measured trunk roll using two-dimensional (2D) techniques (Beekman & Hay, 1988; Castro, Vilas-Boas, & Guimaraes, 2006;
Liu, Hay, & Andrews, 1993; Payton, Baltzopoulos, & Bartlett, 2002; Payton, Bartlett, Baltzopoulos, & Coombs, 1999). Second, the shoulder roll and hip roll of swimmers have been measured separately with the use of three-dimensional (3D) methods (Cappaert, Pease, & Troup, 1995; Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009; Yanai, 2001, 2003, 2004; Yanai & Hay, 2000) or simulation methods (Lee, Mellifont, Winstanley, & Burkett, 2008), while in some of these studies the roll of the entire body (rather than just the trunk) around its longitudinal axis was also considered (Yanai, 2003, 2004).

Research findings suggest that body roll might influence many aspects of front crawl and back crawl swimming performance. In this article, we present a critical review of the swimming literature on body roll, for the purposes of summarizing and highlighting existing knowledge, identifying the gaps and limitations, and stimulating further research. Based on the distinct differences in the definitions and methodologies used and, essentially, the variables analysed when body roll was considered, this review is divided into three sections. The first section presents studies in which trunk roll was calculated. The second section reviews studies that focused on analysing shoulder roll and hip roll separately. The third section summarizes the main research findings and discusses directions for future research.

The following databases were used for this review: SportDiscus, MEDLINE, PubMed, and CINAHL. These databases were searched in March 2009 with “swimming” as the main keyword, combined with each of the following: “body”, “roll”, “body roll”, “body-roll”, and “bodyroll”. The search returned 108 references. Peer-reviewed articles in scientific journals were included in this review, providing that body roll was calculated experimentally or through simulation. The following types of references were excluded: textbooks, papers in conference proceedings, abstracts, theses, and non-peer-reviewed articles. Based on these criteria, 15 peer-reviewed articles, all focused on front crawl swimming and (with the exception of one study) male swimmers, were eventually subjected to critical evaluation and are presented in this review. Research publications on body roll in backstroke are lacking. Thus, research on backstroke swimming and on female swimmers is required.

Assessing body roll as a single value for the roll of the trunk

Computer simulation studies

Hay et al. (1993) developed the first computer simulation model to examine the effect of trunk roll on hand path during the pull phase in front crawl swimming. The trunk and right arm were modelled as two rigid segments, joined at the shoulder by a simple hinge joint. The rigid arm segment was assigned a pre-selected elbow flexion angle and the hand was made to move in a plane through the shoulder parallel to the sagittal plane of the rotating trunk. Payton et al. (1997) attempted to improve the rigid arm model developed by Hay et al. (1993) by modelling the right arm as two rigid segments hinged at the elbow to enable flexion and extension. The arm was also linked to a rigid trunk with a joint capable of shoulder extension and shoulder abduction/adduction.

Based on the findings of the computer simulation studies, the authors suggested that body roll could have an important influence on hand path, assist in the development of propulsive forces and, therefore, the improvement of swimming performance. However, both research teams pointed out that the results of the computer simulation studies were preliminary and should not be generalized until the models are established and validated. Indeed, some of the assumptions made in these studies were proven to be incorrect by later research. For example, Payton et al. (2002) indicated that the investigators in the computer simulation studies assumed incorrectly that the trunk rolls away from the neutral position (i.e. counter-clockwise rotation in Figure 1) for the duration of the insweep and that there is no internal/external rotation of the shoulder during the underwater pull. Nevertheless, the outcome of early computer simulation studies was useful in stimulat-
In all studies in this area, researchers used similar methods to calculate trunk roll. A balsa wood fin mounted on a curved aluminium base was strapped to the back of each swimmer (see Figure 1), a single camera was placed on the pool side, and swimmers were requested to swim away from the camera. Using these recordings, trunk roll was defined and calculated as the angle between the rear edge of the fin and the vertical axis. In studies that have used 2D kinematic analysis, researchers have focused on investigating the influence of trunk roll on hand path and hand velocity (Payton et al., 1999), and on the differences in trunk roll between breathing and non-breathing conditions in front crawl (Beekman & Hay, 1988; Castro et al., 2006; Payton et al., 1999). The standard of the swimmers tested across studies varied from university to national-level male swimmers, while Castro et al. (2006) tested both swimmers and triathletes.

