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Faculty of Fisheries and Protection of Waters

Institute of Aquaculture and Protection of Waters

Bachelor thesis

Critical swimming speed in intensively cultured European perch (*Perca fluviatilis* L.): Influence of fish size, production system and repeated testing

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Thanks

I would like to say thank you to my supervisor Dipl.-Ing. Vlastimil Stejskal, Ph. D. for his professional help and leadership, spent time with helping me. Than I would like to say thank you for professional help to my consultant MSc. Tran Quang Hung and to laboratory staff Ing. Markéta Prokešová Ph. D., Ing. Pavel Šablatura and Ing. Jan Matoušek. In the end I would like to say thank for psychical support to my family and friends.

Content

1. Introduction

Intensive aquaculture farms and recirculation aquaculture system (RAS) are increasing their number at this time as a reaction to rising demand for fish and limited water sources. Especially in Czech Republic with stagnating water reserves this modern and water saving methods will be necessary to produce sufficient quantities marketable fish, juvenile fish or for artificial reproduction in controlled conditions. The biggest advantage of such aquaculture system is, that it is possible to keep large biomass of fish in space with small footprint. Other positives of RAS systems are, marketing advantage (supply of fish throughout the year x seasonality in the classic fish farming), elimination of the negative impact of fish-eating predators (roofed buildings), relatively less dependent on the external environment, minimise the risk of escape of farmed fish and high degree of food safety. In comparison with pond aquaculture it is more effective (one place, possibility of control) but more qualified staff to control water parameters and health of fish is necessary.

One of the potentially attractive species for keeping in RAS is European perch (*Perca fluviatilis*). This species of fish is very popular by consumers in Switzerland, Germany, France, Austria and Scandinavian countries. Production of perch in Europe is not enough to supply whole European market. Majority of European production of perch comes from pond aquaculture or from free waters (lakes in north part of Europe). This source has a disadvantage of difference in fish sizes, seasonality and that the final product is marketed as frozen fillets. Methods of keeping perch in RAS have many shortcomings and it is very difficult to keep perch production commercially feasible.

With this thesis there will be effort to make experiments with testing swimming performance (especially critical swimming speed). Knowledge of fitness and swimming behaviour is a key to design a better keeping system for this fish species. Moreover, in the future there can be a chance to select fish according to their swimming performance to good and worst swimmers. With this selecting we could get better effectivity in growth rate and yield of economically attractive parts of fish body. This selection can help to economics of fish farms itself if our method will be successful, too.

2. Literature research

2.1. Biology of European Perch

2.1.1. Description

Body shape of perch is developed for quick movement and effective hunting. It means that body is relatively high and strong. The highest part is located in the same part as a first dorsal fin. Second part of the scientific name of Eurasian perch - *fluviatilis* - means riverine, what suggests that this species prefer turbulent-like conditions (at least during some period), typical for rivers. European perch (*Perca fluviatilis* L.*)* mouth is terminal, toothed by many small homodont teeth. Back edge of the operculum is stretched to the tip with the big thorn (Hanel and Andreska, 2013). Body is covered by small ctenoid scales and usually is greenish – yellow coloured. On the side there are 5-9 black transverse bands. First dorsal fin is grey with a black spot on the top. Second dorsal fin is greenish – yellow, pectoral fins are colourless, and the other fins are red or orange. We can find many forms and varieties of coloration based on geographical origin or living conditions (Pimakhin 2012). Sexual dimorphism is not clearly visible, except the time of a mating period (Dubský a kol., 2003). During the mating period females have bigger abdominal cavity and brief time after spawning they have a bigger urogenital papilla (Švátora, 1986). Within 2–3 years, when the body length is 15–25 cm, perch reaches sexual maturity (Orban et al., 2005)

2.1.2. Zoogeography of European perch

It is widely distributed across Europe and Asia, ranging from northern Scandinavia to central Italy, and from the west coast of Ireland to the Kolmya river in eastern Siberia (Pyle and Couture, 2016). In Europe it is present except of the Iberian Peninsula, southern Italy and the western part of the Balkan Peninsula (Berg, 1965) and northern part of Scandinavian Peninsula. The geographic distribution of perch is limited by water temperature through its effect on the metabolic process. Perch tolerate a wide range of temperatures (4-31°C) (Rougeot, 2008) with optimal level for growth around 23 °C (Policar et al., 2009). Introduced populations occur in South Africa, New Zealand, and Australia (Nelson, 2006). Whole geographical distribution area is shown in Fig. 1.

