International Journal of Aquatic Research and Education

Volume 2 | Number 4 Article 6

11-1-2008

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Recommended Citation

Prins, Jan and Murata, Nathan (2008) "Kinematic Analysis of Swimmers with Permanent Physical Disabilities," *International Journal of Aquatic Research and Education*: Vol. 2: No. 4, Article 6.
DOI: https://doi.org/10.25035/ijare.02.04.06
Available at: https://scholarworks.bgsu.edu/ijare/vol2/iss4/6

International Journal of Aquatic Research and Education, 2008, 2, 330-345

Kinematic Analysis of Swimmers With Permanent Physical Disabilities

Jan Prins and Nathan Murata

When the movement patterns of persons with permanent physical disabilities are observed from underwater, it is apparent that they have adapted unique variations in their swimming strokes to compensate for existing anatomic and neuromuscular deficits. Using underwater videotaping and subsequent analysis it is now possible to both identify and evaluate the movement mechanics of these swimmers. The purpose of this paper is to describe how motion analysis technology can be used in biomechanical research to examine the stroke mechanics of swimmers with permanent physical disabilities. In addition, we will identify the unique movement patterns of these swimmers, and, when applicable, discuss the limitations to their swimming efficiency.

Aquatic exercise has been used extensively in the past 20 years as a rehabilitative and therapeutic modality for individuals with permanent physical disabilities. The freedom of movement in the water and the ability to exercise muscles which, on land, have difficulty overcoming gravitational constraints makes swimming and related aquatic activities invaluable for persons with a wide range of physically disabling conditions (Daly, 1999; Dummer, 1999; Prins, 1988). Since the primary intent of analyzing the swimming stroke mechanics of disabled swimmers is to improve instructional techniques, the first objective is to examine the underwater movement patterns of these swimmers. The methods for teaching and analyzing the swimming stroke mechanics of swimmers with permanent physical disabilities are similar to those used for assisting able-bodied swimmers. Stroke patterns are videotaped from above- and underwater and evaluated using digital video recorders. Slow motion and freeze-frame capabilities of the video recorders allow more detailed analysis; however, these assessments, no matter how detailed, remain somewhat subjective. With the advent of motion capture technology, which is used for research in biomechanics, it is now possible to determine motion more precisely by quantifying the results.

Biomechanics is divided into two branches of study. Kinematics deals with the description of spatial and temporal parameters of movement measured as linear and angular displacements, velocities, and accelerations. Kinetics examines the forces that lead to the resulting kinematic changes (Griffiths, 2006; Kreighbaum, 1996). Using underwater videography and motion capture technology, the

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kinematics of propulsive movements used in swimming can now be analyzed, allowing a more thorough examination and assessment of each swimmer's stroke mechanics.

Method

Participants

The swimmers analyzed in this paper were either participants in a study funded by the National Institute for Disability and Rehabilitation Research, U.S. Department of Education and/or participants in national and international Paralympic swimming competition. Their swimming experience ranged from recreational to competitive swimming. Swimmers with the following disability categories were selected for analysis:

- Amputation
- Cerebral Palsy
- Paraplegia—secondary to Poliomyelitis, and Guillain-Barre Syndrome
- Quadriplegia
- Thrombocytopenia—Absent Radius (TAR) Syndrome

Data Collection

All underwater videotaping was conducted using digital video. The cameras were housed in custom-designed underwater housings (The Sexton Company, Salem, OR and Gates Underwater Systems, San Diego, CA) and suspended over the side of the pool using custom-designed camera mountings. Participants were videotaped above- and underwater from two views. For the first view, the camera was placed directly in front of the swimmer's path. This "frontal" or "head-on" view recorded the swimmer's strokes as they swam directly toward and away from the camera. When taping from this position, the camera was held stationary at all times. For the second view, the camera was held at right angles to the path of the swimmer. When filming from this view, two methods were employed. First, the camera was held in a stationary position while the swimmers moved past the camera. This method is necessary for calibration and subsequent motion analysis. The second method of filming required panning the camera and was used to follow the subject's path of motion over a longer distance.

Data Reduction

The resulting video footage was analyzed using video-based motion capture software (Vicon—Motus, Denver, Colorado). A four-point calibration rod was used as a scaling factor for 2-D kinematic analysis, which allows determination of linear and angular displacements, velocities, and accelerations. The durations of selected video segments of the stroke cycle were also determined by superimposing a "real-time" digital stamp on the video footage (For-A Corporation, Inc., Cyprus, CA). This second method, while less precise than the motion analysis software, is quicker and easier to use as a visual tool for stroke analysis.

