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Patterns of flow pressure due to hand-water-interaction of skilled breaststroke swimmers – a preliminary study

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Abstract

Self-induced aquatic propulsion is an effect of interaction of the limbs and water mass (LWI) which change the energy-density per volume and the momentum of water mass, simultaneously. The change of volumetric energy-density of water can be measured via pressure tap probes detecting static pressure of unsteady flow via pressure sensors. The data of elite breaststroke swimmers wearing gloves with pressure taps on both sides of the hands were presented as pressure difference per hand (p-diff) in real-time in a split screen video together with the hand action. The purpose of this preliminary study was to check a) the stability of the setup including the data collection under pool condition with various swimmers and b) to answer coaches' questions concerning the relation of peak pdiff-data and hand action. Among others it is shown that p-diff(max) coincides with a) deepest hand penetration at the end of the inward sweep of the hands and b) max body acceleration during hand action, shortly before max body velocity occurs.
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Keywords: pressure measurement; hand action; breaststroke swimming

1. Introduction

Breaststroke swimming is a common self-induced activity in aquatic space. Limb-water-interaction (LWI) is a means to transfer energy to the surrounding water affecting its volumetric energy-density and momentum causing a momentum-couple (conservation of momentum) known as action & reaction. In Fig. 1 various aspects of aquatic locomotion - from origin of motion to the acceleration of the swimmer - are presented, highlighting a level with intermediate effects, which lacks attention in most swimming books. Intermediate effects are related to displaced water mass e.g. by hand action. The intermediate level is essential to understand the interaction and its unsteady flow effects which are the basis to accelerate the swimmer as an end effect.

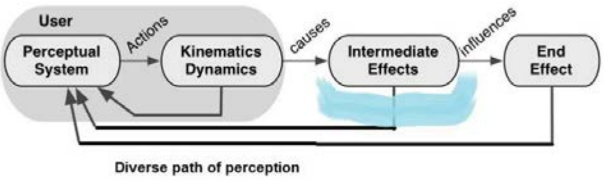

Fig. 1. Various aspects from brain to the acceleration of the swimmer and feedback routes of invisible effects (Herman et al, 2012).

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Aquatic Space Activities (ASA) can be defined as cognitively controlled, goal-oriented self-induced cyclic actions in water with body-water-mass interaction under the conditions of limited energy reservoir with relatively low efficiency. Cognition is defined as the cerebral information processing. Knowledge of cognitive matter in relation to ASA is potentially important for a better communication about specific stroke aspects, like straight path of the hand versus turning of hand orientation in terms of supination / pronation. Provided the rate of energy liberation via the aerobic/anaerobic metabolism are sufficiently trained fast swimming breaststroke demands highly skilled cyclic limb interactions following unsteady flow physics and cover 100m in less than 60 s. Unsteady flow physics considers acceleration and velocity terms without spending too much energy. Concentration on the effects due to the changes of volumetric energy-density in the water is necessary to overcome the myth, that a push off from the water is possible, which is not, even though this is a common saying, since water is giving way to firm bodies (drag does not explain the interaction effects sufficiently even if repeatedly stated).

2. Liquid pressure represent volumetric energy density

The research of the efficient locomotion of aquatic vertebrates with periodical change of their outer form direct the attention to appropriate aspects, like importance of flow pressure. Water mass set in motion by animals or man is invisible but can be sensed (fishes need flow sensing to survive). Elite swimmers are masters of displacing water mass at low energy costs resulting in high swimming speeds. To increase the mastery of self-induced locomotion it is advantageous to possess a specialized cognitive control transmission tool, which is named the "feel for water". Experts, when asked about their opinion concerning the representative agent of the feel for water emphasize the pressure difference of the flow around the hands as a decisive parameter. However, communication between coach and swimmer about the intermediate effects in terms of perceivable parameters is hardly possible due to lack of comparative scales of this particular agent. In the history of swimming research, e.g. documented by the congress series of Biomechanics and Medicine in Swimming (https://www.iat.uni-leipzig.de/datenbanken/iks/bms/) some works related to pressure recordings in conjunction with body actions were published.