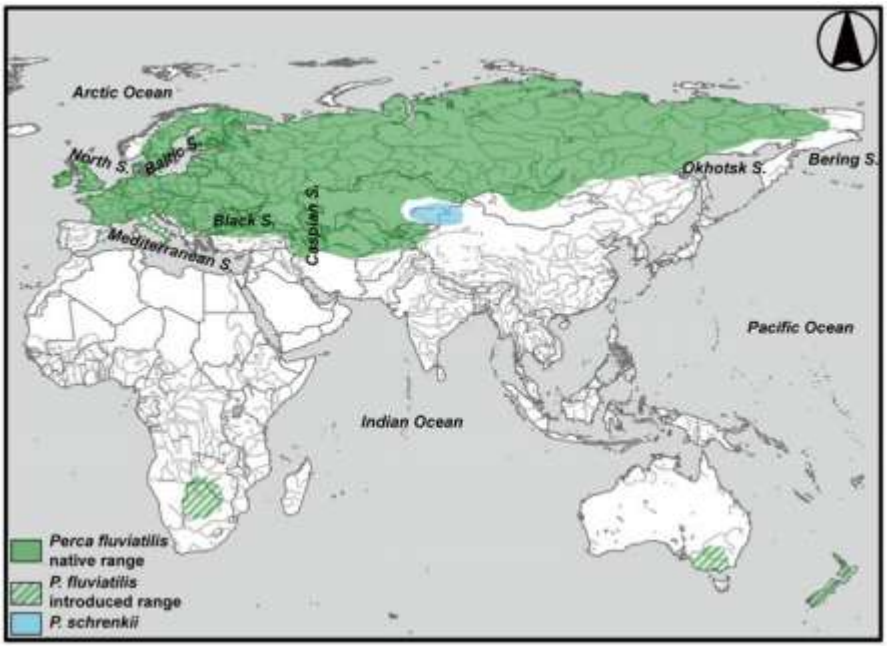


Fig. 1 The native and invasive distribution of European perch. Information adapted from Collette and Bănărescu (1977), Craig (2000), Page and Burr (2011), and Fuller and Neilson (2012).

2.1.3. Environment of European perch

Perch is distributed over almost all suitable habitats, i.e. various floating as well as stagnant waters such as rivers, streams, fishponds, artificial and natural lakes (Hanel and Lusk, 2005). Perch is quite tolerant to temperature, oxygen and well tolerates an increased eutrophication. Because of its euryhaline tolerance, perch is also present in brackish water (example: in the Baltic Sea) (Rougeot, 2008).

Smaller fish live in flocks. Flocks are getting smaller with rising size of fish, just the largest individuals live alone. A flock mainly forms through the day, during the night it usually fall apart (Dubský, 2003)

2.1.4. Nutrition of perch

Natural food preferences are different along the life period of perch. Young larvae first feed on zooplankton (rotifers, cladocerans and copepods) (Rougeot, 2008) and later feed on invertebrates and small kinds of fish. The larger individuals are piscivorous. Cannibalism is an important characteristic in this species and appears firstly in young fingerlings (15 mm). Feeding behaviour occurs mainly about the noon and at twilight (Rougeot, 2008).

Formulated feeds primarily made for feeding salmonids or marine species are used for feeding perch in intensive aquaculture (Policar et al., 2009). Nutrition level of artificial

feed depends on the life stage. Recommended nutrition level is 43 – 50 % protein, 10 – 15 % carbohydrates and 13 – 18 % lipids for highest growth rate (Kestemont et al., 2015). Optimal feeding rate should be counted by formula to specific biomass in tank (Policar et al., 2009; Fiogbé et al, 2003; Mélard et al., 1996).

2.1.5. Growth rate

Perch is middle-aged fish with life length about 15 - 20 years. Average age of fish is about 5 – 7 years (Lusk et al., 1992). Between age 6. – 8. mortality starts to growing rapidly, especially in case of males (Švátora, 1998). Mean body length ranges from 20 to 35 cm with a maximum of 51 cm and mean body weight from 0.2 to 1 kg or more, with a maximum 5 kg (Rougeot, 2008; Švátora, 1986). Perch display a sexual growth dimorphism in which female growth is 20% faster (Rougeot, 2008; Stejskal et al. 2009). Growth rate is very dependent on many environmental factors such as temperature, light, oxygen, prey availability and harvest rates (Zachary, 2015). Maximal daily growth rate in reported intensive aquaculture is between 0.06 to 1.8 g (Kestemont et al., 2015).

Growth differences also exist in different populations according to their geographical distribution. Lower potential for growth has a population from the south distribution area. Populations from north distribution area showed higher growth rate (Mandiki et al., 2004; Vanina et al., 2019).

2.1.6. Importance of European perch

European perch is very known species because of its frequent occurrence in all types of free water. Occurrence of this species has many positives and negatives. European perch is important in commercial and sport fisheries (Pyle and Couture, 2016). In commercial fisheries based on carp European perch makes troubles (destroying population of important species in ponds, food competitor), but helps with elimination of small fish with low economical value. Problems with small European perch feeding on zooplankton in drinking water dams is commonly reported. Quality of this water, in reaction to falling down of zooplankton quantity, falls down (Švátora, 1986).

Majority of production of European perch is still based on fish caught in free water especially in regions of North Europe as Finland (17,000 tonnes), Russia (3,500 tonnes), Poland (2,000 tonnes) and Estonia (1,200 tonnes). The European production from farms

was at 315 tonnes in the year 2005 (Czech Republic just 15 tonnes). The biggest consumers for perch are people in the Alpine region (Watson, 2008).