**Influence of trunk roll on hand path and hand speed.** With respect to the influence of trunk roll on hand path/speed, Liu et al. (1993) reported a mean value of 60.8° for trunk roll to the non-breathing side (trunk roll to the breathing side was not calculated) and stated that the mean contribution of trunk roll to hand path was 52.1% and was nearly equal to the contribution of the medio-lateral motions of the arm (shoulder and/or elbow) to the hand path. Payton et al. (2002) attempted to improve the methods used by Liu et al. (1993) by calculating both positive and negative contributions of body roll to hand speed. The former researchers reported that trunk roll had a negative overall contribution to hand speed. Nevertheless, Payton et al. (2002) underlined that this should not be interpreted as meaning that the swimmers would achieve higher hand speeds by rolling less, as any changes in trunk roll are likely to be accompanied by compensatory changes at the shoulder and the elbow.

**Differences in trunk roll between breathing and non-breathing conditions.** The results of the comparison between breathing and non-breathing conditions have been inconsistent across studies. Beekman and Hay (1988) reported significant differences between breathing and non-breathing conditions for a group with shoulder injury (breathing trunk roll: 60°; non-breathing trunk roll: 48°), but no differences for an injury-free group (breathing trunk roll: 54°; non-breathing trunk roll: 55°). In contrast, for a small sample (n = 6) of healthy swimmers, Payton et al. (1999) found that they rolled on average 9° more during the preferred breathing (66°) than the non-breathing trial (57°). Castro et al. (2006) reported that most of their swimmers rolled more when breathing (with the exception of long-distance swimmers when tested at low self-selected intensities), but there were no differences between breathing and non-breathing conditions for the triathletes.

One explanation for the discrepancies across studies could be that the trunk roll patterns of the injured swimmers (as suggested by Beekman & Hay, 1988) and, perhaps, the triathletes were not as consistent as those of the healthy swimmers. Another explanation could be the large range of swimming speeds tested (which varied from 1.13 to 1.96 m·s⁻¹) and, in some cases, the high standard deviation of the speeds recorded for a given swimming intensity. In line with this argument, the results of Castro et al. (2006) suggested that swimmers seemed to decrease trunk roll when speed increased.

**Limitations of experimental studies.** Although the 2D studies provided some useful data on trunk roll and its potential influence on swimming kinematics, the assumption that the trunk moves as a rigid part during front crawl and backstroke swimming does not enable separate analysis of shoulder and hip roll. Indeed, some studies have indicated that the magnitude and timing of shoulder and hip roll are different (Cappaert et al., 1995; Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009; Yanai, 2001). For example, Psycharakis and Sanders (2008) indicated that swimmers roll their shoulders significantly more than their hips and that the timing of maximum shoulder roll relative to maximum hip roll varied between swimmers, as well as between the left and right sides of individual swimmers. Thus, body roll must be calculated separately for shoulders and hips for the purpose of a more detailed analysis of the rolling motion of the trunk and to improve our understanding of its influence on swimming performance.

**Assessing body roll separately for the shoulders and hips**

Body roll was calculated separately for the shoulders and hips with the use of 3D methods in all studies. The roll angles of the shoulders and hips were determined by projecting the vector of the respective right joint relative to the left joint onto the vertical plane perpendicular to the swimming direction (Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009), or by expressing the shoulder and hip roll angles relative to the long axis of the swimmers (Cappaert et al., 1995; Yanai, 2001, 2003, 2004; Yanai & Hay, 2000). Studies in this area have
focused on: identifying the causes of body roll (Yanai, 2001, 2003, 2004); calculating the magnitudes of shoulder and hip roll and their links to swimming performance (Cappaert et al., 1995; Lee et al., 2008; Psycharakis & Sanders, 2008; Yanai, 2001, 2003); exploring the temporal or rhythmical characteristics of shoulder and hip roll (Cappaert et al., 1995; Psycharakis & Sanders, 2008; Sanders & Psycharakis, 2009); assessing roll asymmetries and the influence of motor laterality (Psycharakis & Sanders, 2008); and exploring the links between the magnitude of shoulder roll and prevention of shoulder injuries (Yanai & Hay, 2000).