Results and Discussion

When evaluating the swimming mechanics of swimmers with permanent physical disabilities, a number of areas of interest can be identified. It is clear that overall propulsion will depend on whether the upper or lower extremities are affected. Limb loss can affect a swimmer's body position and the ability to laterally stabilize the torso, particularly when the arms are used in an alternating rhythm as in the front crawl and back crawl. The loss of limb function, as seen in paraplegia, can also affect swimming efficiency due to the increased drag forces contributed by changes in frontal profile.

It must be remembered, however, that in swimming, with the exception of the breaststroke, the inability to fully engage the arms, specifically the hands, in executing the prescribed stroke patterns will have a major effect on swimming propulsion. Therefore, the loss of an upper-body limb segment will have a major impact on swimming propulsion (Dummer, 1999; Keskinen & Komi, 1993; Pelayo, Sidney, Moretto, Wille, & Chollet, 1999; Prins, 1988). We provide the following examples to examine the use of videography and motion analysis in the evaluation of the underwater movement mechanics of swimmers with varying disabilities.

Example 1: The Effect of Limb Loss on Swimming "Hand Speed"

Swimming efficiency is dependent to a disproportionate degree on the propulsive forces generated by the upper extremities, specifically the hands. When examining the manner in which the hands are used in swimming, the primary means of swimming propulsion takes place by exerting the hydrodynamic forces referred to as "drag" (Knudson, 2003; Kreighbaum, 1996; Pendergast, Zamparo, Termin, Bushnell, & Paschke, 2005). Drag force, when employed in the water, is dependent on two parameters. The first is the "cross-sectional surface area" of the hands and/or limbs, i.e., the area of the limbs that are held at right angles to the direction of the pull. To generate effective propulsive drag forces, the frontal area of the hands, forearms, and upper arms should be maximized (Schleihauf, 1979; Schleihauf, 2004; Wood, 1979). The second parameter is the "velocity" at which the propulsive limbs are moved. Hand velocity is reflective of the function in swimming described as "stroke rate" (Schleihauf, 2004; Wood, 1979).

If anatomical segments of the hands and limb are missing, swimmers must rely on the cross-sectional areas of the existing limbs to exert the propulsive forces. Consequently, the major adjustment when compensating for limb loss is an increase in "stroke rate," which is reflected by the increase in the rotational speed of the available appendages. This function is demonstrated by comparing the duration of the individual phases of the stroke cycles in swimmers who lack limb segments to that of able-bodied swimmers (Prins, 2006).

For this discussion, three female swimmers were selected, two of whom were classified as persons with amputation, while the third was classified as "non-disabled" (ND). Descriptions of the degree of limb-loss for each of the two swimmers were as follows: Swimmer 1—Single-arm limb-loss, below-elbow (SA): Swimmer 2—Bilateral limb-loss, below the wrist and below-ankle (BW&A).

In terms of anthropometric similarity, all three participants had approximately the same upper extremity limb lengths. On the question of swimming speeds, during data collection, all three swimmers swam at close to the same velocity, approximately 0.35 m/sec. The durations of the different phases of each swimmer's stroke cycle when performing the front crawl are presented in Table 1. These measurements were taken by superimposing the digital "real-time" stamp on the video footage. Because the duration of each video frame is approximately three one-hundredths of a second, the observed time for stroke segment was accurate to 0.03 of a second.

Examination of the absolute durations and the relative percentages of the times taken for the two phases of the stroke, the underwater pull and above-water recovery, provide insight into the manner in which swimmers compensate for limb loss when swimming. Interestingly, when observing the percentage differences between the above- and underwater durations of the stroke cycle, only small differences were seen between the subjects, regardless of the degree of limb-loss. The times taken for the underwater pull ranged between 61% and 69% of the total duration of each swimmer's stroke cycle. The balance of the time was taken for the above-water arm recovery. In light of these data, the intriguing question arose as to what adjustments if any were made in the timing of the stroke by the swimmers with limb loss.

