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How Can Asymmetries in Swimming be Identified and Measured?

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Abstract

This paper reviews methods of identifying and measuring asymmetries in swimmers. A model of factors associated with testing asymmetries in swimming was used as a basis for discussion. The testing includes 'dry-land 'assessment and assessment of the swimmer while swimming.

Introduction

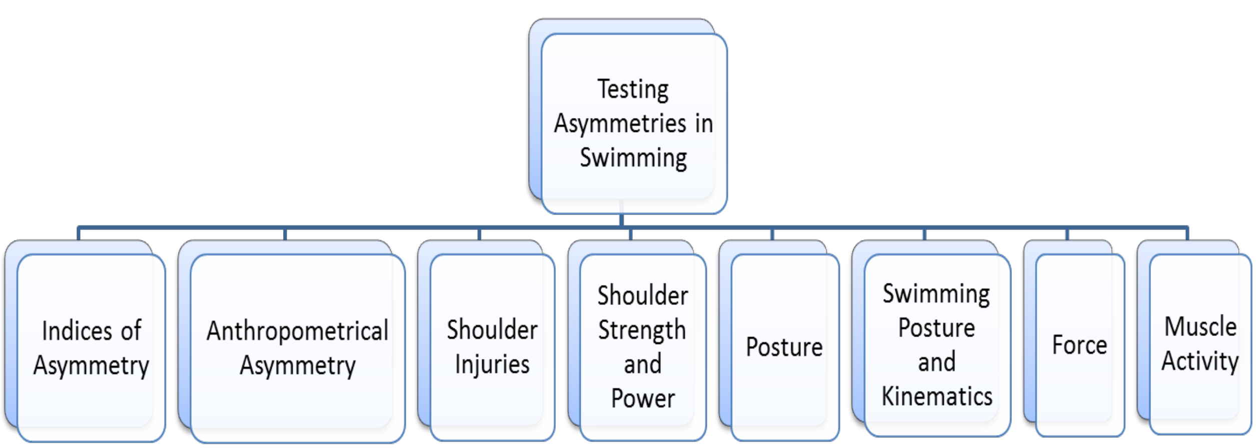
Four general questions need to be addressed with regard to asymmetries in swimming.

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

Sanders, Thow and Fairweather (51) reviewed literature relating to the first question. In this paper the issue of how asymmetries can be identified and measured is reviewed and discussed.

When considering what variables should be recorded or measured reference to the model below is useful.

Figure 1. A Model of Factors Associated with Testing Asymmetry in Swimmers



Indices of Asymmetry

There are a wide variety of variables that can be measured to indicate asymmetry. To enable the measures to have meaning and comparability across individuals and populations, some indices have been developed. Carpes (7) cited a simple formula that is frequently applied to obtain a 'symmetry Index' (SI) as the difference between right and left sides as a percentage of the mean magnitude of the variable:

$$SI\% = ((R-L)/(R+L))*2*100$$

If wishing to obtain mean levels of asymmetry across a sample in which the direction of asymmetry is not important, absolute values may be used. A variation of the same principle is to divide by the maximum of the two values obtained for the right and left sides:

$$SI\% = ((R-L)/(\max(R,L)))*100$$

Anthropometrical Asymmetry

Asymmetries can present themselves in an individual's anthropometry, for example leg length discrepancies (60) and differences in limb sizes, particularly in athletes competing in unilateral sports such as tennis (46). Several methods exist for quantifying anthropometry and therefore anthropometrical asymmetries. A robust methodology to minimize errors, accurately calibrated equipment, and appropriate marking of body landmarks are crucial to the interpretation of data singularly and longitudinally.

The International Society for the Advancement of Kinanthropometry (ISAK) (34) has a standardized protocol that allows detailed quantification of limb lengths, breadths and circumferences alongside skinfold measures, using simple and portable equipment. These measures allow for identification of an asymmetry and also an understanding of the composition of the asymmetry. In high performance sport, the compositional element is of high importance to athletes. A limitation of the ISAK method is that the standard protocol is to take measurements on only the right side of the body. Therefore, a repetition of the protocol on the left side would be required to measure asymmetries.

Technological advances have led to developments of more sophisticated equipment for anthropometrical assessment. For example, three-dimensional laser scanners use laser technology to scan the entire body surface and provide a detailed analysis of the body's shape and volume. A limitation of 3D scanners is that they are unable to provide a direct measure of the composition of the body, i.e. they are unable to distinguish between adipose and other body tissue.

However body composition can be assessed in other ways. Dual-emission X-ray absorptiometry (DXA) passes an x-ray beam in a posterior-to-anterior direction through the bone and soft tissue of the subject lying in a supine position and (58).

DXA scans allow detailed assessment of both body shape and composition, including the bone density, mass and composition of individual limbs. Furthermore, because the scan occurs in the supine position, it negates the influence of posture for asymmetry analysis. The actual methods used to measure anthropometrical asymmetries will depend on the availability of time, equipment, access to the subject and budget.

