# LIFTING PERFORMANCE IN AQUATIC SPORTS

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**INTRODUCTION:** Sports played in or on the water represent a large proportion of human competitive and recreational activity. However, the level of our knowledge and understanding of technique in these activities seems to lag behind those of other popular activities. There are some somewhat obvious reasons for this discrepancy. First, motion in or on the water is dependent on a person's interaction with the fluid environment. Explaining this motion requires measurement of fluid forces acting on the limbs and body of a competitor or their blade or craft. These forces include drag forces, defined as forces in the direction of fluid flow across an object, or lift, defined as forces in a plane perpendicular to the direction of flow. Direct measurement of drag and lift forces acting on individual segments of a system is fraught with difficulties. Estimation of forces using indirect methods is also fraught with difficulty due to the problems involved in collecting accurate kinematic data in an environment in which there is an interface of two media - air and water.

A fundamental question in aquatic sports is how propulsive forces may be produced in an energetically economical way while minimising resistive forces. In some cases, a technique in which the body is propelled by drag forces may optimise performance. In others, a technique in which the body is propelled by lift forces may optimise performance. Therefore, one of the key tasks in analysing technique in aquatic sports is to determine the relative contributions of drag forces and lift forces.

The purpose of this presentation is to review the evidence relating to the use of drag forces and lift forces in three aquatic skills. These skills are freestyle swimming, flatwater kayak paddling, and the water polo 'eggbeater' kick. The implications for technique are discussed. Given the lack of definite findings, the presenter seeks to stimulate further investigation into aquatic sports rather than to draw conclusions.

## Propulsion in Freestyle Swimming

The issue of whether propulsion in freestyle swimming is due primarily to lift or drag appeared to have been settled in the early 1970s. Prior to that time coaches believed that the best way to propel the body forward was to pull the hand directly backwards, that is, to use drag forces. The drag force produced is opposite the direction of hand motion. It was thought that the hand plane should be almost square to the direction of motion. Coaches applied this idea by teaching swimmers to pull directly backwards with the hand at right angles to the pulling direction.

Following observations that the hands of champion freestyle swimmers scribed curved paths during the pull phase of the stroke, Brown and Counsilman (1971) and Counsilman (1971) promoted the idea that good swimmers use 'sculling actions' with their hands pitched to utilise lift forces as the dominant means of propulsion. By definition, lift forces are perpendicular to the flow relative to the hand. Assuming that the hand moves into 'still' water, this means that the lift forces are also perpendicular to the line of motion of the hand. Initially, the lift in freestyle swimming was thought to be generated in accordance with Bernoulli's Principle. When 'foil-like' objects move through a fluid at high speed and small angles to the flow, large lift forces are generated and the drag forces are comparatively small. The lift forces arise from a difference in pressure as the fluid travels further and faster around the more curved side of the foil than the less curved side. It was thought that a swimmer's hand could act as a foil because the back of the hand is more curved than the front. To generate lift by the Bernoulli Principle the hand should be sculled so that the angle between the hand plane and line of motion of the hand is small. This generates forces which are mostly lift rather than drag. A revolution in coaching practices followed Counsilman's work. Coaches taught swimmers to 'sweep' with the hands. Lift as the main source of propulsive force in freestyle swimming became almost universally accepted. Some swimming texts depicted the hand as a 'foil' or as a 'propeller.

Bernoulli's Principle is only one explanation of the kinetics of the lift force (Sprigings and Koehler, 1990). It is now acknowledged that the lift force may be generated by pushing water backwards using intermediate angles of pitch (Costill, et al., 1992). It is also acknowledged that drag and lift both contribute to the net force produced by the hand. Some texts depict the hand at instants through the pull phase of the stroke and indicate the relative magnitudes of lift and drag vectors. Ideally, the combination of lift and drag is such that the resultant force is in the desired direction of travel. It is common for the depictions to indicate lift as the predominant source of propulsion. Thus, the perception that most of the propulsive force in freestyle swimming is due to lift rather than drag has persisted.