The most noticeable difference in the absolute durations of the stroke cycles between the three swimmers was seen when the nondisabled swimmer (ND) was compared with the swimmer with the most extensive limb loss, i.e., bilateral, below wrist and ankle limb loss (BW&A). The duration of the total stroke cycle for swimmer BW&A was approximately 60% of that of swimmer ND, i.e., 1.57 s

Table 1 Comparisons of Durations and Relative Percentages of Stroke Cycles for Nondisabled vs. Swimmers With Amputation

	Duration of stroke cycle for a single arm (seconds)	Percentage Duration of the "underwater pull phase" of the total stroke cycle	Percentage Duration of the above-water "recovery phase" of the total stroke cycle
Non-Disabled (ND)	1.47 s	1.02 s (69%)	0.45 s (31%)
Single-arm (Right) below-elbow limb-loss (SA).	Nonaffected left arm 1.57 s	1.06 s (67.5%)	0.51 s (32.5%)
	Affected Right arm 1.57 s	0.60 s (38%) ** Pause at entry: 0.41 s (25%)	0.56 s (37.0%)
Bilateral, below the wrist and below-ankle (BW&A).	1.19 s	0.73 (61%)	0.46 (36.8%)

vs. 1.19. As expected, the shorter duration of the stroke cycle was coupled with a much higher "stroke rate" with swimmer BW&A, taking 5 strokes to every 3 strokes taken by swimmer ND.

The primary reason for the increased stroke rate is the absence of the hand and foot anatomic surface area whose major function is to create the necessary propulsive forces. Figures 1a and 1b show frontal and lateral views of swimmer BW&A, with double-hand and foot limb loss. It is apparent that this individual must rely on the cross-sectional areas of the upper arms, i.e., the muscle and soft tissue mass surrounding the upper extremities, for exerting propulsive forces. In the lower extremities, the absence of limb segments below the distal talo-fibular (ankle) joints in both legs impose corresponding constraints for generating propulsive forces that normally are generated from the "flutter-kick."

When comparing the stroke cycles between the nondisabled swimmer (ND) and the swimmer with a single-arm amputation (SA) it was evident that swimmers who have unilateral limb deficits maintain the overall cadence and timing of their strokes by allowing a distinct pause at the point of entry. This allows the affected arm to match the timing of the opposite nonaffected arm, without interruption in the overall rhythm.

Also noted was that although unilateral deficits can affect all four swimming strokes, the effects are more noticeable when observing the strokes that require alternating arm movements, i.e., the front crawl (a.k.a., freestyle) and the back crawl. When comparing the total durations of stroke cycle for swimmers ND and SA, it was evident that although overall durations for each stroke cycle were very similar, varying by only one-tenth of a second (1.47 vs. 1.57 s), differences in timing existed within each phase of a stroke cycle. As indicated in Table 1, when comparing the durations of the underwater pull of the nonaffected arm in swimmer SA to that of swimmer ND, there was relatively no difference, 1.02 vs. 1.06 seconds. When the time taken to complete the underwater pull using the limb amputated below the elbow was compared with that of the nonaffected arm, the duration of the underwater pull phase for the missing limb was considerably shorter, 0.60 vs. 1.06 s for the intact limb.

These changes in the stroke cycle are interesting in so far as they demonstrate the need for swimmers with limb loss to make adjustments to the timing of the arm movements during a stroke cycle, particularly when the particular stroke necessitates alternating arm movements as in the front crawl and back crawl. The data also suggest that to compensate for the reduced limb surface areas, there is a need to increase the stroke rates as a means of generating propulsive forces in the water.

Example 2: The Effect of Limb Loss on Buoyancy and Body Position

One of the most important factors relating to efficient swimming is the need to maintain the best possible body position in relation to the surface of the water. The optimum alignment of the body necessitates that the torso be held in a longitudinally extended orientation, close to the surface. A swimmer's natural buoyancy will be the primary determinant of this posture. Because of the difference between the body's "center of gravity" and "center of buoyancy," a rotating moment is created