Shoulder Injuries

Given the cause and effect relationships among muscle and joint function, asymmetry, and injury of the shoulder joint, many assessement procedures have been developed. Researchers commonly use questionnaires as well as clinical examination of posture and muscle/joint function, and isokinetic testing of internal and external rotation (48).

Questionnaire questions:

Gender; age, years of competitive swimming; age of commencing competitive swimming; weekly training hours; average daily swimming distances; preferred hand; current status with respect to shoulder pain; history of shoulder pain; severity of shoulder pain.

Clinical inspection:

Rupp (48) outlined a number of tests to perform during a clinical inspection of the shoulder: scapular winging; palpation for swelling; painful 'trigger' points and crepitus; active and passive range of motion (internal and external rotation and retroflexion); internal and external rotation arm at side; internal and external rotation with the arm at 90 degrees abduction; Neer (39) test for mechanical impingement; Hawkins and Abrams (21) test for mechanical impingement; apprehension sign with the arm abducted at 60, 90, 120 degrees; anterior displacement and relocation test for sulcus sign for multidirectional instability; Yergason test and palm-up test for bicipital tendinitis.

Lewis (33) described a number of useful tests for identifying impingement indicated by pain. These include the Neer (40) 'impingement sign' in which the subacromial tissues are deliberately compressed under the acromonion while stabilising the scapula; The Hawkins and Kennedy (22) impingement test in which the shoulder is internally rotated while flexed at 90 degrees and at various positions of horizontal abduction; the 'empty can' test (28) to check for supraspinatus pathology involves abducting the shoulder to 90 degrees, applying resistance to further abduction and then internally rotating to point the thumb downwards; the 'painful arc shoulder movement test' (29) involves the patient actively abducting the arm between a range including 60 to 120 degrees of abduction; palpation of the supraspinatus tendon at the greater tuberosity of the humerus (5) accessible from under the accromion to a point anterior to the acromioclavicular joint when the hand is placed behind the back with the arm adducted against the chest.

Lewis (33) described tests for laxity of the shoulder joint including the 'sulcus sign test' for inferior laxity (19) indicated postively by an 'excessive' sulcus appearing under the acromion when the clinician grasps the forearm below the elbow and applies downward traction to the shoulder; 'load and shift test' for anterior and posterior laxity (23) of the humeral head on the glenoid fossa in which the clinician gently pushes the humeral head into the glenoid fossa while stabilising the clavicle and scapula and then applies anterior and posterior pressure to observe the translations.

To examine general joint and shoulder laxity and mobility of competitive swimmers and normal controls Jansson (25) performed five manoeuvres according to the scoring system of Beighton (3):

1. Passive opposition of the thumb to the flexor aspect of the forearm (right and left).
2. Passive hyperextension of the fifth finger to >90 degrees (right and left).
3. Hyperextnsion of the elbow > 10 degrees (right and left).
4. Hyperextension of the knee >10 degrees (right and left).
5. Flexion of the trunk with knees extended , and both palms resting on the floor.

Shoulder Strength and Power

Force, torque and power can be measured on land using dynamometers including sophisticated systems such as 'Kin Com', Cybex', and 'Biodex'. These machines can measure torques at preset joint angular velocities. This is termed 'isokinetic' testing. For assessment of shoulder strength in swimming, Rupp (48) recommended concentric internal and external rotation at 60 degrees/s and 180 degrees/s with humerus abducted to 90 degrees and elbow flexed to 90 degrees with range of motion limits of 40 and 50 degrees respectively.

These machines can be very useful for indicating strength asymmetries that may affect swimming technique and performance. For example, Torney-Chollet (56) found that the shoulder with the higher internal rotation strength also had a longer catch and pull phase duration than the non-dominant arm among expert front crawl swimmers. Fowler (17), reported in Fowler (18), found that swimmers had significantly greater imbalances between internal and external rotator strength than the controls due to a significantly greater strength of the internal rotators.

Impellizzeri (24) found that while the reliability of the Cybex NORM dynamometer was high for peak torque and average work measurements of quadriceps and hamstrings, strength imbalance ratio reliability indicated by intra-class correlation coefficents were low to moderate with standard errors of measurement of 3.2% to

8.7%. Thus, interpretation of data from isokinetic dynamometers must be preceded by studies of reliability for the muscles being studied, particularly where muscle imbalance ratios are quantified.

Posture

Postural alignment of the spine and body is often measured by land based measures including the spinal angles of lordosis and kyphosis. Postural alignment and status is recognised as a malleable circumstance and research has shown that a significant change in lordosis spinal angles has a concurrent effect upon kyphosis spinal angles (6, 15). Lewis and Valentine (32) reported a simple and reliable quantitative method that measures thoracic kyphosis using two gravity-dependent inclinometers. One inclinometer is attached to the region of the 1st and 2nd thoracic spinous processes and the other to the region of the 12th thoracic and 1st lumbar spinous processes. Lewis & Valentine (32) suggested that whilst the angle of kyphosis may not affect the shoulder range, the joint/soft tissue stiffness associated with kyphosis could affect shoulder range.