A number of research papers have supported this view (Barthels and Adrian 1974; Schleihauf, 1974, 1979; Schleihauf et al. 1983, 1988; Reischle, 1979). Additionally, there are some compelling reasons why one might accept the idea that sound freestyle technique is characterised by the use of lift forces in preference to drag forces. The first is related to the curved nature of the hand path. It is natural and logical to reason that if a handpath is curved then forces must be generated by lift. Otherwise, why would good swimmers use a curved hand path? An additional advantage attributed to a curved handpath is that the hand moves through a greater distance and/or speed thereby allowing forces to be applied longer and/or be greater in each stroke. It is reasoned that for forces to be in the desired direction when a curved handpath is used then lift must make an important contribution. Thus, to achieve the advantages of a longer handpath a swimmer learns to use sculling motions to produce forces from lift rather than drag. Further, sculling actions may allow the large muscle groups to be used more effectively than when the hand is pulled straight back. Much of the sculling may be produced by the trunk rotators and incorporated into the natural rolling actions which accompany breathing and hand exit. Such a technique may be mechanically and physiologically efficient. Perhaps the most convincing argument is that less energy may be transferred to the water and 'wasted' when forces are generated from lift than from drag (Toussaint and Beek, 1992).

Challenges to the view that lift plays the dominant role in freestyle propulsion have been few and, in general, have been ignored or dismissed. Wood and Holt (1979), Holt and Holt (1989), and Valiant et al (1982) presented evidence in favour of drag being the dominant force. More recently, Cappaert (1993) and Cappaert and Rushall (1994) quantified the direction of hand motion and the orientation of the hand using three-dimensional analysis techniques. By using these data in conjunction with lift and drag coefficients from the work of Schleihauf (1979) the lift and drag contributions to propulsive force were estimated. These studies of champion swimmers have indicated that drag forces are more important than lift forces in all strokes other than breaststroke. Rushall et al. (1994) proffered convincing arguments in favour of drag as the dominant propulsive force in freestyle swimming. Rushall et al. contended that the arguments in favour of lift as the dominating force were ill-conceived. A main argument was that much of the total propulsive force comes from the forearm. Because of its shape nearly all the force generated by the forearm must be due to drag. Further, the forearm has a substantially straighter path than the hand. Thus, freestyle technique may be directed toward generating propulsion from the forearm using drag rather than deliberately using a sculling action to optimise lift forces by the hand. Unfortunately, although researchers have quantified the drag and lift coefficients of the forearm and combined forearm and hand (Berger et al. 1995), no research has effectively quantified the relative contributions of the forearm and hand in actual swimming. One of the major methodological problems to be overcome is that the forearm moves at very different velocities along its length during the swimming stroke. Schleihauf (1984) estimated that the contribution of the forearm in swimming is very small compared to that of the hand. This is because the hand moves at a greater velocity than the forearm. If this is the case, then a focus on the forces produced by the hand remains warranted and the question of whether lift or drag is the more important remains open for consideration. Recent studies quantifying whole body motion have indicated that the hand paths of successful swimmers are not as curved as initially thought (Cappaert, 1993). Thus, swimmers are tending to use a straight pull rather than to maximise pulling distance and speed by using a curved path. If the path is not very curved then the major contributor to force in the desired direction must be drag regardless of whether the hand is angled to the flow.

Through a combination of experiment and simulation (Liu et al. 1993; Hay et al. 1993) showed that the curved path of a swimmer's hand is due to body roll. In fact, when the arm is simulated to move directly backwards with respect to the swimmer's reference frame, the path of the hand in the external reference frame is more curved than in actual swimming. This means that swimmers actually straighten the curve somewhat. This has important implications. It means that the curved hand path is not deliberate. Rather than swimmers adducting the arm to produce the 'insweep' and then abducting to produce the 'outsweep', as commonly demonstrated by coaches, the swimmers are actually reducing the curve by abducting in the early part of the pull and adducting during the latter part of the pull. The fact that swimmers attempt to straighten the path rather than to use sculling actions is strong indirect evidence that swimmers rely on drag forces rather than lift forces.

Recently, Sanders (1997a and 1997b) attempted to shed more light on the lift versus drag issue using hand lift and drag coefficient data obtained from a testing tank at the Iowa Institute for Hydraulic Research. Lift and drag coefficients were determined for the entire range of possible pitch and sweepback angles, defined in accordance with the convention established by Schleihauf (1979). The lift and drag coefficients indicated that the greatest forces were obtained when the pitch angle was close to 90 degrees to the flow (Figure 1). At this orientation the force was due almost entirely to drag. Lift made its greatest contribution to resultant force at pitch angles near 45 degrees (Figure 2). However, even at these angles, the contribution due to drag was as great as the contribution due to lift at most sweepback angles (Figure 3). When these coefficient data were used in conjunction with three-dimensional kinematic data to estimate forces in actual swimming, it was found that drag made a larger contribution than lift throughout the propulsive part of the pull. During the most propulsive phase of the stroke the pitch angle was between 50 and 60 degrees. This means that the hand was pitched to take advantage of drag forces with a smaller contribution due to lift. During the most propulsive phase of the stroke the direction of fluid flow was from the wrist towards the fingers. This is contrary to the situation commonly envisaged and depicted in swimming texts. There, the hand is represented as a foil generating lift forces from lateral movements which produce a flow across the hand.