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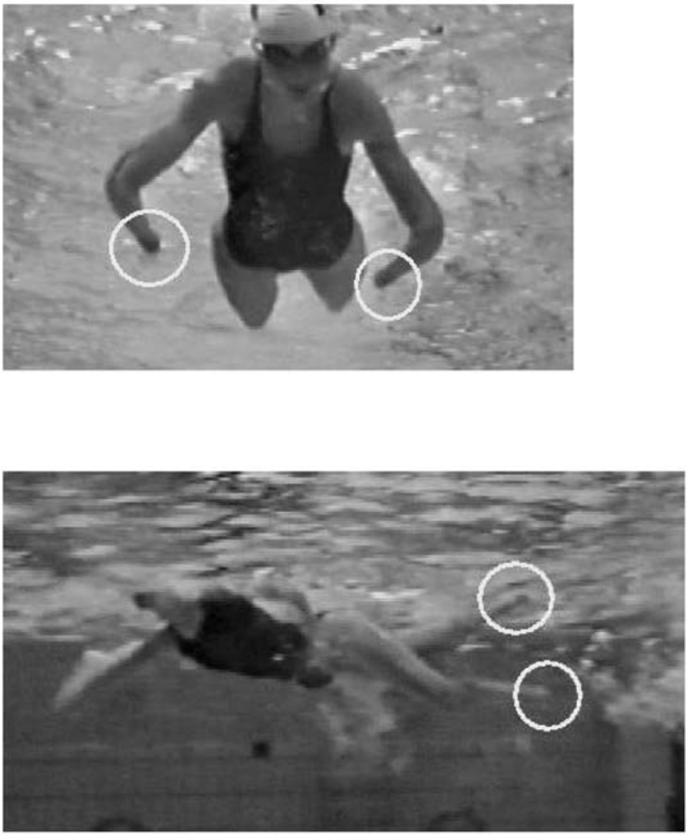

Figure 1 — *a & b* Frontal and lateral views of swimmer with congenital amputation of hands and feet.

when lying motionless in the water either in the prone or supine position (Kreighbaum, 1996; Schleihauf, 2004).

Because is difficult for most persons to lie horizontally on the surface while floating motionless, most swimmers need to generate some amount of propulsive force to compensate for their lack of buoyancy. Under normal swimming conditions, the different kicking patterns employed with each of the swimming strokes help maintain a horizontal body position close to the surface. An inability to use the legs in the prescribed kicking patterns, as is the case with swimmers with permanent physical disabilities, often results in a significantly altered body position. Figure 2 is a lateral view of a swimmer diagnosed with Cerebral Palsy. In this example, the weight of the lower extremities coupled with the inability to use the legs for generating propulsive force, resulted in both the torso and legs sinking. This altered position increases frontal resistance. The degree to which the body position has altered with respect to the surface can be measured using motion analysis software, as shown in Figure 2.

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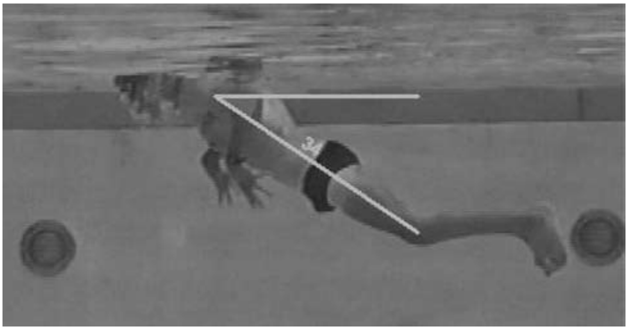

Figure 2 — Lateral view of swimmer with Cerebral Palsy demonstrating low body position (34 degree inclination to the surface),

It should be noted that not all swimmers who lack lower extremity control will float with body positions in which the torso and the lower extremities sink as a single entity. The swimmer shown in Figure 3, diagnosed with quadriplegia, is floating motionless in the water. In this prone floating position, we see his upper torso is maintained in a horizontal position close to the surface, while only the unsupported legs tend to sink.

In contrast to the increased resistance contributed by the lower extremities whose muscles cannot be activated, the loss of both lower limbs, as in the case of "below-the-hip" amputees, creates a unique condition with respect to body position and propulsion. Because a swimmer without legs no longer has to contend with the weight of the lower limbs, the upper torso can maintain a near horizontal body position with respect to the surface, as seen in Figure 4. The result is a posture with greatly reduced frontal resistance and a considerably reduced body mass, requiring less effort be expended by the arms during propulsion. It must be remembered that although frontal resistance is dramatically reduced, there is an obvious tradeoff; in this case, it is the inability to recruit the lower extremities for