Postural and spinal measurement processes can vary from qualitative (e.g., New York State posture rating scale) to quantitative (e.g. 32, 59). Key factors influencing the reliability of postural form include subject awareness of the assessment process. Fairweather and Sidaway (15) suggested that orientating the subject's attention to a distracting circumstance such as walking gait reduces the likelihood of subject's manipulating their postural form when standing still during postural assessment, thereby increasing the reliability and validity of the testing process.

Measurement of the sagittal curves (lordosis and kyphosis) can be important as a land based measure when assessing longitudinal response. However, the transfer relationship of land based postural status to pool based postural response and body positioning is unclear. The interactive postural alignment effects of land based training, swimming training and competing on postures adopted during swimming requires investigation. As such, the capability of land based postural measurement in explaining dynamic postures in swimming must be established in conjunction with the effect on performance. This has major implications for evaluating the efficacy of training and/or postural interventions to improve swimming performance.

Kluemper (30) devised a simple test to measure 'forward shoulder' posture among swimmers. This is associated with strengthening of the anterior shoulder muscles that is not balanced by equivalent strengthening of the posterior shoulder muscles. The test uses a 'double square' instrument to measure the distance of the anterior tip of the acromion process from the wall against which the swimmer stands facing outwards. The square is simply a builder's square with the square projections sliding along a graduated steel rule. One square is placed vertically along the wall and the other suspended vertically from the rule to make contact with the marked anterior tip of the acromion.

To measure scapular upward rotation as an indicator of shoulder mobility in baseball players Downar and Suers (13) used a digital inclinometer which was reported to have sufficient reliability to enable just one measurement per subject. Standard goniometers were used to measure internal and external rotation. Inclinometers were also used by Lewis (33) to determine throacic kyphosis angle as the sum of the readings obtained from placing the inclinometer along the spinous processes of T1-T2 and T12-L1.

The movement of the thoracic spine contributes to, and is essential for, shoulder movement – Crawford and Jull (9) noted that 15° of thoracic extension is required for full bilateral arm elevation. Scapular dyskinesis, that is, abnormal movement of the shoulder blade, has also been found in some overhead athletes with shoulder pain, and in these cases it has been shown that there is a decrease both in temporal characteristics of activation and recruitment patterns of the lower trapezius. This effect on scapular asymmetries and upon dynamic stabilisers of the scapula was shown bilaterally and is therefore likely to be related to a more central spinal source (8).

Oyama (43) described the use of a 'Motion Monitor' electromagnetic tracking device (Innovative Sports Training, Inc., Chicago, IL.) to quantify the resting position of the scapula in three-dimensions based on digitising anatomical landmarks with a stylus. The landmarks used are: spinous process of the 7th cervical vertebra, the flat portion of the acromion process bilaterally, and the midshaft of the posterior humerus bilaterally. Using this device it was found that, in all the overhead athletes tested, the dominant side scapula was more internally rotated and anteriorly tilted than than the scapula on the non-dominant side.

Niekerk (41) defined various angles to assess the posture in a seated position using standard digital photgraphy and digitised marked body landmarks. The measures included sagittal head angle, cervical angle, protraction/retraction angle, arm angle, and thoracic angle. The angles obtained using the digitised photograph method correlated well with angles measured from radiographs using a LODOX (LODOX Pty. Ltd.) system except for the shoulder protraction/retraction angle.

Blanch (4) reviewed methods of testing flexibility relevant to swimming performance and injury while warning that the tests had yet to be scientifically validated. The tests included measures of abduction with internal rotation, related to the ability of the swimmer to achieve a high elbow throughout the front crawl stroke cycle; thoracic rotation, important in the pull phase of front and back crawl; glenohumeral internal rotation, important for making an early catch with the elbow high throughout the stroke; combined elevation involving thoracic spine extension, shoulder extension, and the ability to draw the shoulders back, important for achieving a high elbow position at the start of the stroke, recovery, and for attaining a streamlined position; hip internal rotation and tibial external rotation, relevant for breaststroke swimmers to enable a large surface area to generate force in the kick;

hip extension; and ankle plantarflexion. The protocols for the series of tests are presented and are clearly simple and expedient.

Schiller and Eberson (52) reviewed spinal deformity in athletic activities. Scoliosis of the spine can be measured by the Cobb method which relies on the ability to extrapolate lines parallel to the end plates of the vertebrae. While this can be done readily from X-Rays, it is less accurate when relying on palapation. However, visual inspection when the subject bends forward with legs together and arms hanging can reveal the presence of scoliosis as asymmetries in rib or paraspinal muscle height. Driscoll and Skinner (14) suggested that asymmetries of spinal origin can be manifest in observable features such as pelvic obliquity, shoulder girdle asymmetry, waist crease asymmetry, rib prominence, asymmetry with spinal flexion, and leg length discrepancy.

