Stroke Mechanics of Swimmers with Permanent Physical Disabilities

By Jan Prins and Nathan Murata

When observing the swimming stroke mechanics of persons with permanent physical disabilities, it is apparent the anatomic and neuromuscular deficits present result in the evolution of unique movement patterns in the water (Daly & Vanlandewijck, 1999; Prins 1988). Physical limitations for those with disabilities can influence swimming mechanics. To understand how such disabilities influence stroke mechanics, researchers and practitioners need to employ procedures clearly describing the variety of movement patterns persons with physical disabilities are able to demonstrate. The application of underwater stroke analysis, coupled with biomechanical motion analysis has resulted in more objective evaluation of the underwater movement patterns of such swimmers.

The traditional approach to swimming instruction for persons with permanent physical disabilities has been to modify the standard teaching methods used with able-bodied persons. The expectation is that, in spite of the limited strength and neuromuscular coordination, adequate skills will be acquired provided adequate time is devoted to the activity. This approach, although practically sound, can be improved by increasing our knowledge of the potential and limitations for movement in the water as exhibited by individuals with varied physical disabilities (Dunlap 1997; Dummer 1999; Prins, 1988; Wu & Williams, 1999).

Fundamental Concepts as Applied to Swimming

Certain aspects of swimming are common to all strokes. Overall swimming propulsion is dependent on a number of fundamental biomechanical factors: range of motion, propulsive forces, contribution of the muscles of the upper extremity, minimizing frontal resistance, and the importance of body position in the water.

Acceptable range of motion. This concept takes into account the anatomical and neuromotor capabilities of each swimmer (Prins, 1988). This is particularly important when trying to determine the functional abilities of swimmers with disabilities. Once a swimmer's range of motion, as applied to each swimming stroke is assessed, it will then be possible to determine the potential for executing the recommended changes.

Propulsive Forces used in swimming. All propulsive movements in the water employ a combination of the two primary hydrodynamic forces: drag and lift (Counsilman 1994; Schleihauf, 2004; Vogel, 2004). Drag forces are generated, for example, when paddling a boat or canoe. The oar, or in the case of swimming, the hand, is moved linearly during certain phases of the stroke, in an attempt to push the water backwards to propel the body forwards. In contrast, *lift* forces rely on the property of fluids to develop positive and negative pressures on the surfaces of a moving body. Examples of *lift* forces in nature are the fins of fish. In human swimming, both the pulling and kicking action in the breaststroke, and the dolphin kick used in the butterfly stroke, are good examples of lift forces being employed for propulsion (Counsilman, 1994).

Contribution of the muscles of the upper extremity. With the exception of the breast stroke, the principal contribution to propulsion in swimming comes from the muscles of the upper extremities, primarily the hands (Counsilman, 1994; Prins, 1988). Therefore, the inability to maintain full neuromuscular control of the hands makes it difficult to guide the hands through correct movement patterns with subsequent reduction in swimming efficiency. Swimmers diagnosed with conditions such as cerebral palsy, acquired brain injuries, and Down syndrome fall into this category.

Minimizing frontal resistance. Frontal resistance is another way to describe the resistance produced by the surface area of an object when a body is moving through a fluid. Any part of the body that is aligned at right angles to the flow will slow the motion down because it contributes to *form drag*, which is one of the resistive forces retarding the forward progress of a body moving through a fluid (Schleihauf, 1979). It is, therefore, imperative the orientation of the body should be such that the minimum area of the body and/or limbs should be visible when viewed from the front or *head on* position.

The importance of body position in the water. This concept ties into the discussion of minimizing frontal resistance. Although the kicking actions of each stroke contribute to overall propulsion, proper kicking actions applicable to each stroke will ensure that the torso will be maintained close to the surface in a prone or supine position. When the longitudinal axis of the torso does not lie parallel to the surface (i.e., when it lies at a deeper angle in the water) frontal resistance to forward motion will increase. In the case of swimmers who do not have control over their lower extremities, the alterations in body position are the result, either from the entire torso, or just the lower extremities, lying at a deeper angle relative to the surface. In either case, the change in alignment will dramatically affect efficient propulsion.