**Simulation studies**

Lee et al. (2008) tested 11 national-level swimmers (4 males, 7 females) who simulated 100-m breathing and non-breathing trials on a purpose-built swimming bench that allowed rotation of the head, shoulders, and hips. Each trial lasted 60 s and shoulder and hip roll were calculated separately. An interesting finding was that female swimmers rolled their hips more than male swimmers. Also, there were no significant differences in the magnitude of hip roll between breathing and non-breathing conditions. Male swimmers displayed significantly greater shoulder roll in the breathing than the non-breathing side, whereas the difference was not significant for the females.

It should be emphasized, however, that it is not yet known whether such simulations are valid representations of swimmers’ body roll characteristics while swimming. Furthermore, there are distinct differences between swimming in a pool environment and simulating swimming on a swimming bench with regards to the physical demands, the resistance to the swimmer’s actions, and the mechanisms used to generate body roll. Thus, as the applicability of these results to competitive swimming remains to be established, the generalizability of the findings of the study by Lee et al. (2008) is limited. Further research into establishing the links between pool swimming and swimming simulations on a swim bench should be encouraged, as the advantages of such dry-land methods – compared with complicated 3D analyses – include, among others, ease of use, low equipment cost, short data collection and analysis time and, hence, quick feedback.

**Experimental studies**

*Causes of body roll.* Yanai (2001, 2003, 2004) tested 11 male university swimmers performing long-distance (1.3 ± 0.1 m · s⁻¹) and sub-maximal pace (1.6 ± 0.1 m · s⁻¹) front crawl trials, in an attempt to identify the sources and causes of body roll. Two panning periscope systems were used to obtain the above- and below-water data in all studies. Yanai (2001) showed that the external torque acting on the whole body (determined as the first time-derivative of the angular momentum of the whole body) generally contributed towards propelling body roll, while the reaction effects of accelerating body roll, while the reaction effects of accelerating limbs (i.e. internal torques, determined as the first time-derivative of the angular momenta of the limbs) resisted body roll. In a subsequent study, Yanai (2003) considered the rolling of the entire body around its longitudinal axis and reported that it accounted for 50% of the rolling actions of the shoulders and 68% of the rolling actions of the hips.

Applying modelling techniques with some assumptions regarding the waterline around the swimmer, Yanai (2004) provided some evidence that buoyancy is an important contributor to the rolling action of the entire body, as it accounted for 75 ± 13% of the roll of the body for the long-distance pace (1.3 ± 0.1 m · s⁻¹) and 61 ± 14% of the roll of the body for the sub-maximal pace (1.6 ± 0.1 m · s⁻¹). The contribution of hydrodynamic forces to roll of the entire body was significantly smaller (25 ± 13% for the long-distance pace and 39 ± 14% for the sub-maximal pace). The author used the term “buoyancy torque” to refer to the torque generated during the recovery phase of the arm, when the recovery arm is lifted out of the water (not being subject to buoyant force) and the centre of buoyancy shifts away from the recovery side creating a moment arm with respect to the longitudinal axis through the whole-body centre of mass. Yanai (2004) stated that the buoyancy torque could generate body roll without sacrificing propulsion. The author suggested that swimmers could use buoyancy force more effectively in creating body roll by modifications in stroke technique, including extending the recovery phase by having the elbow exit while the hand is still making the final sweep and keep the elbow high during hand entry (so that the angular impulse generated by the buoyancy torque increases), and coordinate the timing of the recovery phase so that the buoyancy torque effectively decelerates the on-going body roll and facilitates initiation of body roll towards the opposite direction.

Considering that the participants in the above studies were university-level swimmers, researchers should attempt to confirm these findings in future studies by testing swimmers of different standards and perhaps taking into account the possible influence of the breathing actions on buoyant torques. Yanai’s modelling indicated that there may be differences in the relative contribution of the buoyancy torque to total torque, but further research is required to provide further information of the sources of torque and the reasons for the differences.
at different speeds. Other contributions to torque about the long axis of the body, for example the contribution due to the kick, need to be quantified in future studies.