Swimming Posture and Kinematics

To examine the posture and kinematics during swimming, digitisation of video recordings is commonly used. The methods can be categorised into two-dimensional (2D) approaches and three-dimensional (3D) approaches. Two-dimensional approaches can be conducted with just one camera placed with its optical axis perpendicular to the plane of the motion of interest. However, more than one camera is often used to obtain above and below water views or different perspectives simultaneously, for example, front and side views. 3D approaches require muliple camera views and calibration of the 3D space in which the motion occurs. If data from both below water action and above water action are sought a minimum of four cameras (two above and two below), synchronsied to sample at the same instant, are required.

2D methods are much less time consuming to set up, calibrate, and process the data, than 3D methods. However, 3D methods enable mathematical transformations to any perspective and reference frame whereas 2D analyses are limited in the flexibilty of the measurements that can be made. Further, 2D methods are generally less accurate and reliable due to errors in measuring any movement or positon that is not within the plane that has been calibrated. In both methods automatic tracking of marked landmarks is problematic, particularly for underwater views where a reduction in contrast and interference of the image with bubbles and turbulence are prevalent. Therefore, manual digitising, or a time-consuming combination of automatic tracking and manual digitising, is usually required for all but the most simple scenarios with small numbers of points to be digitised.

<u>Examples of Two-Dimensional Video-Based Approaches to Studying Asymmetry</u>

Seifert (53) used 2D analysis techniques with one camera capturing above water motion and one camera capturing below water motion of 11 expert male swimmers. The duration of the gap between the end of propulsion of one hand and the beginning of propulsion of the other hand yielded an index of coordination (IdC) for the preferred side (IdC_P) and the non-preferred side (IdC_{NP}). A symmetry index (SI) was defined as:

$$SI = (IdC_P - IdC_{NP})/0.5(IdC_P + IdC_{NP})) \times 100$$

The SI revealed that breathing to the preferred side creates a greater asymmetry than breathing through a frontal snorkel, no breathing, and bilateral breathing. Breathing to the non-preferred side created an even greater asymmetry.

Using similar 2D approaches and the IdC and SI quantification methods, Tourney-Chollet (56) found that the relative duration of the catch and pull was greater for the dominant arm (51.7%) than the non-dominant arm (48.4%). Similarly, Barden (2) used 2D video approaches to examine the temporal symmetry of the power and recovery phases of eight Canadian swimmers swimming front crawl at paces less than and greater than the speed corresponding to the anaerobic threshold. They found that the increase in stroke rate associated with swimmming at critical speed causes a decrease in the duration of the power phase and the power/recovery ratio and a decrease in the asymmetry of the power phase. Thus, 2D methods can be useful to indicate temporal asymmetries in the coordination of the stroke. Results of these studies also highlight the need to consider swimming pace when assessing the presence of asymmetries.

Czabanski and Koszczye (10) used a 2D method named 'cyclophotography' involving the photographic recording of light bulbs attached to swimmers' heels. While the method of data collection has been superseded by modern video technology, the method of quantifying the asymmetry could remain effective. Their asymmetry index was based on the sum of differences in displacement of the right and left heels from constructed X and Y axes. The Y axis is constructed as the line joining the midpoints of the traces when they are closest to each other near the commencement and completion of the kick. The method was effective in conclusively establishing that asymmetry is present among most breaststroke swimmers and that it increases with swimming speed.

Thow (55) used a multi-perspective 2D videographic approach to establish a battery of kinematic variables that change in response to strength deficits, including those induced by fatigue, in front crawl swimming. These variables include the duration of the pull phase (s), the depth of the pull (m), the bodies horizontal alignment (°) and the shoulder roll maximum angle (°). Simple measures of posture and limb positions are digitised from the video frames corresponding to meaningful and indentifiable temporal events. The measures can be obtained readily from commercial packages such as Dartfish, Quintic, and Silicon Coach. The battery of tests can be used to identify asymmetries and postural deficits during swimming and to assess changes over the course of a race due to fatigue.

Naemi and Sanders (37) developed a 2D video approach to quantify sagittal plane postures during the glide phase of starts and turns. The method employs automatic tracking of joint markers during the glide. A 'glide factor' indicating glide efficiency is calculated based on the rate of deceleration of the body during the glide. By asessing the postures in relation to the glide factor combined with qualitative inspection of the video using 'Glidecoach' software (38), feedback is given to the swimmer to modify their posture and maximise glide performance.

Examples of Three-Dimensional Video-Based Approaches to Studying Asymmetry

Three-dimensional video techniques have been used by Nikodelis (42) to assess the phase durations of front crawl swimming among elite and novice swimmers. Psycharakis and Sanders (45) used 3D analysis techniques to quantify shoulder and hip roll, observing that asymmetries were related to breathing side preference even in non-breathing cycles. One of the advantages of using 3D analysis techniques to measure roll is that the roll of the shoulders and hips can be quantified separately. Psycharakis and Sanders (45) showed that hip roll was much less than shoulder roll. Separate quantification of shoulder and hip roll enabled Sanders and Psycharakis (50) to investigate coordination and rhythm in swimming, in particular the transmission of body waves. Among the findings was that the composition of the rhythmical motions are related to swimming efficiency and performance. If asymmetries disrupt the rhythmical motions of the body waves then performance may be affected through this mechanism in addition to the effects of posture on resistive drag.

