SHORT COMMUNICATION

Swim performance with and without snorkel and the underlying energetic differences

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ABSTRACT

Swimming requires frequent lifting and rotating of the head to inhale. A snorkeler saves energy by avoiding this maneuver, but the snorkel adds breathing work due to air flow resistance. The needed power of these head movements has never been examined, although the extra power of breathing through a snorkel was studied recently. This study aimed:

1) to model the work of vertically lifting and rotating in comparison with the breathing work added by a snorkel;

2) to compare heart rate (HR) and velocity (v) while swimming under both conditions;

3) to evaluate the results for surface-swimming divers.

Presumably the power when using a snorkel is less, and the difference in power predicts the difference in swimming velocity.

Kinematics of head lifting and rotation, and the difference between the hydrodynamics were modeled. A swim test lasting 12 minutes at maximum speed (Cooper swim test) was performed in a pool by nine recreational divers in the front crawl style, with face mask but without fins. All subjects performed the test both with and without snorkel. The average velocity with a snorkel, 0.72 ± 0.09 m·s^{-1}, was $4.4 \pm 3.9\%$ higher than without ($p=0.008$), but HR (144 ± 16 bpm) showed no difference ($0.8 \pm 3.4\%$). The model based on our subjects' performance showed that 7.5% of the total power is spent in the inhaling maneuver while crawling and 2.7% while snorkeling. Theoretically this would allow the snorkeler to swim 5.2% faster. It is concluded that snorkeling is energetically advantageous as well as for divers swimming on the surface.

INTRODUCTION

Snorkels allow a swimmer to observe the underwater scenery uninterrupted, and to breathe while face-down on the surface. Recreational scuba divers also use a snorkel when swimming on the surface to reach shore or the boat and is thus relieved of the effort of repeatedly raising the head to inhale. A snorkel does, however, slightly increase the work of breathing. This extra work is dependent on the respiratory minute volume [1], most often called pulmonary ventilation ($\dot{V}E$). For example, on the dry with a $\dot{V}E$ of approximately 30 L·min^{-1}, the extra physical power ($\dot{W}_{snor}$) is 0.02 Watts (W) which is an increase of only 17% of the breathing power required to overcome airway resistance [1]. For a diver snorkeling on the surface this percentage is much less due to approximately 1 decimeter negative pressure breathing, which substantially increases the breathing expenditure. When using neither snorkel nor regulator ($\dot{W}_{no\text{-}snor}$), divers have to vertically lift and rotate the head to inhale, which is assumed to cost extra work. For swimmers, the situation is similar; also, extra power is needed.

Existing studies on swimming physiology provide no data on which to base an estimate of $\dot{W}_{no\text{-}snor}$, so this study derived $\dot{W}_{no\text{-}snor}$ from a simple model that included: the work of the airway [1], considering the work of negative pressure breathing; the work of head movements estimated with a mechanical and kinematic model; and the extra work of drag and hydrodynamic losses extrapolated from literature data [2].

KEYWORDS: cost of breathing; drag; hydrodynamics; kinematics; swim test

$\dot{W}_{no\text{-}snor}$ was compared to $\dot{W}_{snor}$. The former was expected to be higher than $\dot{W}_{snor}$ since the extra work due to the snorkel is very small [1] and the work of negative pressure breathing is of similar size under both conditions.

When swimming, non-snorkelers will have less energy available for the swim performance itself, so they can be expected to swim slightly slower than snorkelers swimming with the same total energy expenditure. The difference in speed can be predicted from the difference $\dot{W}_{no\text{-}snor} - \dot{W}_{no\text{-}snor}$. A swimming test (with face mask) was conducted to validate this hypothesis, and to establish whether a snorkel is energetically advantageous for a surface-swimming diver.

MATERIAL AND METHODS

Modeling energy expenditure of head movement during front crawl swimming with and without snorkel

Without a snorkel the head and to some extent the shoulder (on the breathing side) are lifted and rotated to allow breathing when a snorkel is not used. These movements are superimposed on the forward movement of the body.

The expenditure for lifting can be calculated from the potential mechanical energy *mgh* (where *m* is the lifted mass; *g* the gravitational constant rounded to 10 $m{\cdot}s^{-2}$; *h* the "lift'" of the center of gravity of that part of the head which is raised above the surface). An approximation of the necessary mechanical expenditure of rotation is given by the rotational kinetic energy E_{rot}:

(1) $$E_{rot} = ½{\cdot}Mi{\cdot}\omega^2$$

where *Mi* is the moment of inertia of a sphere rotating around an axis though its center, and ω is the angular velocity. *Mi* is:

(2) $$Mi = (5/2){\cdot}m{\cdot}r^2$$

where *r* is the radius of the head. It is taken that the center of gravity of the head is located at its axis of rotation (roughly through the atlas vertebra). Besides the energy expenditure, the power of lifting and rotating the head, hydrodynamics must be considered.