Commonly Used Swimming Strokes

Commonly used strokes for all ages and abilities include: front crawl (freestyle), backstroke (single and double arm), breaststroke, and butterfly. These swimming strokes form the basis for many individuals (with disablities or not) as to whether they engage in recreational or competitive swimming.

The Front-Crawl (Freestyle)

The front-crawl is the most extensively used swimming stroke for a number of reasons. When performed efficiently it is the fastest of the four competitive swimming strokes. It is also the most efficient when effort expenditure is related to the amount of distance that can be covered, because the contribution of the kick to the overall propulsion of the stroke is estimated to be in the order of 10% (Counsilman 1994). It should be the primary stroke of choice for swimmers who lack neuromuscular control of the lower extremities.

The Backstroke—Single- and Double-arm

The backstroke allows a swimmer to assume the supine position during propulsion. There are advantages and disadvantages to swimming in the supine position. The major advantage is that there is no restriction to breathing, since the face is not submerged at any time. The primary disadvantage is that in all variations of the backstroke, whether performed with single-arm or double-arm action, there is a greater reliance on the propulsive forces of the legs. Estimations of the contribution of the kick in backstroke is approximately 40 % (Counsilman, 1994). This means swimmers who have limited lower extremity control will have a more difficult time maintaining a suitable body position when lying supine in the water.

Swimmers diagnosed with different degrees of paraplegia can still use a traditional alternating, single-arm action when choosing to swim on their backs. In the case of swimmers who have difficulty coordinating arm and leg action due to brain damage, as with cerebral palsy and acquired brain injury (ABI), these swimmers may do better with a double over-arm action, termed the *Elementary Backstroke*. In many cases it appears that the impediments to coordination, when required to move the arms bilaterally, are not as severe as they are in alternating, synchronized, single-arm motion.

The Breaststroke

The major advantage of the breaststroke is that the arms do not need to be lifted out of the water and consequently, variations of the breaststroke are used extensively by swimmers with permanent physical disabilities (Prins, 1988). A potential disadvantage in using the breaststroke is that the elliptical paths used for the pulling and kicking patterns are considerably different from the predominantly saggital-planar motion of the arm pull and *flutter-kick* used in the front crawl and backstroke. Elliptical motions necessitate higher levels of skill acquisition because they employ more *lift forces* for generating propulsion. Consequently, swimmers with reduced bilateral coordination may have difficulty performing the necessary symmetrical movements required of the breaststroke.

The Butterfly

Although perceived as the most difficult of the four traditional competitive strokes, having a permanent physical disability does not preclude a swimmer from swimming the butterfly stroke. The major requirement is that the arms must be lifted out of the water simultaneously during the recovery phase, and once introduced into the water; they must be guided symmetrically in the traditionally prescribed path for this stroke, termed the *keyhole* pull.

Impact of Selected Physical Disabilities on Swimming Stroke Mechanics

Different physical disabilities can affect the execution of different swimming strokes in unusual ways. For this reason it is important to observe and categorize the probable limitations imposed by each of the categories of physical disability when comparing them to the underwater movement mechanics of non-disabled swimmers. Table 1 provides an outline of physical limitations that can affect swimming stroke mechanics. Swimmers with the following physical disability categories were selected for analysis: (a) amputation; (b) cerebral palsy (CP); (c) paraplegia (secondary to poliomyelitis); and (d) congenital birth defects.

The loss of limbs, either congenitally or through injury, will affect the manner in which swimming strokes are performed. While loss of a lower body segment may primarily affect the alignment of the torso and maintenance of body position during swimming, loss of an upper limb will have a major impact on propulsion. This is because, with the exception of the breaststroke, swimming stroke mechanics are dependent to a disproportionate degree on the propulsive forces generated by the hands. The following areas of focus provide more insight into the manner in which loss of limb segments can affect stroke mechanics.