Sanders (49) has developed 3D analysis programs to calculate many variables of interest when assessing asymmetry and performance in swimming. These include indirect calculation of net forces and torques. To maximise the accuracy of the derived kinetics centre of mass calculations are obtained using customised software (11) that employs the elliptical zone method (27). Angles describing limb and body orientations are calculated as continuous functions of time throughout the stroke cycle.

Force

Information on the force that a swimmer produces throughout an individual stroke provides an insight into the effectiveness of their technique, as it can be used to explain the magnitude of intra-stroke velocity fluctuations that are evident within a swimming stroke. Methods of measuring force and power output in swimming may be categorised as direct or indirect techniques. The former includes measurement of swimmers actually swimming, and measurement of forces and power of simulated swimming actions on land using devices such as swim benches.

Direct Measurement of Force in Simulated Swimming

Jaszcak (26) used a swimming ergometer (Weba, Germany) to measure the forces applied to hand pads during simulated front crawl and breaststroke actions. The system was instrumented with strain gauges mounted between the pads and the ropes enabling separate measurement of the force output by each hand. A coefficient of dynamical asymmetry was applied;

$$Asym = 1/N \sum_{i=1}^{N} (X_{Li} - X_{Ri})$$

Where: Asym is the coefficeint of dynamical asymmetry; N is the number of samples in a cycle; X_{Li} is the force generated by the left upper limb; and X_{Ri} is the force generated by the right upper limb.

This was normalised to the maximum force generated. Using these techniques to test adult male (15) and female (21) students it was found that relative asymmetry was 9% and 8% for males and females in breaststroke and 12% and 14% respectively in front crawl. These techniques revealed that there was less dynamical asymmetry in breaststroke than in front crawl for both males and females.

Direct Measurement of Force in Swimming

Direct force measures in swimming generally involve some limitations leading to error. Swimmers can be tethered and the net force measured by force transducers connected to the tether. However, there is a concern that the forces generated by a tethered swimmer are considerably different from those generated in free swimming due to the different velocity of the swimmer relative to the water. Also, because the tether is attached to a point of the body, for example, the hips, it does not represent the effect of the propulsive actions on the acceleration of the centre of mass. Despite the limitations of tethering techniques, they can be useful to indicate whether the limbs on one side of the body generate more force than those of the other side.

A popular method of measuring active drag is the Meaurement of Active Drag (MAD) system (57). The system comprises a set of instrumented underwater plates against which a swimmer pushes using stroking actions resembling the front crawl. At constant speed the impulse (time integral of force and equivalent to the change in momentum of the swimmer) applied is equivalent to the impulse resisting the swimmer and therefore enables the active drag to be determined. Unfortunately, the swimmer’s technique is altered by pushing against the plates, the mechanism of generating force differs from that of pushing against the water, and the kick is not considered as athletes hold a pull buoy between their legs. Further, only the front crawl can be analysed. However, the system is useful in quantifying the swimmer’s resistive drag and indicating bilateral asymmetries in generation of force in front crawl.

Kolmogorov and Duplischeva (31) developed a system to quantify the net active drag force in all swimming strokes, in almost a free swimming condition. Subjects swim twice with maximal effort, once swimming free and once towing a hydrodynamic body that creates an additional, known resistance. The difference in velocity achieved in the two conditions is used to estimate active drag. The limitation of this method is that the intra-stroke velocity fluctuations and therefore the drag force fluctuations aren't quantified.

A recent development by Mason (35) involves direct measurement of net forces acting on a swimmer throughout a stroke cycle with a reduced level of tethering, as well as towing the swimmer at a slightly higher velocity than their maximal swimming velocity. This method allows for quantification of active drag and propulsive forces throughout a stroke cycle. While validation is incomplete, the method appears promising. Formosa (16) used the towing method to identify left to right asymmetries in the timing and magnitude of maximum and minimum net forces during a freestyle stroke and found that half of their elite male cohort produced asymmetrical stroke patterns.

Impulse generated by the hands during swimming can be indicated by pressure transducers attached to the swimmer's hands (20, 54). These can be useful in showing bilaterally asymmetrical production of force and impulse generated by the upper limbs of swimmers while swimming in a relatively natural and unconstrained manner.

Indirect Measurement of Force and Power in Swimming

Given that net force of a swimmer is equal to the acceleration of the centre of mass of the body multiplied by the swimmer's mass, estimates of force can be obtained by double differentiation of the whole body centre of mass. The accuracy of the estimate depends on the accuracy of digitising the body landmarks, the accuracy of the anthropometric data, these are, the mass and centre mass locations of the body segments of individual swimmers, and the success in eliminating the small random errors in the digitising process by data smoothing. Optimal selection of the degree of smoothing is necessary to avoid loss of real signal while ensuring that high frequency noise is minimised.