For a human swimmer with a swim velocity *v* of 0.3 $m{\cdot}s^{-1}$, the Reynolds number, Re, is $0.5{\cdot}10^6$; therefore, the flow along the body is strongly turbulent. ($Re = vL\rho{\cdot}\eta^{-1}$, where *L* is body length; ρ the density of water, 997 $kg{\cdot}m^{-3}$ at 27°C; η the dynamic viscosity of water, 850 $\mu Pa{\cdot}s^{-1}$ at 27°C.)

In addition to the pure muscular-mechanical cost of moving the arms and legs to finally provide propulsion, there are costs related to the water resistance of the moving body, drag, and hydrodynamic losses due to turbulences caused by the body, especially by the limbs [2].

Also, lifting and rotating of the head incur drag and hydrodynamic losses, which can be estimated by extrapolating published data of front crawl swimmers [2]. However, these extrapolations are very rough estimates. Also, it should be noted that a sphere is only a rough approx0imation of the shape of the head, and the more when considering, for instance, the ears, the facemask and the hair.

None of these costs apply to the snorkeler whose head and shoulder remain largely fixed relative to the body axis. The snorkeler's only added cost is that of the airflow resistance through the snorkel while inhaling and exhaling.

Work, in Joules (J), and power, in Watts (W) are generally presented as physical, not metabolic entities. With front crawl swimming, at a velocity of 1.0 $m{\cdot}s^{-1}$, elite college swimmers have a net metabolic power, E, of 595 W and muscular mechanical efficiency, defined as $\eta_M = W_{tot}/E$ of 0.205 [2]. W_{tot} is the sum of the kinematic, drag and hydrodynamic power components. Extrapolating the E-value of 595 W to 0.7 $m{\cdot}s^{-1}$ yields a W_{tot} of 61 W and an E = 280 W [2]. For a long time it has been known that swimming skill is of importance for E: the lower the skill, the higher E and the lower η_M with the same speed [3,4]. We assumed that our subjects had a W_{tot} of 67 W since less trained swimmers have a higher drag and losses than elite swimmers [3]. With an assumed η_M of 0.18 an E of 370 W results.

Experimental methods

The study was approved by the Medical Ethical Committee of the University of Amsterdam (Project W18_022, Decision #18.033). Nine subjects signed an informed consent and completed a questionnaire (on demographics, pulmonary and cardiac history). All were members of a diving club, certified "fit to dive" less than one year prior, took part in a (nearly) weekly pool snorkel training and performed endurance sports for at least two hour per week. Although not competitive swimmers, they were considered among the fittest members of their club. The swim tests, performed in an indoor pool of 20 meters' length at 27°C, were conducted before 2020. The test was to swim as far and as fast as possible in front crawl style at a steady velocity for 12 minutes (Cooper swim test) with a half-facemask. To maximize the number of breathing cycles per length, no fins were used.

Five of the subjects performed the first test with a snorkel; the subsequent week (or at most the week after that) they swam without snorkel, while the others did it in reverse order. All used the same J-type snorkel that was also used in a previous study [1].

The swim velocity in both conditions was calculated from the scored distances. To be able to count complete lengths, the swimmers were allowed to finish their last length after the 12 minutes, and the exact swim time *T(s)* was recorded with a classic stopwatch. Hence v (swim velocity) equals $20N{\cdot}T^{-1}$ ($m{\cdot}s^{-1}$) where N is the number of lengths. No correction for turning points was made since they were executed in virtually the same way under both conditions.

In the non-snorkel condition, the number of breaths was counted by the experimenter during four lanes. The heart rate, HR – in beats per minutes (bpm) – was continuously recorded with a waterproof A300 Polar monitor (Polar Electro Inc., Lake Success, New York). HR was averaged per subject over the whole test (HR_{av}), as well as over the period after it reached a stable state ($HR_{av\ stabel}$). The maximum HR (HR_{max}) was also noted.

Analysis was performed with the (paired) Student's t-test or the Wilcoxon Rank-Sum test; $p \leq 0.05$ (two-tailed) was considered significant. Normality was tested with the Shapiro-Wilk test.