The recent evidence strongly suggests that the hand is not used like a foil in freestyle swimming. Further, the evidence suggests that although lift makes some contribution to propulsive force in freestyle swimming, drag makes the dominant contribution.

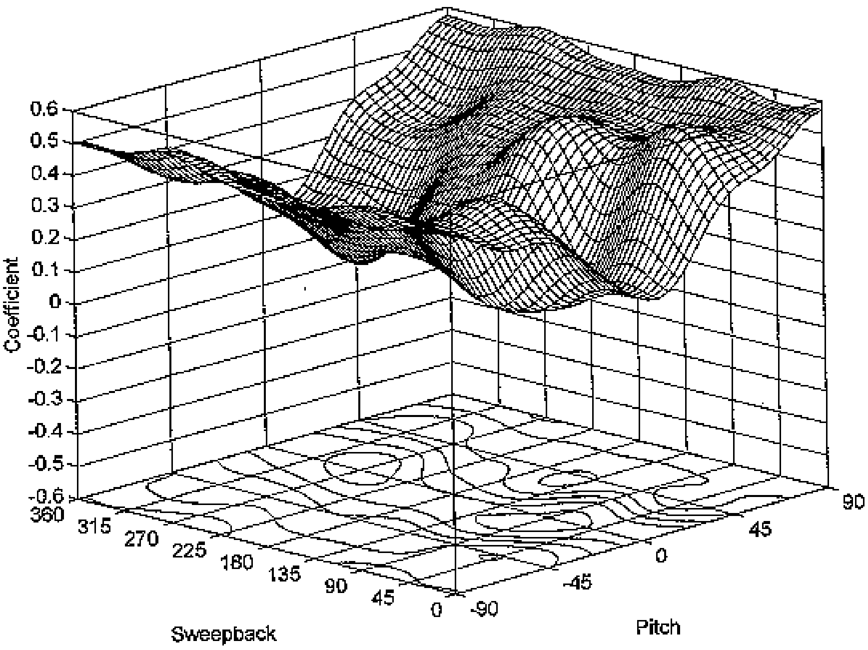



**Figure 1:** Resultant of the lift and drag coefficients obtained from a resin model of a swimmer’s hand with adducted thumb.