Net forces can also be derived from velocity measured by 'velocimeters'. A sensor measures the velocity of a wire trace attached to the swimmer's hips. This method has been applied successfully by Payton and Wilcox (44) to assess bilateral asymmetries in the force produced by single arm amputee paralympic swimmers. The system can also be used to measure passive drag based on the rate of decay of velocity during the glide phase of starts and turns.

Muscle Activity

Muscle activity can be measured using electromyography (EMG). The level of activity of specific muscles is usually referenced to the activity during maximal voluntary contraction (MVC). This can enable differences in muscle activity relative to maximum between equivalent muscles bilaterally and also indicate the extent of involvement of muscles in particular movements and phases of the movement.

Because the level of activity and the frequency content of the EMG signal change with fatigue EMG can be used to assess which muscles are most susceptible to fatigue during a performance and whether there are diffferences bilaterally. EMG can also be used to assess which dry-land exercises are appropriate for developing strength and endurance in the muscles required for each of the competitive strokes in swimming.

Alizadehkhaiyat (1) reported that assessment of EMG frequency content was a reliable method of measuring muscle fatigue in forearm and shoulder muscles of tennis players. A change in balance of the muscle contributions as they fatigue could be a contributing factor in the etiology of tennis elbow. Similarly, based on the changing balance of tibialis and gastrocemius activity with fatigue, Mizrahi (36) concluded that fatigue could presdispose stress fractures in running. Diedrichsen (12) found bilateral differences in activation of shoulder muscles for the dominant and non-dominant sides during abduction. Thus, side dominance can create differences in fatigue rate of muscles even though the requirements of the activity are the same for both sides.

Rouard (47) provided a good example of the use of EMG in conjunction with measures of hand path and force to examine the effect of fatigue on bilateral symmetry and agonist/antagonist balance in swimming.

Capture of EMG during swimming is problematic due to the need to waterproof the electrodes and the inability to telemeter data through water. However, recent technological advances have enabled the production of electrodes with built-in data storage capacity, for example the system developed by Kine (www.kine.is). This means that a swimmer can swim unencumbered by wires and the data can download once the electrodes are free of the water. This technology opens up the possibilities to study muscle function during swimming.

References

1. Alizadehkhaiyat, O., A.C. Fischer, G.J. Kemp and S.P. Frostick. Strength and fatigability of selected muscles in upper limb: assessing muscle imbalance relevant to tennis elbow. *Journal of Electromyography and Kinesiology*, 17; 428-436, 2007.
2. Barden, J., R. Kell and D. Kobsar. Effect of critical speed and exercise on stroke phase duration and bilateral asymmetry in 200-m front crawl swimming. *Journal of Sports Sciences*, 29(5); 517-526, 2011.
3. Beighton, P., L. Solomon and C.L. Soskolne. Articular mobility in an African population. *Annals of Rheumatic Diseases*, 32(5); 513-418. 1973.
4. Blanch, P. Conservative management of shoulder pain in swimming. *Physical Therapy in Sport*, 5; 109-124, 2004.
5. Boublik, M., and R.J. Hawkins. Clinical examination of the shoulder complex. *Journal of Orthopaedic & Sports Physical Therapy*, 18(1); 379-385, 1993.
6. Bullock, J. E., G.A Jull and M.I. Bullock. The relationship of low back pain to postural changes during pregnancy. *The Australian Journal of Physiotherapy,* 33(1); 10-17, 1987.