RESULTS

Experimental results

Table 1: Subject demographics
n=9 (including 1 female)

	age (years)	length (cm)	BMI ($kg{\cdot}m^{-2}$)
mean	53	180	25
SD	13	8	1.7
min	27	170	23
max	70	193	28

Age, length and BMI of the subjects are given in Table 1. Table 2 presents the mean velocities of the nine individual average velocities and $HR_{av\ stabel}$ of the Cooper swim test under both conditions. There was no relation between the relative velocity difference and the velocity without snorkel. $HR_{av\ stabel}$ showed no difference under either condition; the same held true for HR_{av} (3.5 bpm lower) and HR_{max} (6.5 bpm higher).

Observation of the swimmers without snorkel showed a mean breathing frequency of $28{\cdot}min^{-1}$ or one breath per 2.14 seconds (s).

Table 2: Results of the Cooper swim test

	Cooper test	
	velocity ($m{\cdot}s^{-1}$) mean±SD	$HR_{av\ stabel}$ (bpm) mean±SD
with snorkel	0.72±0.09	144±16
without	0.69±0.09	143±14
difference %	+4.4±3.9	0.8±3.4
p-value	0.008*	0.60

* Wilcoxon Rank-Sum test

Results of the modeling

The breathing cycle

The breathing cycle without snorkel consists of four phases: inhalation; breathing pause when turning down the head after inhalation; short period with face down; and lifting of the head at the end expiration. To model costs for each period, the assumed durations were 0.74 s, 0.6 s, 0.2 s, and 0.74 s (including 0.6 s of expiration), respectively. It was further assumed that the breathing cycle with snorkel was also 2.14 s, was sinusoidal, and without pause since the swimming speed was maximized.

From the known relationship $\dot{V}O_2 - v$ [5], considering the swimming skills of our subjects and assuming a $\dot{V}E/\dot{V}O_2$ ratio of 21, our $\dot{V}E$ is estimated to be 56 $L{\cdot}min^{-1}$. It may be assumed that on an individual basis swimming with and without snorkel results in the same $\dot{V}E$.

Work and power of swimming with a snorkel

The needed power of breathing with a snorkel

The breathing power of the snorkel is 0.12 W ($\dot{V}E$ =56 $L{\cdot}min^{-1}$) and the needed power of the airways is 0.68 W (calculated from [1]). When breathing through a snorkel there is negative pressure breathing of about 13 hPa due to the lung being under water (centroid -13 cm). It has been found that with negative pressure breathing of 21.4 hPa, at $\dot{V}E$ = 40.3 $L{\cdot}min^{-1}$, the inhalation expenditure is 9.5 J for a breath taking 5.2 s [6]. Extrapolating to 56 $L{\cdot}min^{-1}$ and -13 hPa (with a cost assumed to increase quadratic to relative pressure), the negative pressure expenditure becomes 8.5 J, resulting in 1.6 W. Correcting for the airways cost on dry land, 0.90 W remains.

Work and power of swimming without snorkel

Power of breathing without snorkel

During an inhalation lasting for 0.74 s, the equivalent $\dot{V}E$ is 76 L·min^{-1}, and during the shorter exhalation (0.6 s) $\dot{V}E$ is 93 L·min^{-1}. This results in an airways power of 1.31 W (calculated from [1]). Also, swimmers have negative pressure breathing, 11 hPa. which adds a breathing power of 1.0 W.

Kinematic cost of head lifting while swimming

Observations have shown that about half of the head and a small part of the shoulder, weighing together approximately 5.5 kg, are lifted out of the water while swimming. After lifting (lasting 0.6 s) its potential energy, *mgh*, equals 1.90 J (with r=10 cm, h=0.0345 m). With a breathing cycle of 2.14 s, the power is 0.9 W.

Extra drag and hydrodynamic losses caused by head lifting

With front crawl swimming at 1 m·s^{-1} the drag and hydrodynamic power losses are each about 55 W [2]. With a velocity of 0.69 m·s^{-1} (as measured for our subjects without snorkel, Table 2), these two values are expected to be halved when extrapolating from ref. [2]. When head lifting, the losses would be comparatively small, since extra turbulence hardly occurs. The power of the drag of lifting is estimated to be about 0.16 W (with an estimated velocity of head lifting of ca. 0.17 m·s^{-1}, a frontal area ratio of head (up) versus body (forward) estimated at 1/6, and the head movements lasting 1.2 s per breathing cycle, after extrapolation [2] and using the drag equation). With the small hydrodynamic losses, the total extra power is in the order of 0.2 W.