2.2. Farming European perch in intensive aquaculture

Percid farming is still in its infancy, however there are already a handful of commercial ventures successfully producing percids (Overton et al., 2015). There are two main percid species used in aquaculture including European perch and pikeperch (*Sander lucioperca*) in Europe. Perspective of keeping European perch is in good knowledge of artificial reproduction, good growing rate in intensive aquaculture and high meat quality without "Y" bones and market interest (Watson, 2008). But there are several critical factors affecting the success of perch intensive culture including poor knowledge of fish nutritional requirements, clinging and non-feeding behaviours, non-inflation of the gas bladder, size heterogeneity and cannibalism (Kestemont et al., 2015).

Three different culture systems exist for percid production. First is a traditional extensive polyculture system, second is a semi-intensive culture farming and third is an intensive perch farming under RAS (Recirculating Aquaculture System) (Policar, 2015). The extensive and semi-intensive systems are limited by many factors like predation, illnesses, higher mortality, climate and changing parameters of water.

2.2.1. Semi-intensive perch farming using the combination of pond and intensive RAS culture

This production system utilizes advantages of both pond and RAS culture systems (Policar et al., 2015). Small ponds or outside tanks are used to rear juvenile to advanced fry stadium, then moved to RAS system and adapted onto dry diet. Before moving the larval stadium to ponds or tanks it is necessary to prepare the ponds and tanks. The ideal pond is smaller than 2.5 ha, with littoral vegetation, mesotrophic (loam - sand ground), quick launching - maximal in 24 hours and possibility of catching under the bank using drain equipment. Wintering (empty pond during winter) and fertilizing by compost, manure or mowed grass (250 – 400 kg. ha^{-1}) are parts of pond preparation. Larvae are moved within 2-4 days after hatching in quantity 100 – 200 000 (500 000) ha^{-1}. Small larval fish are feeding on small zooplankton (rotifers, nauplial and copepodite stadium of *Cyclops*) and then on larger zooplankton species like *Cyclops, Mesocyclops, Bosmina* and

Ceriodaphnia. Growing phase in ponds requires 45 – 60 days of rearing (Stejskal et al., 2010) depending on availability of zooplankton and required size of fish to reach "advanced" fry. For rearing fish in semi-intensive system there are normally used 10 m^2 ($5m^3$) outsides tanks supplied with water from river, or better with oxygenated pathogen-free well water. The tanks are fertilized with an initial single input of 1.5 kg of chicken manure pellets put in a basket that stimulated the development of phytoplankton then zooplankton. 4,000 – 6,000 eggs. m^{-2} is recommended stocking density to produce perch in an outdoor tanks and a rearing temperature of 17°C. Feed of fish is quite same as in ponds (by zooplankton). Rearing period last 44 days (Kestemont et al., 2015; Rougeot et al., 2008). Positives in this method include cheaper rearing of juveniles than in RAS, high effectivity and rationality. Survival rate in a rearing period is 20 – 40%. During habituation survival rate is about 95 % after one week of adaptation (Kestemont et al., 2015).

2.2.2. Intensive farming of juvenile perch in RAS

Intensive farming of perch has many advantages (e.g. stable culture conditions, rearing of fry produced by off-season spawning, more predictable production of juveniles and effective control of cannibalism) when compared to other methods. However, there are several critical factors in the intensive farming system like poor knowledge in requirements in nutrition, non-inflation of the gas bladder and cannibalism (Kestemont et al., 2015). Initial stocking density is usually in ranges between 20 – 50 larvae. l^{-1}, but it is possible to start with higher stocking density (up to 100 larvae. l^{-1}). Then it is necessary to reduce density as the fish grow. Major cause of mortality in this stage is cannibalism as a consequence of high heterogeneity in growth rate. High stocking density (100 fish. l^{-1} and more) caused higher survival compared to low density. Feeding starts in two to three days after hatching using *Artemia salina* nauplii. After 21 days fed by *Artemia* larvae start training (weaning) to accept dry feed. Training to accepting dry feed utilise technique of co-feeding which means mixing of dry feed with *Artemia* in different proportions. Ratio between *Artemia* and dry feed rises in behalf of dry feed. After 25 days there is feeding by dry feed only.