7. Carpes, F.P., C.B. Mota and I.E. Faria. On the bilateral asymmetry during running and cycling: A review considering leg preference. *Physical Therapy in Sport*, 11; 136-142, 2010.
8. Cools, A.M., G.A. Declercq, D.C. Cambier, N.N. Mahieu and E.E. Witvrouw. Trapezius activity and intramuscular balance during isokinetic exercise in overhead athletes with impingement symptoms. *Scandinavian Journal of Medicine and Science in Sports*, 17; 25–33, 2007.
9. Crawford, H.J., and G.A. Jull. The influence of thoracic posture and movement on range of arm elevation. *Physiotherapy Theory & Practice*, 9 (3); 143 – 148, 1993.
10. Czabañski, B., and T. Koszcyc. Relationship of stroke asymmetry and speed of breaststroke swimming. In: J. Terauds & E.W. Bedingfield (Eds.) *Swimming III*. Baltimore: University Park Press, pp. 148–152, 1979.
11. Deffeyes, J., and R.H. Sanders. Elliptical zone body segment modelling software: digitising, modelling and body segment parameter calculation. In Q. Wang (Ed) *Proceedings of XXIII International Symposium on Biomechanics in Sports*. The China Institute of Sports Sciences, Beijing, pp. 749-752, 2005.
12. Diederichsen, L.P., J. Nørregaard, P. Dyhre-Poulsen, A. Winther, G. Tufekovic, T. Bandholm, L.R. Rasmussen and M. Krogsgaard. The effect of handedness on EMG activity of human shoulder muscles during movement. *Journal of Electromyography and Kinesiology,* 17; 410-419, 2007.
13. Downwar, J.M., and E.L. Sauers. Clinical measures of shoulder mobility in the professional baseball player. *Journal of Athletic Training*, 40(1); 23-29, 2005.
14. Driscoll, S.W., and J. Skinner. Musculoskeletal complications of neuromuscular disease in children. *Physical Medicine and Rehabilitation Clinics of North America*, 19; 163-194, 2008.
15. Fairweather, M.M., and B. Sidaway. Ideokinetic imagery as a postural development technique. *Research Quarterly*, 64; 385-392, 1993.
16. Formosa, D.P., B. Mason and B. Burkett. The force-time profile of elite front crawl swimmers. *Journal of Sports Sciences*, 29; 811-819, 2011.
17. Fowler, P.J. Shoulder injuries in the mature athlete. In: Grana W.A., (ed.) *Advances in sports med fitness*. Chicago: Year Book Medical Publishers. Pp.225-238, 1988.
18. Fowler, P. J. The rotator cuff in competitive swimming. *Sports Medicine and Arthroscopy Review*, 3; 39-48, 1995.
19. Gerber, C., and R. Ganz. Clinical assessment of instability of the shoulder with special reference to anterior and posterior drawer tests. *Journal of Bone and Joint Surgery British*; 66; 551-556, 1984.
20. Havriluk, R. Performance level differences in swimming: Relative contributions of strength and technique. In P. Kjendlie, R.K. Stallman, and J. Cabri (eds.) *Biomechanics and Medicine in Swimming XI*. Norwegian School of Sport Sciences, Oslo, pp. 321-323, 2010.
21. Hawkins, R. J., and J.S. Abrams. Impingement syndrome in the absence of rotator cuff tear. *Orthopaedic Clinics of North America,* 18; 373-382, 1992.
22. Hawkins, R, I., and J.C. Kennedy. Impingement syndrome in athletes. *American Journal of Sports Medicine*; 8; 151-158, 1980.
23. Hawkins, R, I., and N.G. Mohtadi. Controversy in anterior shoulder instability. *Clinical Orthopaedics Related Research; 272;*152-161, 1991.
24. Impellizzeri, F., M. Bizzini, E. Rampinini, F. Cereda and N. Maffiuletti. Reliability of isokinetic strength imbalance ratios measured using the Cybex NORM dynamometer. *Clinical Physiology and Functional Imaging*, 28; 113-119, 2008.

25. Jansson, A., T. Saartok, S. Werner and P. Renström. Evaluation of general joint laxity, shoulder laxity and mobility in competitive swimmers during growth and in normal controls. *Scandinavian Journal of Medicine and Science in Sports*, 15; 169–176, 2005.
26. Jaszczak, M. Dynamical asymmetry of the upper extremities during symmetrical exercises. *Human movement*, 9(2); 116-120, 2008.
27. Jensen, R.K. Estimation of the biomechanical properties of three body types using a photogrammetric method. *Journal of Biomechanics*, 11 (8-9); 349-358, 1978.
28. Jobe, F.W., and D.R. Moynes. Delineation of diagnostic criteria and a rehabilitation program for rotator cuff injuries. *American Journal of Sports Medicine*; 10; 336-339, 1982.
29. Kessel, L., and M. Watson. The painful arc syndrome. Clinical classification as a guide to management. *Journal of Bone and Joint Surgery British*; 59; 166-172, 1977.
30. Kleumper, M., T. Uhl and H. Hazelrigg. Effect of stretching and strengthening shoulder muscles on forward shoulder posture in competitive swimmers*. Journal of Sport Rehabilitation*, 15; 58-70, 2006.
31. Kolmogorov, S.V. and O.A. Duplischeva. Active Drag, Useful Mechanical Power Output and Hydrodynamic Force Coefficient in Different Swimming Strokes at Maximal Velocity. *Journal of Biomechanics,* 25(3); 311-318, 1992.
32. Lewis, J.S., & Valentine, R.E. Clinical measurement of the thoracic Kyphosis. A study of the intra-rater reliability in subjects with and without shoulder pain. *BMC Musculoskeletal disorders*, 11 (1); 39-46, 2010.
33. Lewis, J., C. Wright and A. Green. Subacromial impingement syndrome: The effect of changing posture on shoulder ROM. *Journal of Orthopaedic and Sports Physical Therapy*. 35(2); 72-87, 2005.
34. Marfell-Jones, M., T. Olds, A. Stewart, and L. Carter. *International standards for anthropometric assessment.* ISAK: Potchefstroom, South Africa, 2006.
35. Mason, B., G. Sacilott and T. Menzies. Estimation of active drag using an assisted tow of higher than max swim velocity allows fluctuating velocity and varying tow force. In J.P. Vilas-Boas, L. Machado, W. Kim, and A.P. Veloso (eds.) *Biomechanics in Sports 29, Portuguese Journal of Sport Sciences, 11 (suppl.2):* 327-330, 2011.
36. Mizrahi, J., O. Verbitsky, and E. Isakov. Fatigue-related loading imbalance on the shank in running: a possible factor in stress factor. *Annals of Biomedical Engineering*, 28(4); 463-469, 2000.
37. Naemi, R., and R.H. Sanders. A 'hydrokinematic' method of measuring the glide efficiency of a human swimmer. *Journal of Biomechanical Engineering*, 130(6); 061016 (9 pages), 2008.
38. Naemi, R., R.H. Sanders, S. Aritan, S. Haake and S. Goodwill. Development of immediate feedback software for optimizing efficiency and time of initiating post-glide actions. In *Engineering of Sport 7, Vol.1*, *Proceedings of the 7th Conference of the International Sport Engineering Association*. Biarritz, France, June 2-6. pp. 291-300, 2008.
39. Neer, C.S., Anterior acromioplasty for the chronic impingement syndrome in the shoulder. *Journal of Bone and Joint Surgery,* 54-A; 42-50, 1972.
40. Neer, C.S. 2nd. Impingement lesions. *Clinical Orthopaedic Related Research, 173;* 70-77, 1983.
41. Niekerk S., Q. Louw, C. Vaughan, K. Grimmer-Somers, and K. Schreve. Photographic measurement of upper-body sitting posture of high school students: reliability and validity study. *BMC Musculoskeletal Disorders*, 20 (9); 113-124, 2008.