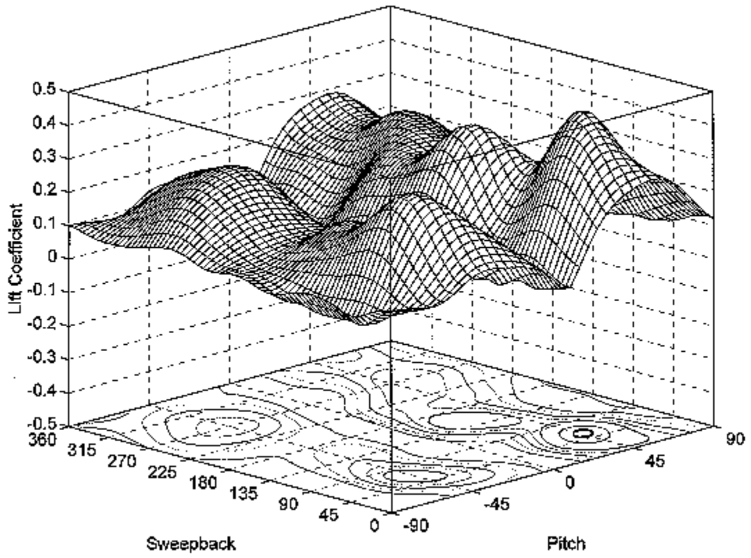



**Figure 2:** Lift coefficients obtained from a resin model of a swimmer's hand with adducted thumb

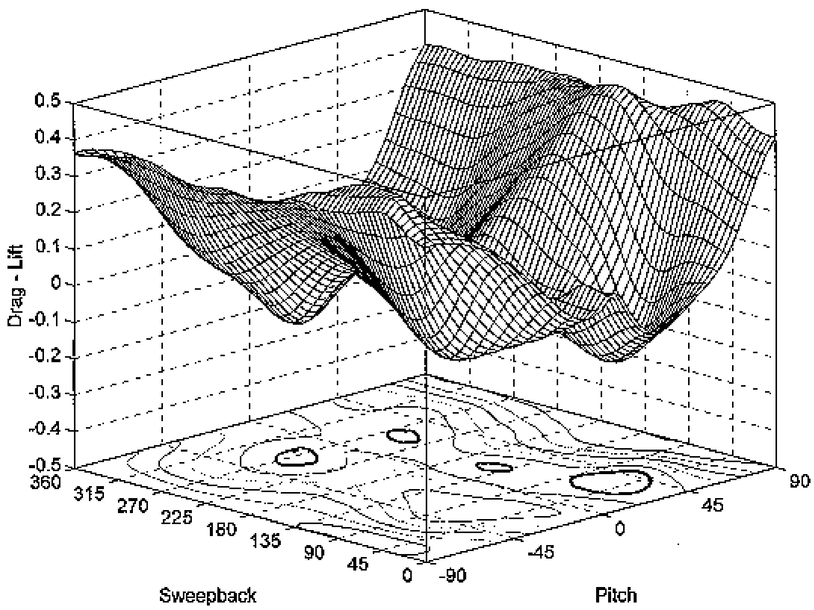


**Figure 3:** Difference in magnitudes of drag and lift coefficients obtained from a resin model of a swimmer's hand with adducted thumb

**Propulsion in Flatwater Kayak Paddling**

Prior to 1985 there was no doubt that propulsion in kayak paddling was dominated by drag forces. A flat blade was pulled almost directly backwards, parallel to the kayak, to drive the kayak forwards (Mann and Kearney, 1980). In the 1980s a new blade design, the 'wing blade', brought about a revolution in kayak paddling technique and an improvement in performance. The Swedish wing was shaped like an airfoil. Presumably its designers reasoned that propulsive forces could be generated more efficiently using lift forces than drag forces. Rather than pulling the blade directly backwards as with the flat blade, the wing blade was moved laterally away from the kayak. More recent blades, such as the 'Norwegian' wing which superseded the Swedish wing, are literally a 'wing with a twist' (Figure 4). According to anecdotal evidence, the twist allows a 'cleaner exit', that is, it is easier for the paddler to withdraw the blade at the end of the stroke with minimal forces counter to the desired direction of travel.

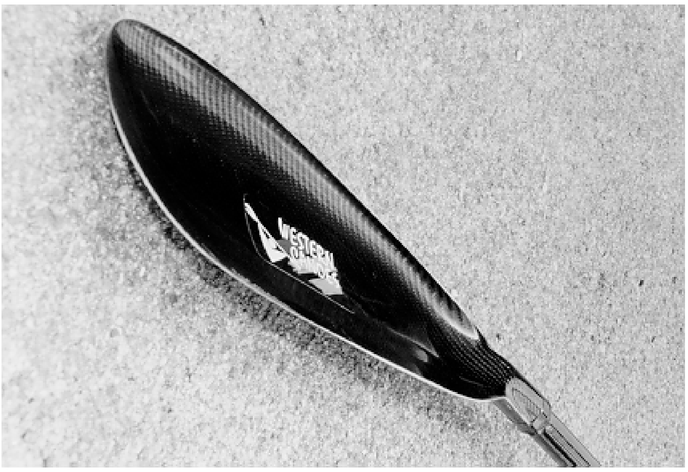


**Figure 4:** A modern 'wing' or 'propeller' flatwater kayak blade

While the design reflects an intention to make use of lift forces, the extent to which modern paddlers rely on lift has yet to be established. There are a number of possible reasons for the success of the wing blade and the demise of the conventional flat blade. The flat blade had several disadvantages.

To apply force to the water the blade must be moving backwards. This means that at race speeds the blade must be moving backwards rapidly with respect to the kayak before it 'catches' the water and starts to produce propulsive force. To avoid large braking forces between entry and catch, the blade must commence moving backward before entry. The paddler must recover the blade well forward and then 'waste' some of that distance by getting the blade 'up to speed' in the backward direction before an effective catch is made. Thus, the effective pull time is shortened and recovery time is lengthened.