Some of these former works, mentioning the term (hand)pressure in their title or obviously recorded pressure components, however, presented the data as normalized hand force terms ([3] Havriluk, 2006, [9] Takagi & Wilson, 1999), an approach which is not followed in this paper. The works which focus on the nature of flow pressure change due to interaction of body parts and deformable water mass which provide information about the pressure data ([1] Dubois et al, 1979, [6] Loetz et al , 1984, [10] Toussaint et al. 2002, [11] Ungerechts, 1983) is followed here because it is still a matter of discussion how changes of flow pressure contributes to reaction in and against swimming direction, simultaneously.

Using the term flow pressure one should keep in mind that it is not equivalent to the pressure term used in daily life (e.g. physios exert pressure) since water gives way to solid objects. [5] Klauck & Ungerechts (1997) showed that the mere kinematics of limb actions is no indicator of flow effects since the effect of interaction with water mass is not considered. From studies considering the unsteady flow in human swimming ([7] Matsuuchi et al., 2009, [10] Toussaint et al. 2002, [12] Ungerechts & Klauck, 2008) it can be concluded that the focus on changes in static (also named hydrodynamic) pressure component is justified because it represents the origin of the work done on the water ([13] Webber et al, 2001). Unsteady flow means that time-average methods cannot be applied since static pressure varies locally and with time (see body undulation) while so-called engineering turbulence can be treated by time-average equation ([8] Naka & Obi, 2009). As mentioned, self-induced interaction in aquatic space simply transfer metabolic energy via limb action to the energy field of a unit of water volume. For pressure terms the same unit, named Pascal (Pa) is correct; this applies also to the change of energy density per unit volume or volumetric energy-density as well as the static pressure, respectively. Placing emphasis on the flow pressure, instead on pressure values, normalized to a unit area, called hand force, has to do with the claim of elite swimmers that pressure is the essential parameter feeding their elaborated perception of water flow. The purpose of this preliminary study was to check a) the stability of the setup including the data collection under pool condition with various swimmers and b) to answer coaches' questions concerning the relation of peak pdiff-data and hand action relative to the water.

3. Methods

Related to the purpose of this preliminary study of a setup enabling to measure, calculate, register and show the results in real-time need to be explained as well as the description of the hand actions relative to the water. Defining key points of the hand action instead listing of propulsive phases result from a study following the strategy of functional attribution of actions modes. As explained by [12] Ungerechts & Klauck (2006) the functional attribution of swimming strokes activities is closely related to the idea about flow conditions induced by hand-water-interaction and leads to more conceptual description of hand positions facilitating communication about stroking and overcome the gross distinction into – pull and push - per stroke (which hardly applies to hand-water-interaction in breast)stroke. Key points (Act) relative to the water were defined per cycle and shown along the hand path in Fig 2: (act 1) hands outwards action begin, (act 2) hands turning action begin, (act 3) hands moved inwards halfway, (act 4) hands inwards action end, (act 5) hands forwards action begin - the feet (heels) near the body coincides more or less with the act 5 -, (act 6) hands remain stretched out. Numbering the key points is logical and can be used as an ordinal like scale, including the possibility to express deviations from the defined point, e.g., when the hands are in a position an instant later a 0.3 or 0.6 can be used.

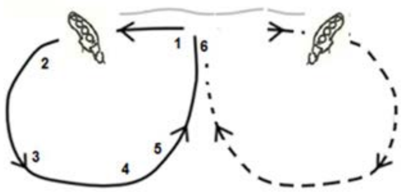

Fig. 2 Frontal view of the hand path in breaststroke swimming and key (1 – 6); from point act 5 on the path is directed in swimming direction, when hands move forwards and point act 6 hands remain in gliding position

To measure the static pressure component of water the “piezo-probe” pressure tub method was used, which, basically, is an open hole on a wall on one side of a tube and differential analogue pressure transducers above water level (4 tubes means a set of 4 differential analogue pressure transducers). The open ends are incorporated as “piezo-probes” or “pressure tubs” into a glove at the palmar side and the backside (Fig. 3a).