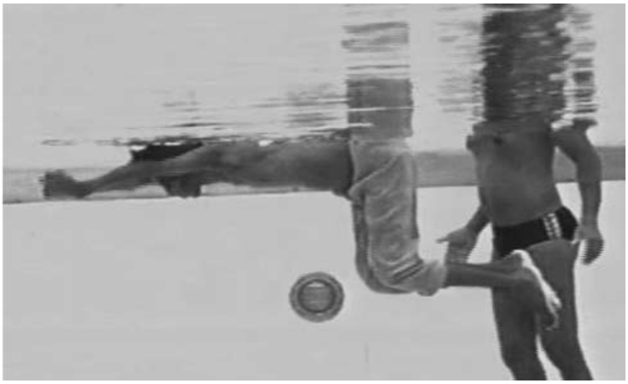

Figure 3 — Swimmer with quadriplegia floating motionless in the prone position.

Figure 4 — Swimmer with double, below-the-hip amputation, demonstrating the ability to float almost horizontally near the surface.

propulsion or to counteract rotational forces created by the upper extremities (Counsilman, 1994; Deschodt, Arsac, & Rouard, 1999).

Example 3: The Effect of Limb Loss on "Body Alignment"

Body alignment is an essential feature of efficient swimming. Not only is it necessary to maintain a position that is as close and horizontal to the surface as possible, it is also important to hold the body in a straight or longitudinal alignment during the time the arms and legs are used for propulsion. The consequences of optimal versus misaligned postures can be observed when swimmers are viewed from "head-on" as they move toward and away from the camera. For efficient movement through the water, the frontal profile of the swimmer must be reduced to minimize drag forces. Conversely, as the torso and body parts move more laterally during the stroke cycle, there is a greater frontal profile, resulting in a reduction in swimming velocity due to increased form drag.

When swimming front crawl, two factors contribute to maintaining an optimum longitudinal orientation. The first is the position of the hand with respect to the head and shoulders as it is introduced into the water. To minimize lateral body motion, the hand entry should be made between the midline of the face and the tip of the shoulder on the ipsilateral side, i.e., the side of the body of the observed hand. The second factor is the contribution of the "flutter kick." The primary role of the kick in the front crawl is to maintain body position close to the surface and provide lateral stability to the torso during both the above-water arm recovery phase and the period of the underwater pull.

When observing the contributions of the kick to longitudinal orientation of the body in a nondisabled swimmer, the degree to which the hips and torso swing laterally would be dependent on the stabilizing effect of the flutter kick. The more effective the kick, the less the lateral drift of the torso. An effective kick, while providing propulsion, would also use optimum amplitude; that is, it would not sink too deep in the water.

The degree to which the hand entry and the flutter kick contribute to body alignment can be demonstrated by examining the front crawl stroke mechanics of a swimmer with congenital loss of the right lower leg, below the knee. When observing this swimmer's hand entry, it must be noted that she is introducing her hands into the water at a point that is "too far across" the midline of her face, as seen in Figure 5.

Example 4: Examination of Stroke Mechanics in Swimmers With Paraplegia

Paraplegia is a condition in which the lower part of a person's body lacks neuromuscular control resulting in paralysis. It is usually the result of spinal cord injury or a congenital condition such as poliomyelitis or spina bifida, (Daly, 1999; Davis, 1993; Lepore, Gayle, & Stevens, 2007; Sherrill, 1999; Wu & Williams, 1999). When a swimmer with paraplegia assumes a prone position in the water, the existing flaccid paralysis can result in the hip and knee joints maintaining a flexed posture, changing the alignment of the body. What occurs during swimming is that the propulsive forces produced by the arms, coupled with the force of the water acting against the lower limbs, causes fluctuations in the lower extremities as swimming speeds vary during each phase of the stroke cycle (Prins, 2006).

When examining the oscillating movements of the legs in the sagittal plane, which occur primarily at the hip and knee joints, it is evident that during the course of each stroke cycle, the alternating degrees of flexion and extension are a function of swimming speeds. The lower limbs start extending as propulsive forces build, reaching maximum extension when maximum swimming velocity is achieved. As the velocity begins to slow, the limbs start to bend, reverting to the initial flexed position. As discussed earlier, although floating limb positions are contingent on the natural buoyancy of each individual's lower extremities, the ensuing degrees of hip and knee motion are an indicator of the efficiency of the propulsive forces produced by the hands. For swimmers who lack lower extremity control, we may be able to gauge the effectiveness of the individual's stroke mechanics by observing the rhythmic fluctuations in the angular translations of the lower extremities throughout the stroke cycle. This offers a unique opportunity to observe swimming stroke efficiency, an avenue of investigation that has not previously been explored.