Similarly, to avoid large braking forces prior to exit, the paddler must withdraw the blade before full extension so that the blade is still moving backwards with respect to the water. This rapid backward motion with respect to the kayak must then be reversed before the blade can be recovered forward for the next pull phase. Such an action will also delay the entry of the opposing blade as the paddler must recover the body forward to obtain a suitable forward reach prior to entry.

Because the flat blade is pulled directly backward there is a great reliance on shoulder extension. Although the trunk rotators can assist with the backward motion, the backward motion does not allow them to be used in the easiest and most effective way.

The problems described above are not completely overcome by using lateral motions with a wing blade. When the wing blade is entered without much backward motion with respect to the kayak there is forward motion with respect to the water. This means that braking forces occur. However, if the blade is moving rapidly in a lateral direction at the time of entry, then the braking forces may be offset by lift forces.

An associated benefit of lateral motion of the wing blade is that the paddler's forward reach is not reduced by the need to be pulling the blade backwards prior to entry. This shortens the recovery period and may increase the duration of the time of propulsive force relative to the duration of the stroke cycle.

Another advantage of the wing paddle arises from the idea of 'finding still water'. Because water starts to move in the direction of motion of the blade, that is, opposite the direction of the drag force, some of the energy supplied to the blade by the paddler is 'lost' to the water. Researchers of related aquatic activities, particularly swimming, have proposed that it is more efficient to use lift forces to generate propulsion than to use drag forces (Alexander and Goldspink, 1977; deGroot and van Ingen Schenau, 1988; Toussaint, et al. 1991; Toussaint and Beek, 1992).

Investigation and modelling of vortices suggests another important reason for the superior performance of wing blades that is somewhat related to the idea of energy loss outlined above. Mathematical modeling by Jackson (1995) has indicated that less energy is transferred to the water and wasted by a wing blade moving diagonally from the kayak than a conventional blade moving parallel to it. The wing blade produces a large vortex area compared to the conventional blade. Jackson estimated that this raises efficiency to 89% compared to 74% for the conventional blade.

A third advantage of the wing blade is related to the physiological benefits of 'rounding out' the motions. It is less costly physiologically to 'keep things moving', thereby making full use of the motion already established, than to 'stop and start'. Using lateral motions at entry and exit probably assists in 'rounding out' the motions. In addition to improving physiological economy, the curved motion may assist in maintaining a smooth rhythm with fast and easy transitions between pull and recovery phases of the stroke.

Another advantage of the blade being moved laterally is that the force may be directed more in the forward direction throughout the pull than when using the conventional blade. The wing blade technique may allow the blade to maintain an almost vertical orientation, when viewed from the side, for a longer period than the technique with the conventional blade. This would maximise the component of force in the forward direction compared to components in the upward or downward direction.

The wing blade may enable the body's muscle, joint, and lever system to be used more effectively. By moving the blade laterally rather than directly backwards, the body is placed in a good position to generate large forces throughout the pull phase of the stroke. Lateral motions of the blade are produced more naturally and with less effort than motions parallel to the kayak. The paddler can easily use rotations about the long (vertical) axis of the trunk to produce fast motion of the blade.

It is likely that lateral motions are more physiologically economical in generating forces than motions parallel to the kayak. This is because it is easier to use the large muscle groups that rotate the trunk than the muscles that extend the shoulder. This may have physiological benefits with respect to minimising oxygen consumption and reducing local muscle fatigue.

While the design of the wing blade reflects an intention to utilise lift forces, the relative contribution of lift and drag in skilled performance remains unknown. Kendal and Sanders (1993) studied seven male and one female New Zealand National paddlers in an attempt to quantify the path and orientation of the blade. The orientation of the submerged blade and the path of the centre of the blade were estimated from the known position of a marker projected from the paddle shaft (Sanders and Kendal, 1992a). Unfortunately, the size of the field of view required to capture the full stroke cycle meant that reliability of the calculated angles was generally poor. However, one angular measure of the blade showed reasonable reliability and provided useful information. This was the angle between the perpendicular to the blade plane, projected onto the horizontal plane, and the line of travel. From this angle, the angle of attack, that is the angle between the blade plane and the water flow, was approximated. The results indicated that the paddlers varied considerably in their techniques. In particular, the paths of the blade centres varied considerably. All subjects moved the blade laterally away from the kayak until near the time of exit. At entry there was rapid motion in the forward as well as lateral directions. From about 0.07 to 0.1 seconds after entry of the tip, the blade centre had stopped its forward motion and commenced moving backwards. The main variability among subjects was in the amount of backward movement of the blade. One subject had no backward movement while another had 18cm of backward movement. The best paddler, a previous Olympic medallist, had 5cm of backward movement (Figure 5a). Most of the backward movement occurred during the period known to be the most propulsive part of the stroke (Aitken and Neal, 1992; Baker and Kelly, 1997; Baker and Walker, 1997). The variability in the quantity of backward motion indicated that some paddlers were relying primarily on lift forces while others had large contributions due to drag as well as lift. All subjects rotated the blade as it moved outwards. For the subjects with little backward movement of the blade, the blade was angled so that there were small angles of attack throughout the pull (Figure 5a). For the subjects with larger backward motions the angles of attack were greater but still considerably less than 90 degrees throughout the pull (Figure 5b). This means that lift and drag were both important for these subjects.