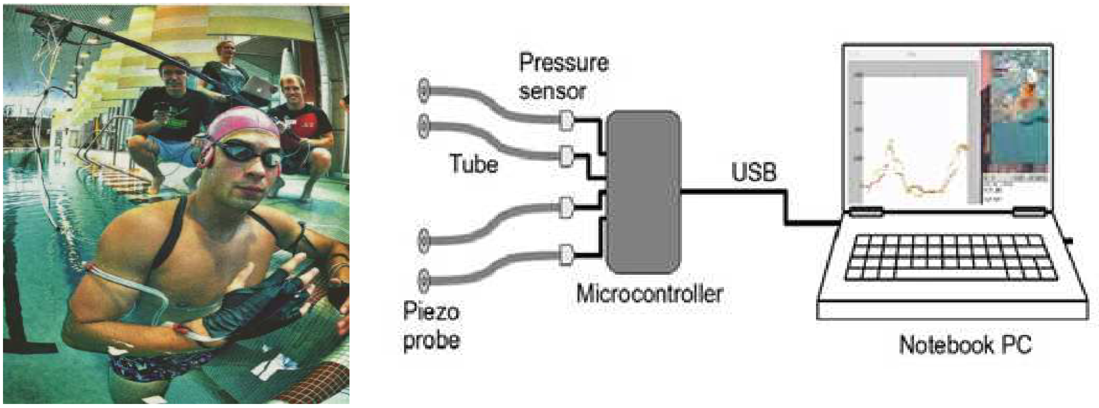

Fig. 3 a) Setup to measure static pressure on two sides per hand of a swimmer; 3 b) setup details

From the hand flexible tubes (Diameter 4mm) runs along the arm to four pressure sensors (Specs: Freescale MXP5010DP analogue pressure sensor, 0-10 kPa pressure range). The data from the pressure sensors (sampled at 100Hz) were processed via a microcontroller (Specs: Atmel ATmega328, 8-bit RISC, at 8MHz, programmed in C); in Fig. 3b it is shown that the p-diff-curve are presented in a split screen together with video. The data flow from the sensors was stored as pressure differences per hand (pdiff), defining flow variation data on the palmar side as minuend and flow variation data from the dorsal hand side as subtrahend. During the cyclic hand action the flow is unsteady, thus the flow effects can change suddenly and totally due to changes of the hand position and accompanying vortex dynamics ([7] Matsuuchi et al, 2009). (e.g. when the vortex is shed). The value of pdiff can either be positive or negative, depending if the minuend is larger or smaller than the subtrahend or visa versa. Consequently, pdiff become positive when the pressure figures are larger at the palmar side and pdiff becomes negative when the pressure figures are larger at the dorsal side. Considering maximal positive p-diff values, Rx max, it can be concluded that pressure values at the palmar side is dominant. Considering maximal negative p-diff values, Rx min, it can be concluded that pressure values at the dorsal side is dominant. Each cyclic mean-data-time-curve of pdiff show one individual maximum and minimum, respectively. The appropriate value of each swimmer right hand was taken to calculate a group mean and standard deviation of Rx max (pdiff) and Rx min (pdiff). Taking right hand’s data as a reference has to do with the aspiration to get nor lost in numbers. The group mean and standard deviation of Rx max (pdiff) and Rx min (pdiff) is a calculated figure, just to give an idea about the range of measurement.

There are two ways to answer the question concerning the relation of peak pdiff-data and hand action a) relate mean peak value to the % of cycle duration and b) relate it to the occurrence during the hand path using act 1 – act 6. Option b) was executed using slit-screen video in which the swimmer and the analogue signal of data on notebook PC (Fig 3b). The split screen observation was done as follows: the video was operated frame by frame with Quicktime and the video was stopped when the peak point occur and the number of the appropriate action was noticed (including deviations). Finally mean and standard deviation of the appropriate action was calculated. These procedures were executed for the pre-test and repeated for the post-test; the swimmers are identical, the data are interval scaled as well ordinal / ratio scaled.