Figure 5 — Extreme rotational movements of the torso as a result of single-leg amputation and exaggerated arm entry.

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A swimmer with Guillian-Barre Syndrome (GBS), which resulted in permanent paraplegia, illustrates these findings. Guillain-Barre Syndrome is described as an “acute idiopathic polyneuritis, meaning the condition has unknown causation, thought to be of viral origin, and affects a large number of spinal nerves. The affected participants show marked paresthesia of the limbs, muscle weakness, or in severe cases, flaccid paralysis (Green & Ropper, 2001). This swimmer presented flaccid paralysis from the waist down and, consequently, had no control over the musculature of the lower torso including the pelvic region. Because the sensory neurons to the upper extremity were unaffected by either condition, his ability to perform the required pulling patterns for each swimming stroke was unimpaired.

Biomechanical analysis was used to examine how swimming speeds were affected by the manner in which the hip and knee joints oscillated during a series of swimming stroke cycles. Following a prescribed 2D calibration procedure, the individual’s front crawl stroke was videotaped from underwater. The footage was then analyzed using motion analysis software (Vicon-Motus, Denver, CO), resulting in the calculation of kinematic variables. It this case, changes in linear velocities, together with concurrent changes in angular displacements of the hip and knee joints were examined during two stroke cycles. The software also permits segmental “stick figures” to be superimposed over the video images. Once the data are processed, a “report” can be generated for viewing the selected parameters together with the corresponding video footage. Reports allow the synchronization of the selected video segment with a graph that shows how the selected variables change during the elapsed time.

In this example, the changes in hip flexion as a function of the horizontal swimming velocity were examined. Figures 6 and 7 show “Reports” generated from data obtained from two stroke cycles of the front crawl performed by the swimmer diagnosed with GBS. When “time” is chosen as the independent variable, a vertical line scrolls horizontally across the graph, synchronizing each video frame with the variables selected for monitoring. Using this feature and selecting the corresponding still frames from the accompanying video segments, the following information was extracted from the analysis of the GBS swimmer. In Figure 6, the vertical line in the graph indicates the point at which the velocity of the hips has significantly slowed down. The corresponding video clip (see IJARE on-line for the video) shows this time-interval coinciding with the hand preparing to exit the water, a position usually seen at the conclusion of the propulsive phase of the pull and one that should result in maximum propulsive force. In this case, the hand has not been used effectively to produce propulsion at the conclusion of the pull, resulting in a pause in forward motion. The video frame also shows the hip angles close to maximum flexion, caused by the lower extremities sinking due to the reduction in forward motion. Figure 7 shows the opposite scenario (see IJARE on-line for the video). The selected video frame indicates the point where the hands were able to produce a relatively high propulsive force and consequently generate a high hip velocity. The result of this increase in forward motion is that the lower extremities were moved backward to where the angles of the hips and knees assumed more extended positions.

By observing these two extremes in body orientation, we can deduce that the resulting fluctuations in lower extremity limb position are the consequence of