Magnitude of shoulder roll and hip roll. Cappaert et al. (1995) calculated shoulder and hip roll for five elite (participating in the finals, mean speed: 2.01 m · s⁻¹) and seven sub-elite swimmers (participating in the heats, mean speed: 1.87 m · s⁻¹) during the men’s 100-m freestyle event at the 1992 Olympic Games. Swimmers generally rolled their shoulders considerably more than their hips, with sub-elite swimmers having similar shoulder roll to elite swimmers. The mean values reported for shoulder and hip roll were 34.4° ± 1.7° and −17.8° ± 1.5° respectively for the sub-elite group and 35.4° ± 2.5° and 8.3° ± 1.5° respectively for the elite group (the negative hip roll of sub-elite swimmers indicates that the hips were rolling to the opposite direction to the shoulders; see also pp. 000–000). Nevertheless, two elite swimmers (including the gold medallist) displayed equal amounts of shoulder roll and hip roll. Yanai (2001) reported mean values of 58° for shoulder roll and 36° for hip roll at a swimming speed of 1.6 m · s⁻¹, and in a subsequent study (Yanai, 2003) he reported that swimmers decreased shoulder roll from 75° to 66° when speed increased from 1.3 to 1.6 m · s⁻¹. Based on suggestions that body roll reduced active drag by reducing frontal surface area (Clarys & Jiskoot, 1974), Cappaert et al. (1995) stated that the opposite roll of the shoulders and hips of the sub-elite swimmers in their study might have increased active drag, as the downward motion of the hip increased the frontal surface area. In line with this, Yanai (2001, 2003) stated that a large trunk twist might increase the resistance acting on a swimmer. The possibility that the amount of “twist” of the trunk is associated with performance warrants further investigation.

There was general agreement in the above studies that the shoulders roll considerably more than the hips. However, there was some discrepancy in changes in roll with speed, as Cappaert et al. (1995) reported no difference between swimmers’ shoulder roll for different velocities, while Yanai (2003) reported a decrease in shoulder roll when speed increased. There are several possible explanations for the differences between these studies. First, the standard of swimmers and the velocities tested were different. Moreover, there was no control over the breathing actions of the swimmers and no identification of the preferred breathing and the non-breathing sides, which suggests that the effect of the breathing patterns in the rolling actions of swimmers in both studies was unknown.

In a recent study, Psycharakis and Sanders (2008) tested 10 male swimmers of national and international standard during a 200-m maximum front crawl trial. A system of four below- and two above-water synchronized cameras was used and the swimmers were asked not to breathe when swimming through a 6.5-m long calibration space. Shoulder and hip roll were calculated four times during the 200 m (once for each 50 m). Swimmers rolled their shoulders significantly more than their hips (P < 0.001), with the mean 200-m values of the total range of roll from left to right sides being 106.6° ± 8.4° for shoulder roll and 50.4° ± 12.3° for hip roll (for a breakdown of shoulder and hip roll to each side according to the swimmers’ handedness and breathing preference, see pp. 000–000). In a subsequent study, Sanders and Psycharakis (2009) examined the relationships between the kicking actions and the magnitudes of shoulder and hip roll, and reported that the kicking actions had a minor influence on shoulder roll but a considerable influence on hip roll. The authors hypothesized that the smaller magnitude of hip roll compared with that of shoulder roll was due to the hip rotation being damped by the action of the lower limbs – that is, the kicking action applied a torque to the hips that limited the range of hip roll.