Elite breaststroke swimmers (n = 9, 686 Fina points on average) swam, after giving written consent, 2 x 25 m full equipped (Fig 2 a). They have never swam before with that setup that also enabled to listen to the flow effects while swimming; this sonification, resulting in Eigen-sound of the displaced water was used as an intervention tool during 8 x 25 m swims. After that, the swimmers swum another 2 x 25 m without sound. This preliminary study did not intend to handle the issue "sonification" because the swimmers were not tested other than to swim with the device. Before studying any effects of sonification the stability of the setup was determined in 1st place. Effects of sonification as an intervention tool cannot be expected after just 8 x 25 m. The breaststroke swimmers were asked to swim smoothly with a pronounced glide while choosing the speed individually. The data flow from the sensors was stored as pressure differences per hand (pdiff) and later used to investigate among other the repetitiveness of the data-time-structure per (breaststroke) cycle. To get a first idea of the shape of the pdiff-time-curve the data 8 cycles (from the mid-section of 50 m) were taken into consideration from the pre-test and the post-test, respectively. Because of the natural variation in stroking and in stroke period it is necessary to use some time-normalization technique so that a point-to-point comparison of data-intensity is possible. The method selected here was, to convert the experimental-recorded data's time axis linearly to an axis representing percentage of the stroke cycle, while the shape pattern differences were influenced minimally. The data of 8 "time-normalized" cycles were taken to calculate mean and standard deviation per "frame".

Concerning the statistic issue the authors presently do not intend to use qualitative methods to generalize from a sample to a population. However, mean and standard deviation and coefficient of variation can be used to gain an idea on the variation of the parameter over several cycles.

4. Results

In Fig 4 a) the raw data all four probes of three breaststroke cycles are shown, showing the stability of repetition, i.e. the signal-to-noise ratio is with 34 dB fairly high; Fig. 4 b) shows a cyclic mean-data-time-curve of p-diff, enveloped by the standard deviation.

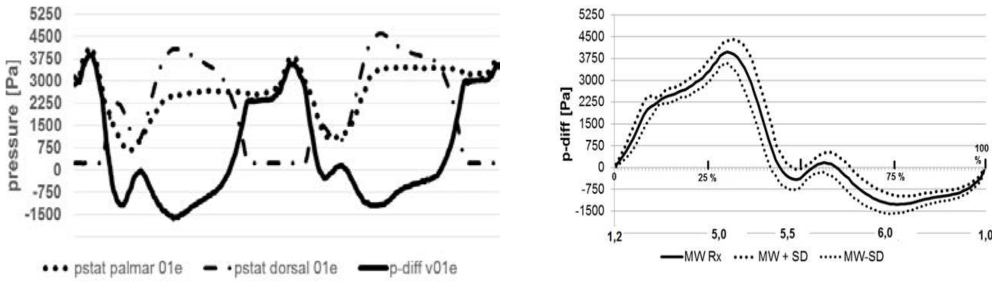

Fig. 4a) Static pressure (p) – time curves of the right hand and two pressure tubs (palmar and dorsal) and the p-diff (bold line) while swimming breaststroke and 4b) resulting mean pressure difference (p-diff) over a normalized cycle period on the basis of 8 cycles of a male elite breaststroke swimmer

Fig 4b can be taken as an example for the shape of cyclic mean-data-time-curve of pdiff of the right hand of 9 breaststroke swimmers. For this group of 9 swimmers the p-diff-values cover a range of 3,343 Pa (pretest) and 3,344 Pa (posttest). From its beginning the pdiff-curve raises remarkably than raised more gently until the positive maximum Rx max (pdiff) than decreases below zero line until an individual minimum Rx min (pdiff) and raise again gently. Taking right hand's data as a reference is a didactical reduction, although this does not mean that the p-diff of the left hand acts is mirrored. The mean of Rx max (pdiff) center around 2,398.08 Pa, ± 211.72 Pa (pre-test) and 2,420.08, ± 246.36 Pa (post-test), giving Coefficient of Variation (CV) of 8.82 % and 10.2 %, respectively: The mean volumetric energy-density of post-test is equal to that of the pre-test plus 22 Pa. The mean of Rx min (pdiff) center around – 944.9 Pa, ± 224,9 Pa (pre-test) and – 924.3 ± 192,1 Pa (post-test), giving Coefficient of Variation (CV) of 23.8 % and 20.7 %, respectively. The mean volumetric energy-density of post-test is equal to that of the pre-test minus 20 Pa.