42. Nikodelis, T., I. Kollias, and V. Hatzitaki. Bilateral inter-arm coordination in freestyle swimming: effect of skill level and swimming speed. *Journal of Sports Sciences* 23 (7); 737-745, 2005.
43. Oyama, S., J. Myers, C. Wassinger, D. Ricci, and S. Lephart. Asymmetric resting scapular posture in healthy overhead athletes. *Journal of Athletic Training*, 43(6); 565-570, 2008.
44. Payton, C.J., and C. Wilcox. Intra-cyclic speed fluctuations of uni-lateral arm amputee front craw swimmers. *Portuguese Journal of Sport Sciences, 6;* 73-75, 2006.
45. Psycaharakis, S.G. and R.H. Sanders. Shoulder and hip roll changes during 200-m front-crawl swimming. *Medicine and Science in Sports and Exercise*, 40(12); 2129-2136, 2008.
46. Rogowski, I., G. Ducher, O. Brosseau and C. Hautier. Asymmetry on volume between dominant and nondominant upper limbs in young tennis players. *Paediatric Exercise Science*, 20, 263-272, 2008.
47. Rouard, A. Biomechanical evaluation of freestyle swimming. In L. Seifert, D. Chollet, and I. Mujika (eds.) *World Book of Swimming: From Science to Performance,* New York: Nova Science Publishers, pp69-118, 2011.
48. Rupp, S., K. Berninger and T. Hopf. Shoulder problems in high level swimmer – Impingement, anterior instability, muscular imbalance? *International Journal of Sports Medicine*, 16(8); 557- 562, 1995.
49. Sanders, R.H. *Swim3D*. Unpublished MATLAB program for 3D analysis of kinematics, kinetics, and rhythms in swimming. The University of Edinburgh, 2005.
50. Sanders, R.H., and S.G. Psycaharakis. Rolling rhythms in front crawl swimming with six-beat kick. *Journal of Biomechanics*, 42; 273-279, 2009.
51. Sanders, R., J. Thow and M. Fairweather. Asymmetries in Swimming: Where do they come from? *Journal of Swimming Research*, 18; 1-11, 2011.
52. Schiller, J., and C. Eberson. Spinal deformity and athletics. *Sports Medicine and Arthroscopy Review*, 16(1); 26-31, 2008.
53. Seifert, L., A. Chehensse, C. Tourny-Chollet, F. Lemaitre, and D. Chollet. Effect of breathing pattern on arm coordination symmetry in front-crawl. *Journal of Strength and Conditioning Research*, 22(5); 1670, 2008.
54. Takagi, H. and R.H. SanderS. Hydrodynamics makes a splash. *Physics World,* September 2000, 39-43, 2010.
55. Thow, J. The development and validation of a battery of swimming technique measures associated with strength deficits among competitive front-crawl swimmers. Unpublished masters thesis. The University of Edinburgh, 2010.
56. Tourney-Chollet, C., L. Seifert and D. Chollet. Effect of force symmetry on coordination in crawl, *International Journal of Sports Medicine*, 30; 182-187, 2009.
57. Toussaint, H.M., G. deGroot, H.H.C.M Salvelberg, K. Vervoorn, A.P. Hollander and G.J. can Ingen Schenau. Active drag related to velocity in male and female swimmers. *Journal of Biomechanics,* 21; 325-328, 1988.
58. Wagner, D. R., and V.H. Heyward. Techniques of body composition assessment: a review of laboratory and field methods. *Research Quarterly for Exercise and Sport*, 70; 135, 1999.
59. Wickens, J. S., and O.W. Kiputh. Body mechanics analysis of Yale University freshman. *Research Quartlerly*, 8; 38-48, 1937.
60. Woerman, A. L. And S.A. Binder-Macleod. Leg length discrepancy assessment: accuracy and precision in five clinical methods of evaluation. *Journal of Orthopaedic Sports Physical Therapy*, 5; 230-239, 1984.