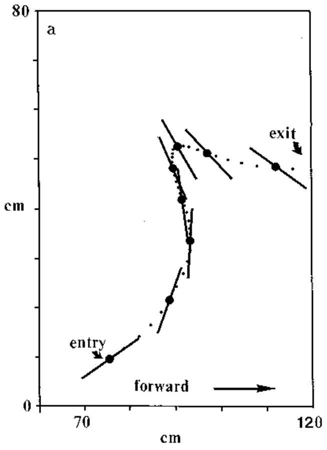
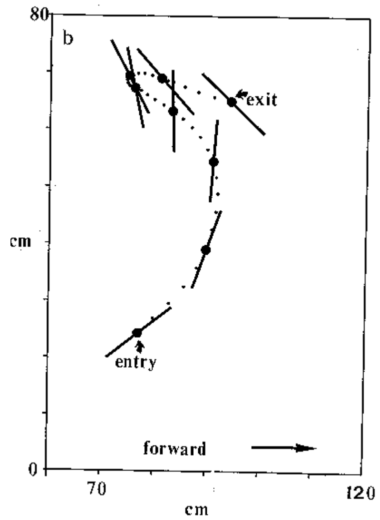



**Figure 5:** Plan view of the left blade centre path and orientation of the most successful international paddler (a) and the paddler with the most backward motion of the blade (b) in the Kendal and Sanders (1993) study




The observed paddle paths seem compatible with the use of trunk rotation. Trunk rotation that is commenced prior to entry would assist the initial outward motion of the blade. As the trunk rotates throughout the pull, the blade would naturally follow a curved path. Although paths vary in shape, all investigations of technique with the wing blade have shown that the paths are curved (Sanders and Kendal, 1992b; Kendal and Sanders,1993; and Hay and Yanai, 1995).

Although much more research needs to be done to develop a fuller understanding of the use of lift and drag forces in flatwater kayaking it appears that skilled technique with the wing blade involves the use of both lift and drag. The relative contributions of lift and drag may vary considerably among paddlers.

### The Eggbeater Kick in Water Polo

Two skills used to raise the upper body for the purpose of receiving a pass, passing, shooting for goal, or blocking those of an opponent, are fundamental to performance in water polo. One is a ‘boost’ in which the upper body is driven upward explosively to achieve maximum height. The second is a ‘hold’ in which the body is maintained in an elevated position. Both involve the use of an ‘eggbeater kick’ to generate upward forces. The eggbeater kick is a cyclical action of the lower limbs with the actions of the right and left sides being similar but opposite in phase. In a ‘hold’ the cyclical action must be maintained for a considerable period.

In a recent study (Sanders, accepted), twelve male water polo players ranging in ability from novice (in their first year of competition) to elite at national level used an eggbeater kick to ‘hold’ their elevated position for a period of 30 s. Subjects were not permitted to scull with the hands and were required to have both hands above the surface of the water.

Three-dimensional videography and analysis techniques were applied to quantify the variables of interest. The selection of variables to be analysed was based on a qualitative model of factors affecting height (Figure 6). The goal in a hold is to maintain the upper body in as high a position as possible. The variables quantified for analysis were those in the model over which the players had control. These were the speed of the feet, the joint actions contributing to the motion of the feet, the orientation of the feet, and the joint angles influencing the orientation of the feet. Pitch and sweepback angles were defined in accordance with the definitions of pitch and sweepback angles of the hand in swimming (Schleihauf, 1979).