Concerning the relation of peak pdiff-data and hand actions reveal the following. The mean of Rx max (pdiff), when related to the cycle duration, is placed 23.53 ± 5.57 % (pre-test) and 23.73 ± 5.65 % (post-test) after the cycle started, giving CV of 23.7 % and 23.8 %, respectively. The same mean of Rx max (pdiff), when related to the key points of hand action, is related to ordinal like scaled 4.04 ± 0.92 (Pre-Test) and 3.92 ± 0.93 (post-test), giving CV of 22.7 % and 23.7 %, respectively. It can be concluded that the mean of Rxmax (pdiff) is related to the key point act. 4 "hand inwards action ends", however with remarkable scattering. The mean of Rx min (pdiff), when related to the cycle duration, is placed 55,2 ± 8,2 % (pre-test) and 55.2 ± 7,2 % (post-test) after the cycle started, giving CV of 14,8 % and 13.0 %, respectively. The same mean of Rx min (pdiff), when related to the key points of hand action, is related to ordinal like scaled 5.9 ± 0.17 (Pre-Test) and 5.99 ± 0.02 (post-test), giving CV of 2.9 % and 3.3 %, respectively. It can be concluded that the mean of Rx min (pdiff) is related to the key point act. 6 “hand remain forwarded”, thus during the entire glide the volumetric energy-density raises.

The value of p-diff becomes positive when hands begin outwards sculling (act 1) and raises steadily until Rx max (pdiff) is achieved which coincides with: hands are near to the end of the inwards sculling (act 4) followed by steadily drop until Rneg which coincides with hands started forward action (act 5). This terminates the effectual period of the hands. The effectual period covers 44.4 ± 4.9 % of cycle duration (pre-test) and 43.7.± 7.2 % (post-test). In conjunction with the 3D motion of the hand-action, the maximal p-diff coincided with the deepest position of the hand before moving hands forwards. After that, a longer period of another hand orientation follows. During the remaining approx. 56 % of the cycle the swimmer executes a) the effectual period of the feet and b) a prominent glide without visible limb actions (relative to the body). During this remaining period, p-diff archives its negative maximum, Rx min (pdiff) which coincides with a) hands are mostly forwarded and b) acceleration of the body is highest due to action of lower limbs.

During the effectual period of hand action the orientation of the hands is changing (here: successive supination) and finally the swimmer may look at the palms. This is followed by a fast pronation action, placing the palms into a nearly palm-down position while the hands are moved in direction of the swimming velocity, fingers first. The maximal positive values, Rx max (p-diff) indicate dominance of the pressure values at the palmar side while the hand nearly finishes the inwards sweep while the orientation of the hand never oriented orthogonal to its path of motion. The maximal negative values, Rx min (p-diff), indicate dominance of the pressure values at the dorsal side of the hand while the hand nearly finishes the forward motion when the fingers of the flat hand lead the path of motion.

5. Discussion

In this preliminary study the static flow pressure of a hand of swimmers was measured while swimming breaststroke, gliding variant, which results in moderate swimming speed. The swimmers wear a glove on each hand, each glove with pressure tubs on the palmar und dorsal side, respectively. The pressure data were stored as pressure difference (pdiff) with palmar pressure as the minuend and dorsal pressure as the subtrahend. The expectation is that p-diff represent the work of displacing water particles ([13] Webber et al, 2001). The pdiff data of the right hand were considered more closely. Based on the mean of pdiff-time-curve and the standard deviation as an envelope the stability of the setup and of the data collection under pool condition with various swimmers is considered to be sufficient repetitive. Thus the device can be used in future to answer questions concerning “Where does the energy from the limbs, moving in aquatic space, go too?” or “Can sonification of the effects due to hand-water-interaction act as an interventional tool?”