2.2.3. Intensive farming of adult perch in RAS

Farming in RAS is an effective method of producing market size fish. For the best effect of growing water temperature about 23 °C is ideal. Higher temperature than 27 °C and lower than 11 – 20 °C reduces the growing rate. For example, 15g fish reared at 27°C has reduced growth rate by 12% when compared with fish reared at 23°C. Difference is even higher at larger fish, as 100g fish reared at temperature lower than 20 °C reduces growth rate by 20% when compared with fish reared at 23°C (Mélard et al., 1996). It is recommended to maintain pH level in range from 6 to7.5 (Policar et al., 2009). Other important parameter of water is oxygen saturation. The oxygen level should be maintained above 5 mg O_2. l^{-1}or above 60 % saturation at outflow from fish tanks (Kestemont et al., 2015). Oxygen less than 5 mg O_2. l^{-1} or below 60% of saturation can cause problems like stress and higher mortality. Other very important parameters are concentration of ammonia ($N\text{-}NH_3$) and nitrite (NO_2^-). Acute lethal concentration (96hLC50) of ammonia is 0.80 mg. l^{-1} but negative effects (reduced growing rate) are visible at level 0.03 mg. l^{-1} $N\text{-}NH_3$ (Vandecean et al., 2008). Maximal tolerated level of nitrite for long term rearing is 0.5 – 0.7 mg NO_2^-. l^{-1}. Kroupová et al. (2013) reported that lethal concentration of nitrites is 11 mg. l^{-1} NO_2^- (48hLC50). Lethal concentration of nitrite is even significantly lower (1–3 mg NO_2^-. l^{-1}) during intensive perch culture under RAS (Kestemont et al., 2015).

Market size of European perch is 120-150 g (Kestemont et al., 2015) or 100 g (Policar et al., 2009) and it is reached after 12- 14 months of rearing in water of 23 °C. This production is faster compared to culture in ponds. Production cycle in ponds is about 800 days (Rougeot and Mélard, 2008; Policar et al., 2009). Optimal biomass ranges from 35 $kg.m^3$ for 5 g fish to 80 $kg.m^3$ for 150 g fish (Policar et al., 2015). Maximal daily productivity in intensive farming ranges from 600 g. m^3 (approx. 5 g perch) to 350 g. m^3 (approx. 150 g perch). Survival rate is fluctuating between 60 % and 70 % (Mélard, 2008). Nowadays pelleted feed is used for feeding perch in rising diameters (from 0.8 mm to 3 mm). Recommended content of protein is 37 – 43 % and of fat about 12 % (Policar et al., 2009). Some farmers are using floating feed for better inventory and adjustment of daily feeding rate. Feeding by pellets has disadvantage such as negative effect to livers of fishes and saving fat in abdominal cavity.

2.3. Measurement methods of oxygen consumption

Respiratory is one of the important physiological and environmental function. Measurement methods of oxygen consumption rates on fish and other water organisms commonly involves using one of four different methods:

1. Closed respirometry (constant volume respirometry)
2. Flow-through respirometry (open respirometry)
3. Intermittent flow respirometry (stop-flow)
4. Bimodal respirometry

Each type of respirometry method has advantages and disadvantages that will be described.

2.3.1. Closed respirometry

Measurements take place in a closed (sealed) metabolic chamber of known volume. It measures the decline in oxygen concentration in the metabolic chamber. In this method oxygen content of the water is measured first at the start of experiment, then the respirometer is closed and at the end of the experiment the oxygen content is measured again. The method of the measurement is shown in the Fig 2. (Loligo system – published papers; Svendsen et al., 2015).

The advantage of this method is, that it is quite simple (easy to construct and operate with it). In this method it is inevitable for the organism to experience progressive oxygen depletion (hypoxia), and a simultaneous increase level of carbon dioxide (progressive hypercapnia) and nitrogenous waste (ammonia and nitrite) levels in the metabolic chamber, especially if the organism is used to test hypoxic condition (Svendsen et al., 2015).

$$\boldsymbol{VO_2} = ([\boldsymbol{O_2}]_{\boldsymbol{t0}} - [\boldsymbol{O_2}]_{\boldsymbol{t1}}) * \frac{\boldsymbol{V}}{\boldsymbol{t}} * \frac{\boldsymbol{1}}{\boldsymbol{BW}}$$

VO_2 = oxygen consumption rate (mg. kg^{-1}. h^{-1})

$[O2]_{t0}$ = oxygen concentration at time t0 (mg. l^{-1})

$[O2]_{t1}$ = oxygen concentration at time t1 (mg. l^{-1})

V = respirometer volume minus volume of experimental animal (l)

t = t1 – t0 (h)

BW = body weight of experimental animal (kg)

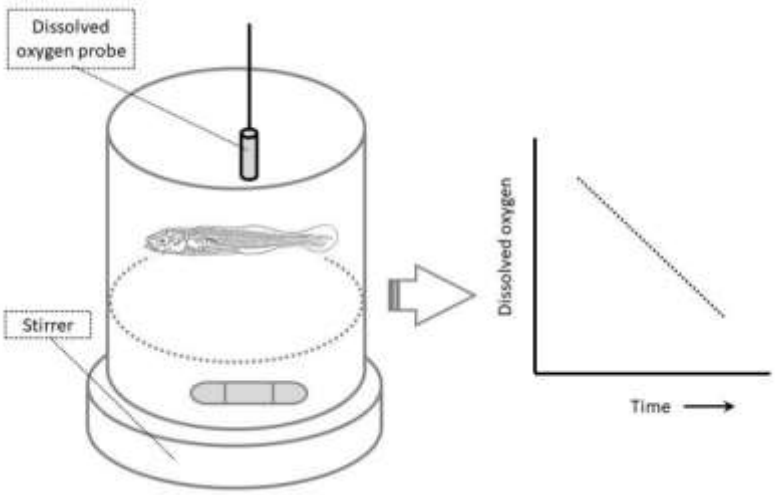


Fig. 2 Method of closed respirometry.