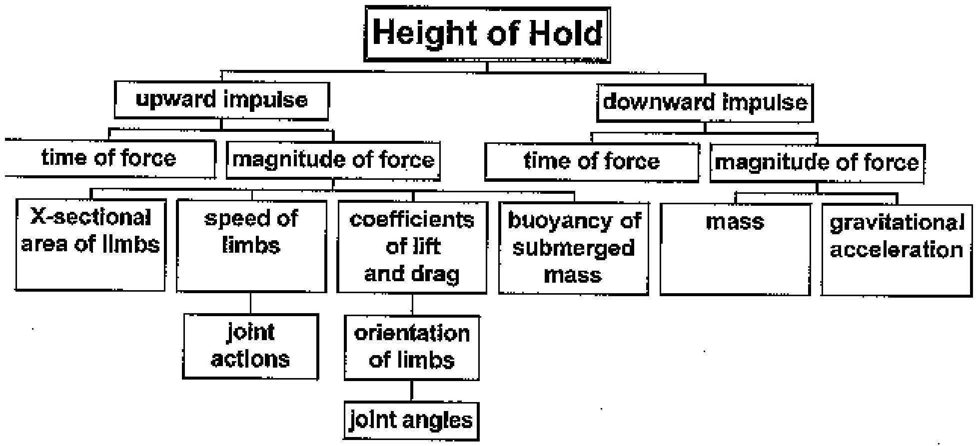



**Figure 6:** Qualitative model of factors contributing to height achieved using the eggbeater kick in a water polo ‘hold’

The height of the vertex of the head that could be sustained by the players ranged from 0.22 m to 0.42 m. The feet moved in curved paths such that there were substantial contributions from movements in the vertical direction, anteroposterior direction and mediolateral direction. The movements of the players who achieved great height appeared more ‘rounded’ than those of the less successful players. In particular, the better players had much greater movements in the anteroposterior direction than the novices. This is particularly noticeable for the positions near the time of maximum knee flexion. The better players ‘rounded out’ their motions around the time of maximum knee flexion whereas the less successful players had sudden direction changes (Figure 7).

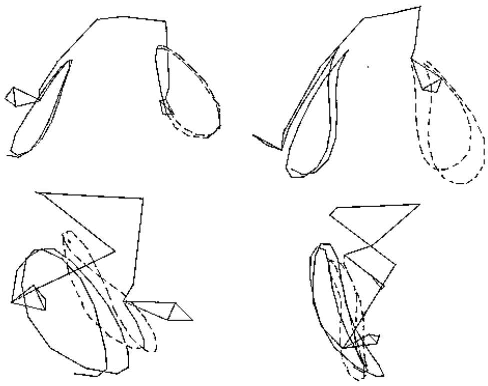


**Figure 7:** Paths of heels viewed from the front (top) and side (bottom) of the players who maintained greatest height (left) and least height (right)

The mean of the squared foot velocity was strongly related (r = 0.85) to height maintained in the hold, and the percent contribution of the vertical and anteroposterior components of foot velocity (r = -0.72 and r = 0.72 respectively). The percent contribution by mediolateral motions was substantial for all players but was not significantly related to height (r = -.26). However, this should not be interpreted as meaning that mediolateral movements were not important or necessary. The lack of a relationship was due to the fact that all players, not merely the better performers, had considerable mediolateral motion. This assisted in rounding out the movements and maintaining flow velocity. Anteroposterior and mediolateral motions made important contributions to maintain flow velocity at times when the vertical component was small. In this regard, mediolateral motion played an important role near the times of minimum and maximum knee flexion.

These results implied that performance was maximised when players ‘sculled’ the feet with large horizontal components rather than merely pushing downward. Although pushing downward can generate force, much of this advantage would be lost when the foot is recovered upwards to begin the next cycle. Therefore, downward movements should be minimised.