Relating p-diff-time curve with hand actions some characteristics could be established: p-diff i) increases with the outward sweep continuously, ii) shows an “intermediate shoulder” before the inward sweep starts and iii) reach maximum at the beginning of the forward sweep, iv) decreases but remains positive until halfway reaching forwards and v) remains more or less remains below zero line until the end of the stroke cycle while the hands are stretched forwards in gliding position. This study can be related to results of a former study by [6] Loetz et al (1988) who applied another “difference-pressure method” in breaststroke. They claimed that subtraction is “leaving the hydrodynamic pressure” while the hydrostatic pressure is eliminated, found two peaks giving information that “1st peak after 35 % and the 2nd after 64 % of a ½ cycle”, one at 4,250 Pa the other at 9,000 Pa (the values were recalculated from the given normalized data). They referred minimal pressure values to as “higher pressure” on the back of the hand and they advertised the setup to find norm of swimming motion at each level. In this paper positive maximal pdiff were much smaller probably because of lower swimming speed (which [6] Loetz et al did not report). The occurrence of peaks probably cannot be compared because the term ½ cycle is not defined well. Fact is that [6] Loetz et al did not report negative maximum values of pdiff. [1] Dubois et al (1978), using another measuring device, reported p-diff(max) coincides with deepest hand penetration at the end of the inward sweep of the hands. In the presentment study the mean of positive maximal pdiff, Rxmax (pdiff) is related to the key point act. 4 “hand inwards action ends” which coincides with deep hand position (for sure, in 1970ties the breaststroke technique was quite different).

Studying effects of the hand-water-interaction (HWI) is still far from being easy to discuss. HWI produce unsteady flow effects due to changing hand acceleration with added mass effect and a vortex formation ([Matsuuchi et al, 2009). The pressure components in unsteady flow conditions remain to be studied more deeply. Knowing well that water gives way to a moving hand (which makes a push of from water impossible) and referring to the fact that swimmers transfer energy to a volume of water to yield propulsion it is proposed to have the change of volumetric energy density, measured in Pa, in mind when discussing pressure measurements in swimming. The Bernoulli Equation already expressed the connection of liquid pressure and energy since long, because it is a statement of the conservation of kinetic, potential energies and flow work of a fluid mass in motion in a unit volume. The opinion like “the pressure difference between the palm and dorsal sides increased, producing a drag force” ([9] Takagi et al, 2014) is not favored here because this approach does not tell what to do with negative pressure values as shown in Fig 4b. The meaning of pressure below zero was not discussed yet. [10] Toussaint et al (2002) pointed out that arm segments were mainly rotating rather than translating influencing the pressure gradient towards the hand “transporting water towards the hand thus boosting the suction (low pressure) of the wake”. [1] Dubois et al (1974), studying swimming fish, reported that negative pressure is associated with “accelerated water” which “could prevent boundary-layer stall“. In this context, it is more than expected that the generation of vortex influence the unsteady flow; [7] Matsuuchi et al (2009) pointed out that vortices move under the influence of pressure field, which influences the unsteady flow effects. In the communicating aquatic space the particles in a cube of water flow to the lee side of lower pressure. With the supination of the hand from act 1 until end of act 4 the particles rotate in direction from palmar to the dorsal side of the hands (known from heaving and rotating fluke of dolphins). When the hand position is rapidly starts pronation together with another orientation of incoming flow (now the finger tips are leading) another pressure situation occurs. One vortex is shed at the end of the inward sweep remaining at the place and another one is generated which rotates in the opposite direction when hands start moving forwards ([7] Matsuuchi et al, 2009) which is now from dorsal side to palmar side indicating enhanced dorsal pressure which accounts for negative p-diff values. If the sense of rotation of the new vortex is in opposite direction could be studied using PIV-method. Knowing the pressure distribution is thought to be a major issue to understand vortex-induced aquatic propulsion.

The aim to measure effects of LWI by means of pressure tubs was sufficiently reached. The amount of remaining questions in connection with flow forms and development of liquid pressure components which are due to the simplified concepts of unsteady flow. However, that should and must not prevent researchers to continue looking after the potential of measuring parameters that cannot readily observed and analyzed. In addition one must not underestimate that skilled swimmer perceives the pressure changes which may help to clarify the issue. Next, new devices with different pressure sensors will be developed to enhance sonification of liquid effects when used as training/research tool in elite swimming, aquatic therapy or flow sensing research.

Acknowledgements

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