2.3.2. Flow-through respirometry

This method is more sophisticated method for measurements of oxygen consumption than closed respirometry. This respirometry system measures consumption of oxygen (VO_2) or carbon dioxide (VCO_2) (Withers, 2001). Measurements are performed in the flow through respirometer with known flow rate. Calculation is based on difference between inlet and outlet oxygen concentration and adjusting the flow of water through the respirometer to maintain a stable oxygen content difference (Loligo System – published papers; Svendsen et al., 2015). Oxygen consumption rate in this method is calculated by equation:

$$\boldsymbol{VO_2 = \frac{F * ([O_2]_{in} - [O_2]_{out})}{BW}}$$

F = flow rate of water (l. h^{-1})

$\mathbf{[O_2]_{in}}$ = oxygen concentration inflow (mg O_2. l^{-1})

$\mathbf{[O_2]_{out}}$ = oxygen concentration outflow (mg O_2. l^{-1})

BW = body weight of fish (kg)

Respirometry system is fed from an accumulating (header) tank with stable level of oxygen. Water in this tank is saturated by air pump. Water leaving the respirometer system is recycled in accumulating tank and re-oxygenated there (Lighton, 2008).

This method has advantages that improve measurement. Advantages include unlimited duration of the experiment, fact that metabolites are not accumulated (specially CO_2) and measuring take place at constant oxygen level. One of the biggest disadvantage is that oxygen consumption is performed in steady state. That means that the level of oxygen of the inflow, outflow and fish oxygen consumption must be constant (Loligo System – AutoResp user manual).

In RAS it is necessary to add oxygen into the water to maintain required water quality (Stejskal et al., 2009). Flow – through respirometry can be used to control level of oxygen and measure oxygen consumption by comparison of differences in inflow and outflow. Testing schema are shown in Fig. 3 and 4.