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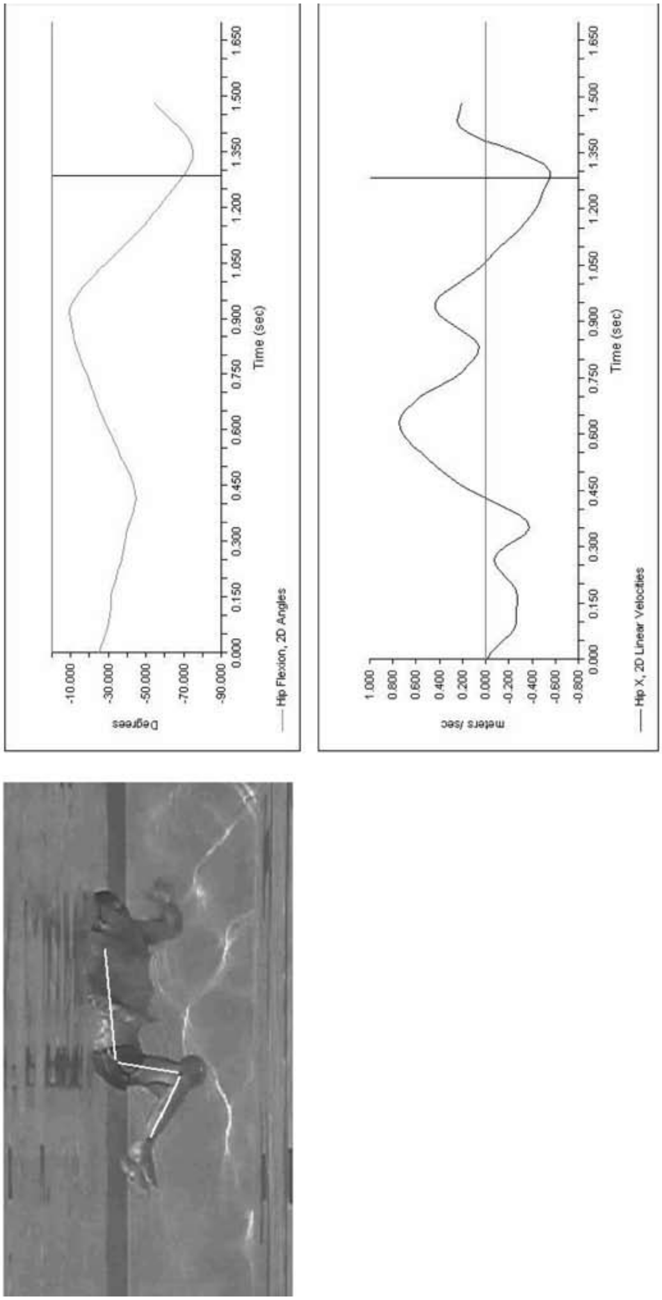

Figure 6 — Motion analysis report of GBS swimmer at the lowest relative swimming velocity.

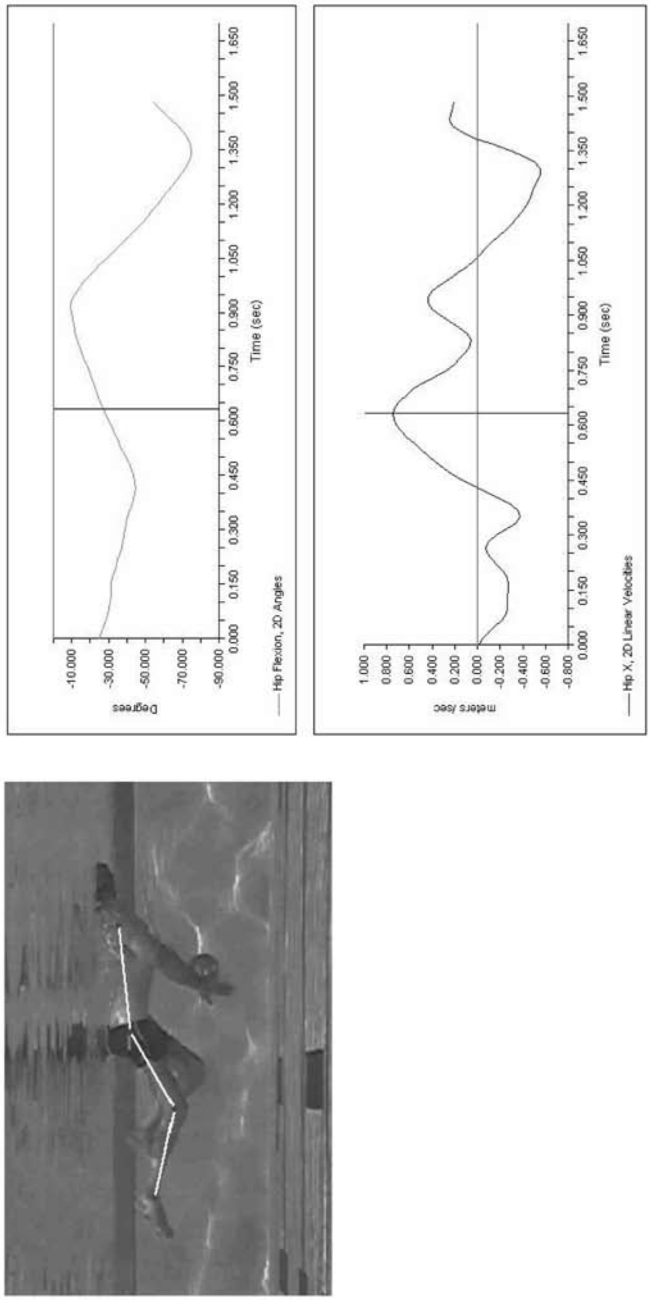

Figure 7 — Motion analysis report of GBS swimmer at the highest relative swimming velocity.

varying degrees of propulsive efficiency. Therefore, it should be possible with effective instruction and subsequent practice for this swimmer to produce measurable reductions in the periodic oscillations of hip and knees during the stroke cycle. These reductions in lower extremity motion could be viewed as an objective indication of improved swimming stroke mechanics.