Table 1
Factors contributing to reduction in swimming propulsion

Affected Disabilities	Physical Limitation	Effect on swimming stroke mechanics
Cerebral Palsy	Difficulty in sustaining coordinated muscular activity. Spasticism – muscle stiffness and rigidity. Athetosis – involuntary muscle movements. Ataxia – inability to maintain balance.	Reduction in the ability to coordinate unilateral and bilateral arm and leg movements. Loss of kinesthetic awareness of the water secondary to muscular rigidity of hands and feet. Difficulty in maintaining the body in a required orientation in the water.
Amputation – Congenital or following injury.	Absence of whole limbs or limb segments in either upper and/or lower extremities.	Reduction in the potential to generate propulsive forces by either the upper and lower extremities. Absence of limbs can affect balance and posture when swimming in either prone or supine positions in the water.
Paraplegia (secondary to Poliomyelitis or Guillain-Barre Syndrome).	Absence of lower extremity control. Impending spasticity.	Increase in frontal resistance to swimming caused by increased hip & knee flexion. Inability to use legs for propulsion.
Congenital Birth Defects	Anatomical differences in limb appearance and size.	Limitations in active range of motion of existing limbs. Reduction in propulsive potential.

The effect of limb loss on *body alignment*

Figure 1 shows an underwater view of a swimmer with a congenital loss of the right lower leg, below the knee. When swimming the freestyle, as shown in the figure, the absence of the stabilizing effect of the traditional flutter kick results in significant lateral excursions of the remaining lower extremity when attempting to combine the alternating arm strokes with the accompanying flutter kick. It is apparent the swimmer is trying to use the non-affected leg to generate propulsive forces, disregarding the exaggerated oscillations of the torso and lower extremities. These excessive lateral motions are counter productive and will increase the frontal drag forces and slow forward progress.

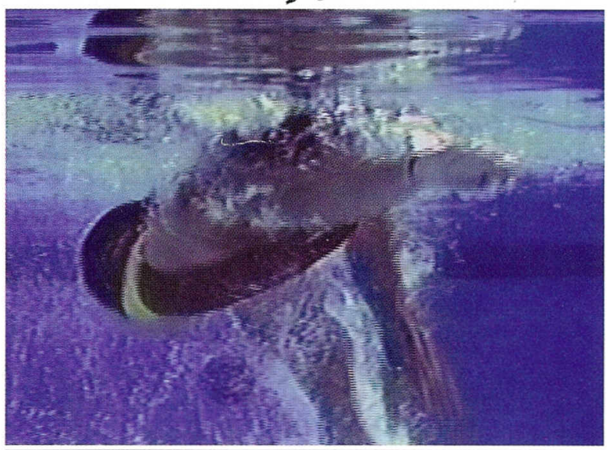

Figure 1. Frontal view of the front crawl as performed by a swimmer with right leg, below the knee, limb-loss. Note lateral excursions of torso and lower extremity.

The effect of limb loss on propulsion

A second major consequence of limb loss on swimming is the reduction in the ability to apply propulsive forces. Swimming the front crawl and backstroke relies primarily on the hydrodynamic force referred to as *drag* (Schleihauf, 1979; 2004). In simplistic terms, when drag forces are employed, the ability to propel the body in an intended direction is the result of pushing the water backwards, which, if performed at an optimum rate, produces better propulsive forces. In order to generate drag force, the frontal area of the limbs used for stroking, primarily the hands should be maximized in order to achieve the desired thrust. As expected, larger hands will have the potential to exert higher drag forces.