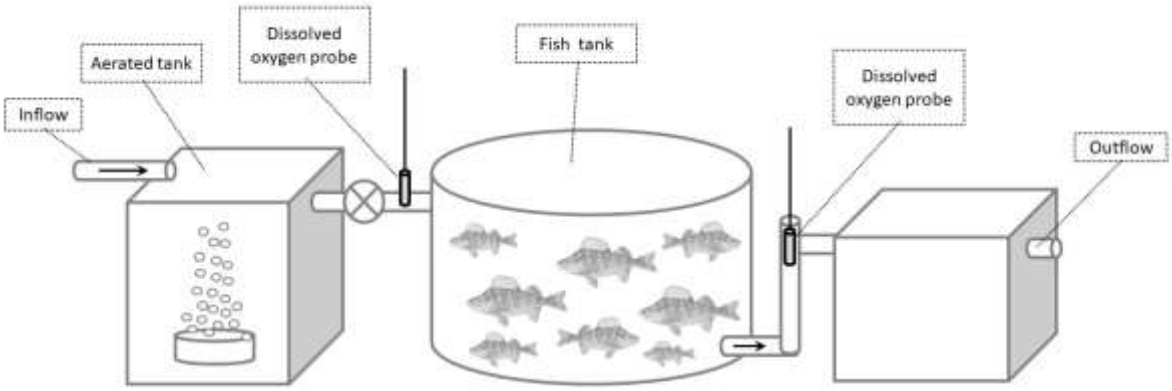


Fig. 3 Model of flow- through respirometry

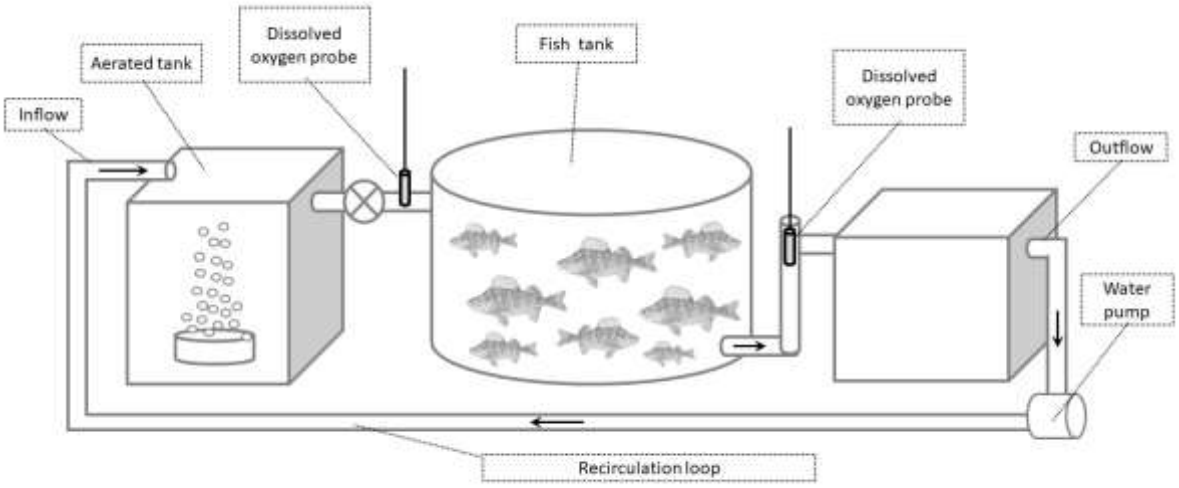


Fig. 4 Model of recirculation flow-through respirometry/intermittent – flow respirometry

2.3.3. Intermittent-flow respirometry

Intermittent-flow respirometry utilises best properties of closed and flow-through respirometry and eliminate or reduce their problems or issues (Svendsen et al., 2015). Generally, the system is divided to inner chamber and ambient tank. The inner chamber is placed into the ambient tank. The experimental fish is placed in a sealed inner chamber with ports for recirculating the water from the ambient tank. Mixing the inlet and outlet water (from the ambient tank) must be avoided in the chamber during measurement. The complete cycle of one measurement consists of an open system period of a flush and closed system period consists of waiting period and measurement period (Loligo System – AutoResp user manual, Svendsen et al., 2015).

The first period is flushing. The flushing is pumping water from the ambient tank to the inner chamber. Water must have the same temperature (± 0.1 °C). Total volume of water flushed out during each flush period should be at least five the respirometer volume. When the flush pump stops to flush, the second period starts – waiting period. During this period, it is necessary to stabilize a delay in the system response resulting in a non-linear oxygen curve (Rosewarne et al., 2016; Loligo System – AutoResp user manual). Schema of this two periods is in Fig. 5.

The third period is the measuring period. It is necessary to have the flush pump off and the chamber must be perfectly sealed. During this period water recirculates just in the chamber because of the oxygen sensor and the level of oxygen. Calculation of fish respiration is from declining of oxygen level in chamber (Loligo System – Auto Resp user manual).

This method uses advantages of closed and flow-through respirometry methods. Especially time option (possibility to perform long-term experiments) is an advantage of this method. The flush pump is controlled by a computer, which means that there are many possibilities of settings.

$$y = \frac{K.V.\beta}{BW}$$

K = rate of decline in oxygen content over time in the respirometer during the measurement period ($kPa.h^{-1}$)

V = volume of the respirometer (l)

β = solubility of oxygen at the experimental water temperature and salinity ($mgl^{-1}\ kPa^{-1}$)

BW= body weight of fish (kg)

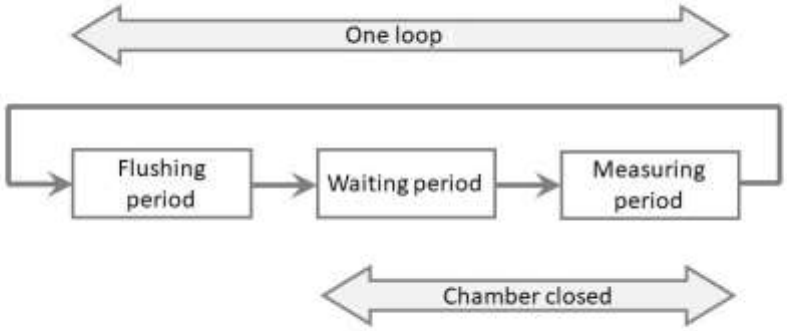


Fig. 5 Scheme of intermittent – flow respirometry

2.3.4. Bimodal respirometry

This method of measuring oxygen consumption uses combination of measuring oxygen consumption in water and in the air. For this parameter measuring it is necessary to have a bimodal respirometer with an aquatic phase and an aerial phase, which quantify respiratory concentrations changes (Lefevre et al., 2016). Such apparatus was constructed for measuring oxygen consumption in species, that can use oxygen from water or from air, with specific respiratory organ. Three methods are used for the bimodal respirometry: closed, volumetric and flow – through respirometry.

The method of bimodal closed respirometry has the same base as the method of closed respirometry just in water. The principle of this method is measuring of decreasing level of oxygen in water and air without aeration. Advantages and disadvantages are similar to closed respirometry in water.

Volumetric method is the most frequented method of bimodal respirometry measuring. It is based on the fact that fish breathe from constant pressure of water and air and released CO_2 by the fish is removed by some absorbent (for example KOH) (Scholander &Edwards, 1942).

The flow – through bimodal respirometry method is based on a flow – through respirometry in water. Principle of this method is that constant flow of air and water hold constant levels of oxygen saturation in measurement tank. This method can be used for longer measuring periods (Lefevre et al., 2016). Method is shown in Fig. 6.