Example 5: The Role of Hydrodynamic Lift in Swimming as Observed in Swimmers With Congenital Birth Defects

Current theories of human swimming propulsion are in agreement that humans use a combination of "drag" and "lift" forces to produce movement in the water (Counsilman, 1994; Keskinen & Komi, 1993; Knudson, 2003; Kreighbaum, 1996; Schleihauf, 1979; Schleihauf, 2004). "Drag" forces, when associated with whole body motion, are usually identified with a reduction in an object's velocity as it moves through a fluid and, consequently, these forces are typically viewed as a deterrent to forward motion. "Drag" forces can also be employed for propulsion. In a manner similar to a paddle or oar, the hands can push backward through the water to move the body forward (Schleihauf, 1979). "Lift forces," in contrast, do not require that the water be pushed or pulled backward to move the body forward. Although technically more complicated, practical applications of lift forces are numerous. The undulations of the wings of birds or fins of fish, either to hover or when used for propulsion, are examples of "lift" forces occurring in nature (Vogel, 2003). Although debate continues as to the relative contributions of each force in swimming in humans, good examples of lift forces can be seen in both the arm and leg movement patterns used in the breaststroke and butterfly.

When observing the stroke mechanics in individuals with congenial birth defects, it is evident that persons with these conditions develop unusual propulsive patterns when swimming. As discussed earlier, some of the swimmers with amputations or congenital limb malformations rely on drag forces, pushing the water back in a paddling motion. Others are unable to produce sufficient drag forces or are incapable of performing even small degrees of linear translations with their upper extremities for swimming propulsion. Because they are unable to move their limbs in straight-line paths for even short distances in the water, they cannot push the water backward, particularly during segments of the front crawl and backstroke stroke cycles that are known to benefit from these movements. Instead, these swimmers use the available upper and lower extremities to perform sophisticated sculling movement patterns for propulsion (Prins, 2006).

Figure 8 shows the upper and lower anatomical characteristics 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 preclude his ability to perform sufficient amounts of what could be described as a "paddling" action, thereby applying primarily drag forces, either with the upper or lower extremities. Consequently, he has to rely exclusively on rotational and/or sculling-type movements, which are effective because they allow him to employ a combination of both types of propulsive forces, i.e., "drag" and "hydro-dynamic lift" (Schleihauf, 2004).

Another unique example of lift forces being used as the predominant means of propulsion in the water is used by a subject diagnosed with the condition

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Figure 8 — Frontal view of swimmer with extreme congenital limb loss.

Figure 9 — Frontal views of swimmer with TAR syndrome.

referred to as Throbocytopenia Absent-radius Syndrome (T.A.R. Syndrome). This particular syndrome is identified as resulting from an autosomal recessive gene and is characterized by the absence of upper extremity limb segments (Hall, 1987; Ray, 1980). The swimmer was a 12-year-old male who started swimming at the age of seven. He lacks both the humerus and radio-ulnar bones in the upper extremity and the structural abnormalities of his lower extremities limit his ambulation on land (Figure 9). Being restricted to circular, rotating movements in the water demonstrates his need to rely exclusively on "sculling" movements.

Conclusions

There has been limited research with regard to the swimming stroke mechanics of persons with permanent physical disabilities. By employing the current technology used in biomechanical analysis, we studied the variations in swimming propulsion

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DOI: https://doi.org/10.25035/ijare.02.04.06

of these special groups of swimmers. It is apparent from the observation and analysis of the underwater stroke patterns of these swimmers that they have developed unique modifications to traditional swimming strokes. With increased awareness of these modified stroke patterns, it may be possible to improve the methods of teaching aquatic skills to persons with permanent physical disabilities.

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DOI: https://doi.org/10.25035/ijare.02.04.06