Kinematics of head rotation

Observations have shown that for inhalation the head rotates upward and sideways; combined about 1.5 radians. The angular velocity at the end of the movement is assumed to be about 3 rad·s^{-1}. Then, the rotational kinetic energy E_{rot} is 1.24 J according to eq. (1) and eq. (2). The deceleration of the rotation is assumed to have a low cost of 0.1 J, since it is nearly passive (angular excursions roughly maximal). Since the rotation lasts 0.6 s, this results in 0.62 W. Also, the reverse rotation is estimated to require 1.34 J. Hence, the total rotational power is 1.24 W. The kinematics of the small and slow side-roll of the shoulder can be ignored.

Extra drag and hydrodynamic losses due to head rotation

To estimate these costs by extrapolation[2], the following factors were taken into account: the mean tangential velocity of the surface of the head during its to and fro rotations, ca. 0.2 m·s^{-1}; the mean water-exposed skin surface during these rotations, ca. 7 dm^2; non-spherical head shape; some shoulder losses; rotation time per breathing cycle. The power was estimated to be about 0.3 W.

Table 3: Results of modeling of components of $\dot{W}_{snor}$ and $\dot{W}_{no\text{-}snor}$

	$\dot{W}_{snor}$ (W)	$\dot{W}_{no\text{-}snor}$ (W)
snorkel*	0.12	
airways*	0.68	1.3
negative pressure breathing#	0.90	1.0
kinematics of head lifting*		0.9
drag and losses of head lifting#		0.2
kinematics of head rotation*		1.24
drag and losses of head rotation#		0.3
total	1.70	4.94
expected velocity difference (%)	5.2	
measured velocity difference (%)	4.4±3.9 (m±SD)	

* Is the same on dry land. # Only when swimming.

Comparison of $\dot{W}_{no\text{-}snor}$ and $\dot{W}_{snor}$

Table 3 summarizes the various powers with and without snorkel. The estimate of $\dot{W}_{no\text{-}snor}$ was 4.94 W, 7.5% of $\dot{W}_{tot}$ (66.6 W) and that of $\dot{W}_{snor}$ (1.70 W) 2.7% respectively. The non-breathing part of $\dot{W}_{no\text{-}snor}$ (2.64 W) was estimated to be 4.0% of $\dot{W}$. By expressing the difference between $\dot{W}_{no\text{-}snor}$ and $\dot{W}_{snor}$ as a fraction of $\dot{W}_{tot}$, the product of $\dot{E}$ (370 W) and η_M (0.18), the difference in swimming velocity v_{diff} (%) can be calculated (under the assumption that power versus velocity is linear for small changes):

(3) $v_{diff} = 100/(1-(\dot{W}_{no\text{-}snor}-\dot{W}_{snor})/(\eta_M \cdot \dot{E}))-100$ (%)

This results in 5.2%, suggesting that one can swim faster with a snorkel. The actual measurements showed a difference of 4.4% (95% confidence limits 1.4% and 7.4%).

DISCUSSION

General considerations

Despite the many uncertainties in the calculations and simplifications of the model, the swimmer without a snorkel needs more power to breath, resulting in slower swimming. The practical experiment confirmed this theoretical prediction.

Can an increase in swimming speed of 5.2% of the snorkeler be explained by considering the mass of the muscles involved? The musculature to rotate and lift the head (M. sternocleidomastoideus, M. trapezius, inner neck muscles and involved shoulder muscles) has a mass of about 1.7 kg, and this musculature is active for about 60% of the time. While swimming, the involved musculature of legs, arms and shoulders has a mass of about 30 kg [7]. It is assumed that all these muscles work continuously and at the same level, and expend 84% of the work of the entire body [8]. Then, the energy expenditure of the muscles contributing to lifting and rotating the head will amount to approximately 2.9% of that of the total body (84 x 0.6 x 1.7/30).

Main findings

1. $HR_{av\ stabel}$ with and without snorkel is virtually the same (0.8% difference, p=0.60) suggesting that the cardiac output is the same, and that the subjects did maximize their exertion under both conditions with the same total energy expenditure.

2. Modeling shows that swimming with a snorkel has a 0.40 W lower pulmonary power and 2.64 W less additional mechanical power (Table 3). With the same energy expenditure as the non-snorkeler, more energy is available to the snorkeler for propulsion, resulting theoretically in a 5.2% higher swimming velocity. Experimentally, 4.4% was measured.

3. Based on the ratio of muscle mass for rotating and lifting versus that for propulsion (mainly arms and legs) the extra power without snorkel is about 2.9% of the total, whereas the model predicted 4.0% more power for head movement.