Psycharakis and Sanders (2008) also reported that the swimmers increased hip roll as speed decreased during the 200-m test. The increase in hip roll could be associated with the decrease in stroke frequency and the longer durations of the stroke cycles as the race progressed, or a possible reduction in vigour of the kick as swimmers fatigue. Nevertheless, shoulder roll values remained remarkably consistent. Interestingly, Psycharakis and Sanders (2008) indicated that faster swimmers were rolling their shoulders less than slower swimmers (P < 0.05 for the correlation between shoulder roll and swimming speed) with the exception of the fourth 50 m of the 200-m swim. However, no such pattern was found for hip roll. The authors reported that although it is possible that the amount of shoulder roll is constrained by the duration of the stroke cycle, swimming speed was not correlated with stroke cycle time or frequency. Moreover, given that the swimmers did not change their shoulder roll when speed decreased during the 200-m swim, it would appear that the magnitude of shoulder roll could be related primarily to a swimmer’s skill, rather than the speed at which he or she swims. Considering that the velocities tested by Psycharakis and Sanders (2008) varied from 1.45 ± 0.06 m · s⁻¹ (in the final 50 m) to 1.68 ± 0.05 m · s⁻¹ (in the first 50 m), more data on a wider range of velocities and swimming distances are required to confirm and generalize this finding.
Roll symmetry and motor laterality. Most researchers have not distinguished between roll to the dominant and non-dominant side (in terms of motor laterality). However, qualitative evidence suggests that bilateral asymmetries in body roll are common among swimmers and might be related to swimming speed (Arellano, Lopez-Contreras, & Sanchez-Molina, 2003). To investigate this possibility, Psycharakis and Sanders (2008) calculated shoulder and hip roll separately for the right and left sides. The group of 10 swimmers tested during the 200-m front crawl event was homogenous with respect to handedness (right) and breathing side preference (right), with only non-breathing stroke cycles being analysed. Mean shoulder roll was 57.1 ± 4.6° for the left and 49.6 ± 5.4° for the right side, and mean hip roll was 24.6 ± 8.1° for the left and 25.7 ± 6.0° for the right side. Mean asymmetries of 8.2 ± 4.8° for shoulder roll and 5.9 ± 3.9° for hip roll were reported. The amount of roll asymmetry was not correlated with swimming speed and did not change with fatigue during the maximum 200-m swim, providing no evidence that asymmetric shoulder or hip roll affects swimming performance. The hip roll asymmetries were highly individual as no systematic bias was found for the group. However, the results indicated left-side shoulder roll dominance throughout the 200-m trial, indicating that the swimmers were rolling their shoulders significantly more to the left than the right side. Although the causes of body roll asymmetries were not investigated by Psycharakis and Sanders (2008), the authors suggested that as shoulder roll to the left coincided with the underwater phase of the right (i.e., dominant) arm of the swimmers, possible causes of asymmetries include laterality and possible differences in strength and the magnitude, duration, timing or direction of propulsive forces between the dominant and non-dominant upper limb.

Temporal characteristics of shoulder roll and hip roll. Cappaert et al. (1995) reported that the hips of some sub-elite swimmers were rolling to the opposite direction of the shoulders during a 100-m freestyle race, which suggests that the shoulders and hips might peak at different times. Psycharakis and Sanders (2008) calculated the timings of shoulder relative to hip roll peaks and neutral positions (defined as the positions of 0° roll). Despite the variability and differences in timing among swimmers, the authors found no dominant pattern for the group. Psycharakis and Sanders (2008) also reported that the timings of shoulder and hip roll peaks did not change with fatigue during the 200-m front crawl trial. It was pointed out that swimming performance (as indicated by each swimmer’s speed) did not seem to be linked to shoulder or hip roll timing differences, as there was no evidence that hip roll either leading or trailing shoulder roll can lead to improvements in performance. Psycharakis and Sanders (2008) stated that swimmers might optimize their coordination in ways that suit their individual characteristics and that optimal patterns of coordination are perhaps specific to each individual. In view of this evidence, researchers could explore in future studies the possible links between shoulder/hip roll and arm coordination modes such as opposition, catch-up, and superposition (for a description of these modes, see Chollet, Chalies, & Chatard, 2002).

Sanders and Psycharakis (2009) examined the rhythm characteristics of front crawl swimmers using a six-beat kick. A noteworthy finding was that it was not just the upper body that rolled, since there was a roll of the imaginary line between the knees and imaginary line between the ankles about a longitudinal axis. Moreover, the authors reported that the timing of the roll of the hips, knees, and ankles about the longitudinal axis indicated the progression of a torsional wave, of which the speed of travel reduced with increasing skill. These results suggest that it would be interesting in future studies to expand the body roll analysis beyond shoulder and hip roll to incorporate the analysis of the roll along the whole body. The results of Sanders and Psycharakis (2009) also suggested that the kicking action might have limited the rotation of the hips, with hip roll increasing as the swimmers fatigued and the kicking became less vigorous.