If hands and limb segments are missing, swimmers must rely on the cross-sectional areas of the existing limbs to exert drag forces. If this is the case, the primary compensation in order to achieve propulsion, is to increase the rotational speed of the available appendages. This is demonstrated when examining the durations of the individual phases of the stroke cycles in swimmers who lack limb segments and comparing them to the performance of non-disabled swimmers (Prins, 2006 a). Hand speeds were compared between two swimmers, both of whom were swimming at approximately the same speed (0.35 m/sec), using motion analysis software. Both had approximately the same upper extremity limb lengths, except one of the swimmers had limb loss below the elbow on the right side. The following differences were noted:

- The total time for each stroke cycle was very similar, (1.47 vs. 1.57 seconds).
- The durations of the underwater pull of the non-affected left arm in the swimmer with limb loss, closely matched that of the non-disabled swimmer (1.02 vs. 1.06 seconds).
- However, the time taken to complete the underwater pull by the affected right arm was considerably faster (0.60 seconds) than the non-affected arm.
- Consequently, in order to maintain a symmetrical overall stroke cycle, a distinct pause at the point of entry of the affected right arm was in effect. This adjustment in the phases of the stroke cycle is interesting in that it demonstrates the fact that when an alternating stroke pattern is in effect, as in the front crawl and backstroke, changes in coordination are made instinctively to ensure the overall timing of the stroke leads to as rhythmic a stroke pattern as possible.

Swimming with Cerebral Palsy

Cerebral palsy (CP) is an umbrella-like term used to describe a group of chronic disorders impairing control of movement that appear in the first few years of life and generally do not worsen over time. Thus, these disorders are not caused by problems in the muscles or nerves. Instead, faulty development or damage to motor areas in the brain disrupts the brain's ability to adequately control movement and posture (Carroll, Leiser, & Paisley, 2006; Odding, Roebroeck, & Stam, 2006).

There are a variety of movements distinctly symptomatic of cerebral palsy, and consequently, a number of broad categories of CP have been identified. Athetosis is the generation of involuntary muscle movements and consequently may affect gross motor function of swimmers while in the water. Ataxia is the disruption of the ability to maintain balance and an erect posture due to damage of the cerebellum. Swimming with ataxia may interfere with the ability to maintain the orientation of the body when lying prone or supine on the surface. Spasticism is characterized by taut muscles and movements executed with abnormal rigidity and muscle tension. Because spasticism is characterized by increased tension of the limbs, this trait has a significant impact on the swimmer's ability to execute propulsive movements in the water. Hypertonicity in the muscles can affect swimming propulsion in the following areas: (a) rigidity at the glenohumeral and elbow joints affects the ability to change limb angles for optimum positioning of the arms; (b) holding the wrists in a fixed flexed position, with respect to the forearm, makes it difficult to change the pitch of the hands for maximizing pulling efficiency; and (c) holding the hands with fingers either forcibly held together, or at the other extreme, with fingers splayed, reduces the sensitivity of the palms to the changing pressures of the water during the pull, reducing the potential for effective propulsion. It is also important to note holding the wrists and fingers in a rigid position is not limited to swimmers with clinical hypertonicity. It is common for beginning able-bodied persons to hold their fingers apart in an attempt to maximize their ability to pull their hands through the water. The ideal hand position is when the hands are held in a relatively relaxed posture, fingers held neither pasted together nor splayed wide, with the wrists maintaining good control.

Inflexible ankles prevent the rhythmic dorsi- and plantar flexion of the feet as required when swimming the front crawl, backstroke, and butterfly. The breaststroke kick requires movements that combine dorsi- and plantar flexion with ankle rotation. Furthermore, rigid ankles are often accompanied by stiff, hyper-extended knees, both of which make it difficult to develop acceptable kicking patterns. The swimmer in Figure 2, diagnosed with spastic diplegia, is swimming the breaststroke. Examining the upper extremity, the fingers appear held in a permanently *splayed* position, while the wrists, particularly in the right hand, are *ulnar flexed,* rather held longitudinally aligned with the forearm. When examining the position of the lower extremity, we see the legs maintained rigidly in an almost fully extended position, with heels closely touching. The trunk remains arched or hyper extended (see Figure. 3).