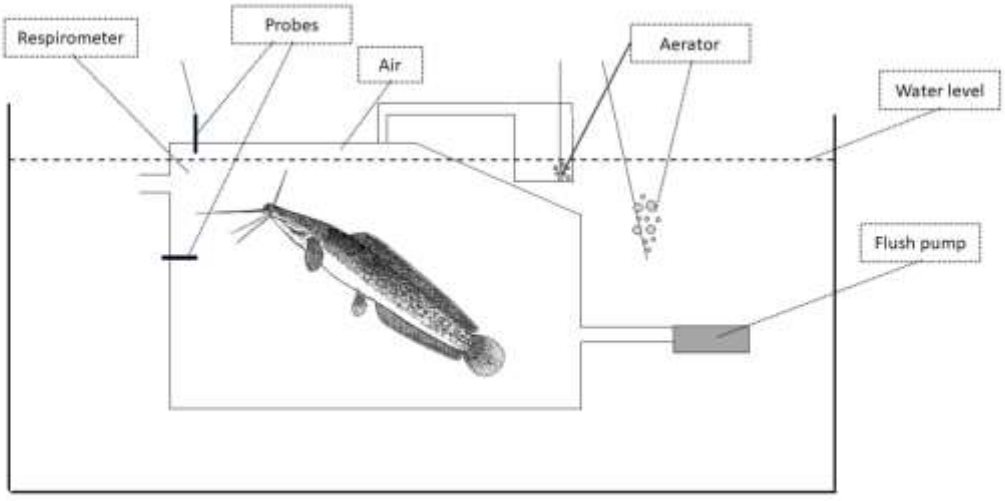


Fig. 6 Principe of measuring bimodal respirometry

2.4. Evaluation of methods for fish swimming performance

2.4.1. Swimming chambers – schema of two types

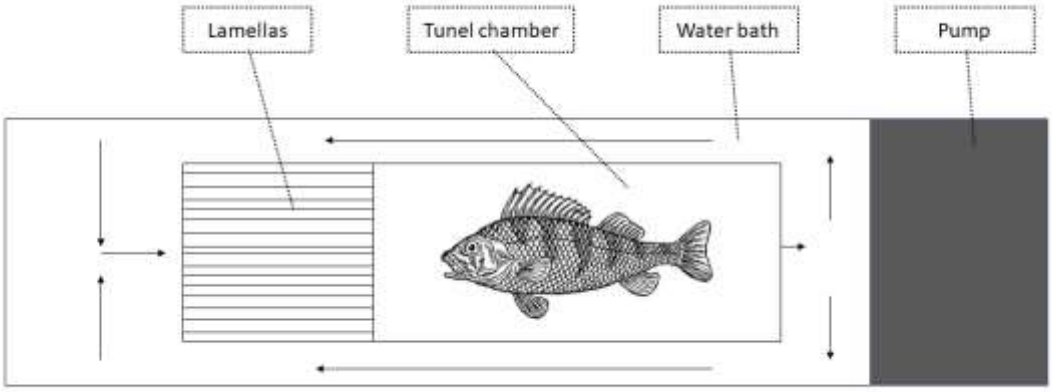


Fig. 7 Principle of Blažka – type swimming chamber (Tudorache et al., 2012)

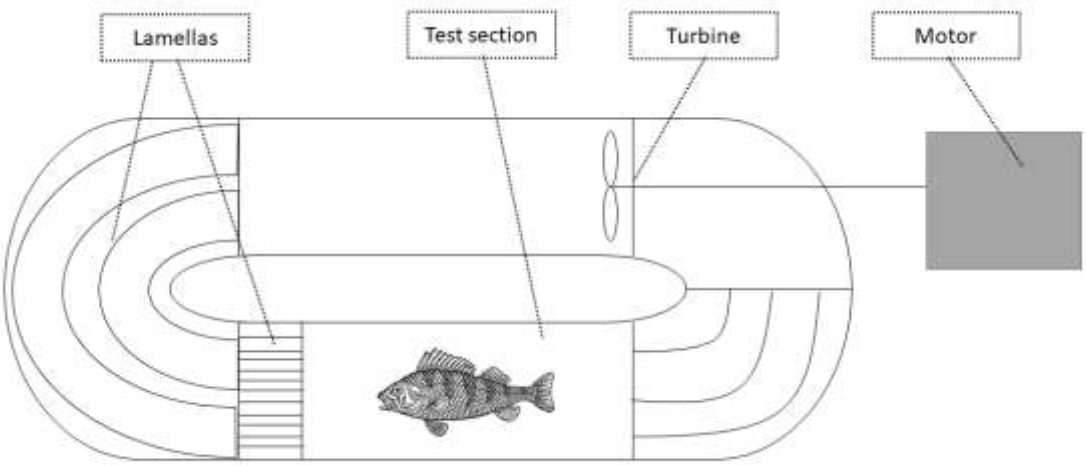


Fig. 8 Principle of Brett – type swimming chamber (Tudorache et al., 2012)

2.5. Swimming performance

Swimming performance is considered as a one of the most important parameter that determines survival and ability of adaptation of many kinds of fish in the nature. Swimming, for fish, is a way to escape from predators, find some food, a mate, and so on. The two main parameters of swimming performance are swimming speed (the most important parameter) and swimming time (Gui et al., 2014). Data on fish swimming performance are measured in swim tests conducted in swim chambers, tunnels or respirometers. Testing of swimming performance is used to determinate muscle energetics, swimming mechanism, gas exchange, physiology of cardiac system, reaction to pollution or hypoxia and others (Tierney, 2015). Testing of swimming performance has many variants (shown in Fig.9).