Magnitude of roll and prevention of shoulder injuries. Overuse shoulder injuries are quite common in swimming. It is estimated that up to 80% of competitive swimmers experience shoulder pain at some time in their career to the extent that there is an interruption to their training (McMaster & Troup, 1993). The impingement of subacromial structures has been proposed as a major cause of overuse shoulder injuries in front crawl swimmers (Yanai & Hay, 2000). The shoulder movements used in swimming, when repeated over years of swimming practice, are believed to cause such impingements and develop a pathological condition called "shoulder impingement syndrome", commonly known as "swimmer's shoulder", which is believed to be the most common swimming injury (Fowler, 1994).

Some authors have recommended increasing the amount of body roll as one of the measures for the prevention and treatment of overuse shoulder injuries (Ciullo & Stevens, 1989; Penny & Smith, 1980; Weldon & Richardson, 2001). This recommendation is based on the argument that failure to correct body rotation forces the arm to be elevated lateral to the function arc of elevation and invites
further impingement, and that as a swimmer breathes, rolling about the longitudinal axis is enhanced and the amount of shoulder abduction required to clear the hand above the water is reduced (Neer & Welsh, 1977; Penny & Smith, 1980). Yanai and Hay (2000) argued that if this reasoning is valid, then swimmers with large shoulder roll angles should also have lower shoulder horizontal abduction angles and less shoulder impingement than swimmers with smaller shoulder roll angles. However, this was not supported by their experimental data on university-level swimmers, which showed no clear links between shoulder rotation and shoulder horizontal abduction angle or shoulder impingement. Yanai and Hay (2000) suggested that the attainment of a large shoulder roll angle should be considered together with other factors of stroking technique for the purposes of reducing individual susceptibility to shoulder impingement.

It must be noted that Yanai and Hay (2000) tested male university swimmers during front crawl trials only. For the purpose of obtaining a more complete picture of the links between shoulder roll and the prevention/treatment of overuse shoulder injuries, research should be expanded to include swimmers of a range of different abilities and both sexes. Moreover, consideration of other variables could improve further our understanding of any links between shoulder roll and injury prevention and treatment. For example, Psycharakis and Sanders (2008) found side dominance, asymmetries, and inter-swimmer variability in shoulder roll. Although such asymmetries are not clearly linked to performance, it has been suggested that asymmetries and movement variability could be functional, for the purpose – among others – of reducing injury risk (Davids, Glazier, Araujo, & Bartlett, 2003). Thus, the study of the links between shoulder roll and injury prevention/treatment could include consideration of shoulder roll side dominance, asymmetries, and variability.

Summary and future directions

Biomechanical research in this area has improved our understanding of the functions of body roll and its links to front crawl swimming. The main research findings can be summarized as follows:

- Buoyancy contributes strongly to generating roll for the entire body in front crawl swimming. However, the influence of the kick on hip roll also seems to be important and requires further investigation.
- Swimmers roll their shoulders significantly more than their hips. Therefore, shoulder roll and hip roll should be calculated separately in swimming.
- Front crawl swimmers tend to increase hip roll but maintain shoulder roll when fatigued during a maximum swim.
- Faster swimmers roll their shoulders less than slower swimmers throughout a 200-m race.
- It would appear that roll asymmetries, temporal differences in shoulder and hip roll, and shoulder roll side dominance exist in front crawl swimming, but there is no evidence to suggest that they affect swimming performance.
- Research on university-level swimmers did not support the theoretical view that increasing shoulder roll could help reduce the risk of shoulder injuries. Future research should include swimmers of different standards to allow confirmation and generalization of these findings.

Based on and stimulated by current knowledge, investigators should conduct further analyses to explore issues not yet addressed completely in the extant literature. Some of the main topics to be addressed in future studies are:

- Calculation of shoulder roll and hip roll and their influence on backstroke swimming.
- Investigation of shoulder and hip roll among female swimmers.
- Differences in shoulder and hip roll between breathing and non-breathing cycles.
- Causes of shoulder and hip roll asymmetries and their relationship to motor laterality.
- Analysis of the magnitude and phase differences of shoulder and hip roll for the different parts of a stroke cycle.
- Analysis of shoulder and hip roll across a wide range of velocities and swimming distances, for the purposes of confirming and generalizing existing findings.
- The relationships between shoulder and hip roll and the magnitude and direction of propulsive/resistive forces developed during the stroke cycle.
- Exploration of the relationship between shoulder roll, hip roll, and the kicking action.

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