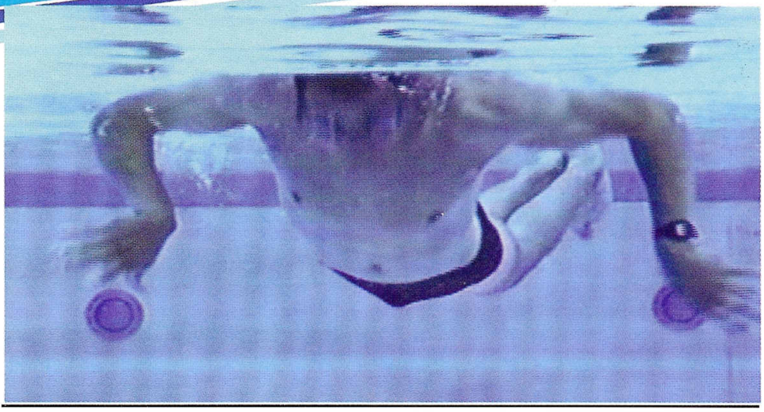

Figure 2. Rigid hand and wrist positions seen in a frontal view of a swimmer diagnosed with spastic diplegia, performing the breaststroke.

Swimming with Spinal Cord Injury

Paraplegia is a condition in which the lower part of a person's body lacks neuromuscular control resulting from paralysis. It is usually the result of spinal cord injury or a congenital condition such as poliomyelitis or spina bifida. However, polyneuropathy may also result in paraplegia (Davis, 1993; Daly & Vanlandewijck, 1999; Lepore, Gayle, & Stevens, 1998; Sherrill 1999; Wu, 1999). Two swimmers with Guillain-Barre Syndrome and poliomyelitis were observed. Guillain-Barre Syndrome is described as an *acute idiopathic polyneuritis* (Green & Ropper, 2001). The swimmer in question presents flaccid paralysis from the waist down and consequently has no control over the musculature of the lower torso, including the pelvic region. The second swimmer, diagnosed with *poliomyelitis,* also demonstrates similar loss of lower extremity limb control.

When lying motionless in a prone position, the existing flaccid paralysis causes the hip and knee joints to remain in a flexed posture (see Figure 4, page 24). In contrast to floating motionless, when propulsive movements are generated by the arms, one can observe involuntary oscillations in the lower extremities during swimming (Prins, 2006 a). Because these oscillations at the hip and knee joints are a consequence of upper extremity swimming activity, these movements offer a unique opportunity to observe the efficiency of the pulling actions used in the different strokes. What one observes is the alternating hip and knee flexion/extension motions in the saggital plane during the course of each stroke cycle.

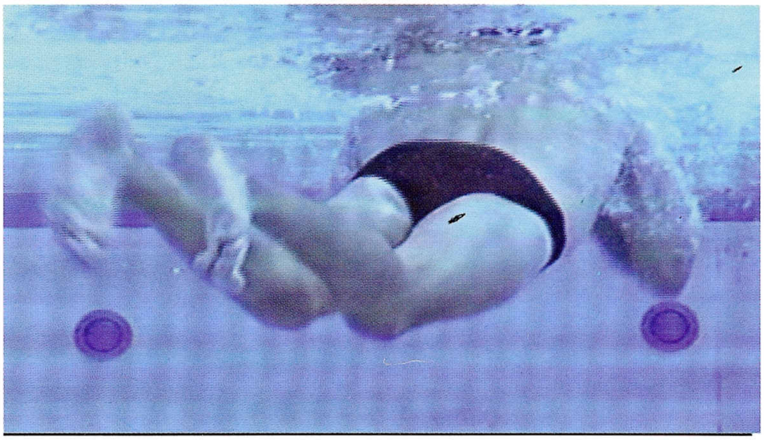

Figure 3. Posterior view of swimmer shown in Figure 2 showing rigidity of lower extremities.