Players appeared to compromise between having a range of knee flexion and extension that was too small to attain large flow velocities and having a large range that required great extension or flexion. Great extension would be a disadvantage because of the difficulty of recovering the foot without having substantial magnitude and duration of negative pitch. The direction of the forces during that time would tend to have a downward rather than upward component. Great flexion would be a disadvantage because the position is awkward for maintaining flow velocity and

favourable positive pitch angles near the time of maximum flexion. Thus, the mean range of extension was approximately 90 degrees for each knee.
Pitch angles were generally small throughout the kick cycle (Figure 8a). The small pitch angles indicated that 'sculling' motions were used to generate upward forces. Thus, lift as well as drag was used. The more successful players maximised the period of positive pitch by dorsi-flexing the feet during their anterior motion, plantar-flexing the feet during their posterior motion, and everting the feet during the period of lateral motion. Although negative angles of pitch occurred during knee flexion the more successful players moved the foot posteriorly with the foot plantar flexed. Thus, pitch angles were small and the downward forces were probably small. By contrast, the less successful players pushed downward with little anteroposterior movement. These players had relatively large angles of pitch and had long periods of negative pitch during recovery of the foot (Figure 8b).

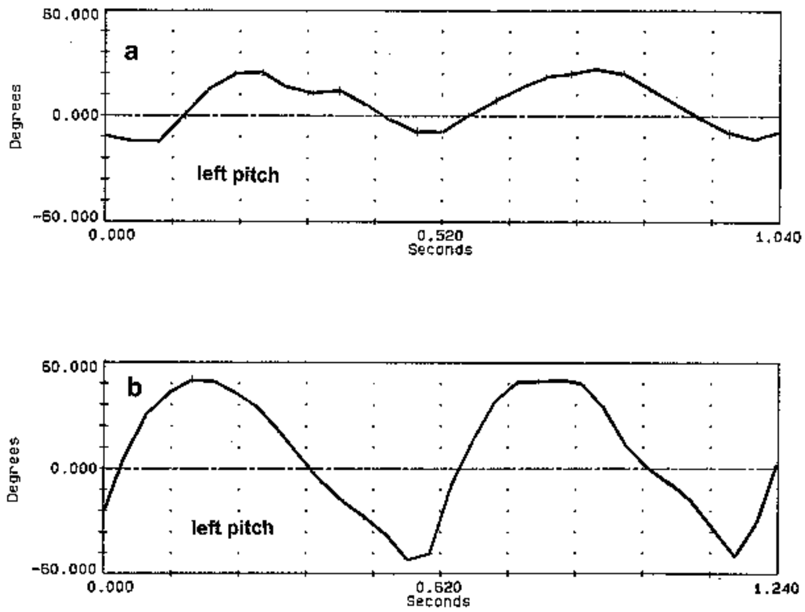



**Figure 8:** Pitch angle profile of the left foot of the player who maintained the greatest height (a) and the player who maintained the least height (b)

For most players the flow was across the medial side of the foot, that is between 0 and 90 and 0/360 and 270 degrees for at least 66% of the cycle time. The short period of flow across the outside of the foot, that is between 90 and 270 degrees, occurred late in the period of knee flexion and early knee extension as the foot moved laterally. By everting the feet during the period of lateral motion, pitch angles were small and positive for most of this period.
At the commencement of knee extension all players had the foot in a laterally rotated position. The foot rotated medially as it moved laterally and anteriorly. The sweepback angle changed from 90 to 0 degrees due to the increasing anterior motion and decreasing lateral motion. The foot continued to rotate medially as its

motion changed from lateral to medial and from anterior to posterior. As a result, the sweepback angle changed from 0/360 degrees to 270 degrees.

Good technique in the eggbeater kick involves 'sculling' the feet with small angles of attack. Skilled players minimise vertical motions of the feet. This evidence strongly sugests that lift is the predominant means of generating forces in the desired upward direction.

## CONCLUSIONS - LIFT VERSUS DRAG IN AQUATIC SPORTS

In this paper the relative contributions of lift versus drag have been investigated with respect to three aquatic activities - freestyle swimming, flatwater kayaking, and the water polo eggbeater kick. Although the contributions of lift and drag have not been determined directly for any of those activities, the available indirect evidence based on kinematic analysis suggests the following:

1. The widely held view that freestyle swimmers use sculling motions to generate propulsion from lift must be seriously questioned. Recent evidence suggests that drag makes the predominant contribution to propulsion in freestyle swimming.
2. Lift appears to play an important role in offsetting braking forces during entry of the wing blade in flatwater kayaking. It is possible that both lift and drag make important contributions during the most propulsive part of the pull. From the limited data available, it appears that the path and angle of attack of the blade vary considerably among paddlers. Therefore, the relative contribution of lift and drag to propulsion in kayak paddling may vary greatly among paddlers.
3. Skilled technique in the waterpolo eggbeater kick involves 'sculling' the feet. This evidence suggests that lift plays an important role in supporting the body in an elevated position.

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