Weaknesses and limitations

An important weakness is that many variables were not measured; only reasoned estimates were made. The components of both cost models contribute differently to the results and have different levels of reliability. The parameters for hydrodynamic losses and drags contribute little, and have low reliability while those for the kinematics are (rather) large and more robust; this also holds true for the airways contribution. Underestimates of drags and losses give a too low difference between $\dot{W}_{no\text{-}snor}$ and $\dot{W}_{snor}$ and hence too low an estimate of the velocity difference. Overestimates give the opposite effect.

All subjects without snorkel showed a vortex under the armpit on the side of inhalation. Its cost was not taken into account, nor was that behind the neck considered.

Observation of the turning points showed no difference in efficiency, but a small difference in turning time cannot be excluded. Suppose that in a worse-case scenario the swimmers needed even 0.3 s more time, then the difference in speed would decrease from 4.4% to 3.4%.

After the test, subjects were not completely exhausted. They recovered rather quickly and then continued their weekly training within five minutes. This is the reason that the $\dot{V}E/\dot{V}O_2$ ratio was assumed to be close to 21. Larger ratios increase the $\dot{V}E$ estimate and consequently the inhaling cost difference between snorkeling and non-snorkeling.

During the study the method for modeling energy expenditure underwent refinements and additions of new components. In all these versions the gain in velocity by the snorkeler ranged from 3% to 7%, which can be seen as a sort of range of confidence of the modeled outcome.

The Cooper swim test was performed by well-trained snorkelers. Their freestyle skills varied, as illustrated by the velocity range of 0.58 to 0.85 $m \cdot s^{-1}$. In this small sample, no indication was found that the faster swimmers show a smaller relative velocity difference than the slower swimmers, but we cannot exclude that. Since we did not examine competitive swimmers with snorkel experience we will not speculate about their velocity difference.

In the literature it is often stated that breathing though a snorkel may induce hypercapnia (i.e., dead-space effect). However, in view of the high tidal volumes snorkelers generally have, this is highly unlikely [9].

The snorkel adds some drag to the total body drag. The drag of the mouthpiece is virtually zero. The part of the snorkel pressed against the temporal skin is just before the shoulder. Possibly, the effective cross-frontal area of the whole body, including the moving hands, arms, legs and feet increases with about 1% to 2% and so does total drag. This is probably smaller than the difference in body drag between the swimmer and the snorkeler since the latter has better streamlining (decrease of drag coefficient). Extra hydrodynamic losses are nil.

Equation (3) implies that v_{diff} is reciprocally dependent on $\eta_M \cdot \dot{E}$. Therefore, a reasonable estimate of both parameters is crucial for the outcome. We cannot exclude that the used values deviate some 15% from the actual values. However, an underestimate of $\dot{E}$ implies an overestimate of η_M; hence both inaccuracies cancel more or less. Consequently, for such changes the outcome is fairly robust.

The swimmer and the snorkel

Orientation at the surface is necessary while swimming with scuba gear. For propulsion, the surface-swimming divers generally use fins, not arms. Without a snorkel divers must lift and rotate the head to inhale, resulting in speed reduction. When lifting only the head, the cost of the maneuver doubles and the speed reduces by nearly 5%. Inflation of the buoyancy compensation device (BCD) so that the mouth becomes free (requiring at least 8 L of air) obviates the need for lifting but increases the equivalent cross-sectional area of the diver by about 15%. Since theoretically drag force is proportional to area, this will cause a substantial velocity reduction. Swimming on the back with the BCD inflated increases the cross-sectional area even more due to the oblique body position, and orientation is hindered. So, without a snorkel the diver is at a disadvantage in both situations. These disadvantages increase with surf and swell, making swimming without a snorkel even more tiring. This may increase the risk of arterial gas embolism in a surfaced diver who has to swim a substantial distance [10].

CONCLUSIONS

This study suggests that use of a snorkel when swimming on the surface saves a significant amount of energy by obviating the need to rotate and raise the head when inhaling. The extra breathing work added by the snorkel is negligible. With a snorkel, swimmers are able to swim faster and surface-swimming divers will tire less quickly and experience more comfort. It is recommended to make the snorkel a mandatory piece of equipment of the scuba diver.

A physical model was presented for predicting energy expenditure when swimmers rotate and raise the head to breathe. This model appears to give meaningful results but requires further validation and refinement.

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Conflict of interest statement

The authors have declared no conflicts of interest.

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