Swimming with Congenital Birth Defects

Observing swimmers with congenial birth defects provides an opportunity for analyzing unusual propulsive patterns. One feature that applies to the majority of the swimmers with congenital limb malformations is their inability to perform linear translations (i.e., they are unable to move their limbs in a straight line) for even short distances in the water. Consequently, this limitation prevents them from employing drag forces as a form of swimming propulsion, (i.e., pushing the water backwards in order to move forwards, as used in the front crawl and backstroke) (Prins, 2006 b). In contrast, it is evident these swimmers use the available upper and lower extremities to perform sophisticated sculling movement patterns for propulsion. Figure 5 shows the upper and lower limb malformation characteristic of a swimmer with extreme reduction in limb formation. When observing this particular swimmer's movement patterns in the water, it is evident that structural limitations in anatomy preclude his ability to perform linear translations of either the upper- or

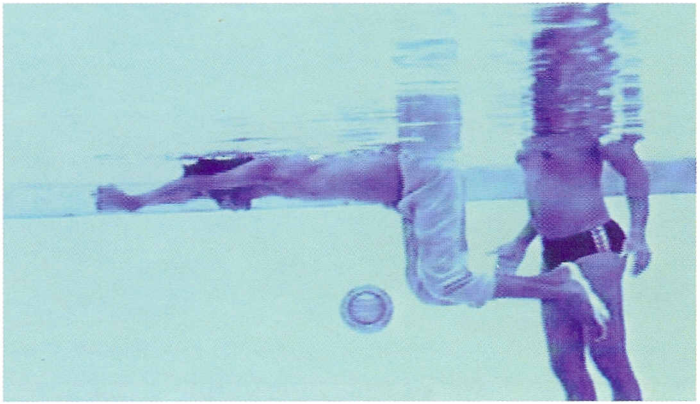

Figure 4. Supine floating posture of swimmers with "flaccid paralysis." Absence of lower extremity neuromuscular control results in involuntary flexion at hips and knees.

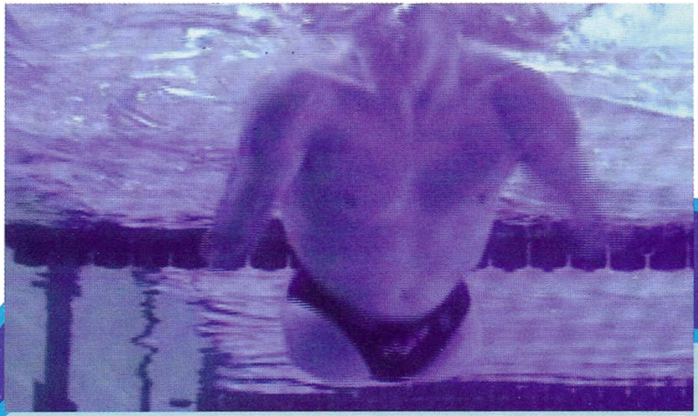

Figure 5. Swimmer with dysmelia floating vertically underwater.

lower-extremities. Consequently, he has to rely exclusively on rotational and/or sculling-type movements which are effective because they allow him to employ the propulsive forces of *hydro-dynamic* lift (Schleihauf 2004).

Recommendations

Based on the information presented in this article, the following recommendations are offered:

- The process of swimming *stroke analysis* requires an understanding of the underwater propulsive movements used for each of these strokes. The most effective method of analyzing swimming stroke mechanics is to video tape the activity from above and underwater.
- Most swimmers with permanent physical disabilities use variations of the traditional stroke patterns based on their anatomic limitations. In observing the swimmers selected for illustra-

tion, it is evident the stroke patterns demonstrated have evolved primarily through experimentation and repetition. Although stroke patterns demonstrate an ability to maximize propulsive potential, some patterns demonstrate counterproductive movements, traditionally referred to as *stroke defects*.

- Once a potential stroke defect is identified, in order to improve swimming efficiency, a determination must be made as to whether the particular movement can be modified with instruction.
- In the case of swimmers with permanent physical disabilities, the existing stroke pattern has been developed because the swimmer is attempting to compensate for the loss of a limb or a reduction in motor control, and at the same time maximize propulsion.
- In either case, what is important is to first identify these patterns, and then through analysis, develop recommendations for possible changes to improve swimming efficiency.

Conclusions

The potential for research and instruction lies in the examination of the degrees to which the loss of body segments and loss of motor control reduce the potential for swimming propulsion. As such, it is reasonable to conclude the study of movement patterns of swimmers with permanent physical disabilities can be both challenging and rewarding—yet much remains to be discovered.

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