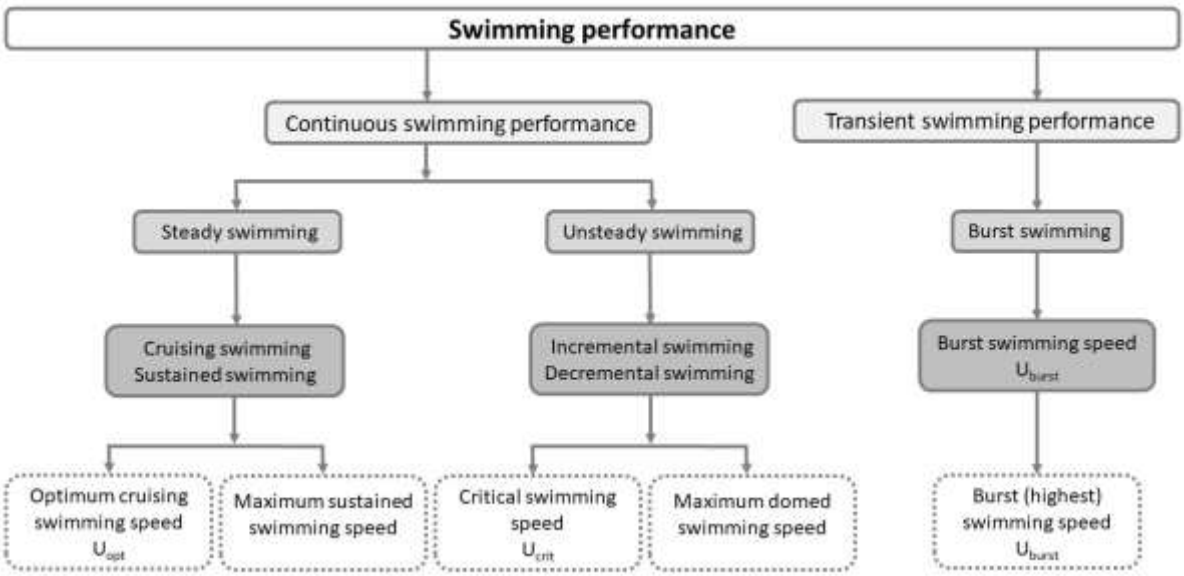
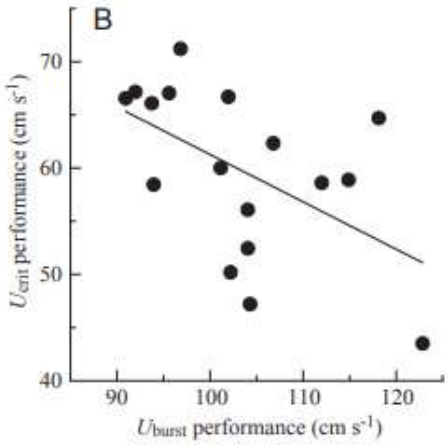


Fig. 9 Terminology and classification of swimming performances in fish (Gui, 2014)

2.5.1. Transient swimming performance and burst swimming

Transient swimming performance is in fact a testing of activity of white muscles and it is performed anaerobically. Maximum duration of this method is 15-20 seconds



(Gui et al., 2014). Method of burst swimming is used to measure transient swimming performance. Burst swimming method is used for measuring glycolytic-based swimming capacity used in situation to avoid predator attack, to gain food, escape from danger and it is placed in swimming chamber. For many species it is a prerequisite for their continued well-being and existence (Beamish, 1978). It is classified as the highest speed attainable by fish. Burst velocity decreases exponentially in time but increase fish with size in absolute units (cm. sec^{-1}) (Reidy et al., 1999). Comparison burst and critical swimming speed is show in Fig. 10.

Fig. 10 Comparison of burst and critical swimming speed (Reidy et al., 1999)

Wiehs (1974) came with suggestion that with a combination of burst swimming and immobile (recovery) phases fish can reduce the expenditure of energy required to cover a given distance by over 50%.

For measuring burst swimming value U_{burst} or U_{max} is used and it is usually measured in centimetres per sec (cm. sec^{-1}) or in body length per sec (BL. sec^{-1}). Before measuring there is a long acclimatization (better 24h) and then swimming in set velocity. During measurement water velocity rise with quickly (approx. >5 $cm.sec^{-1}$) (Reidy et al., 1999). Formula for measuring is:

$$U_{burst} = \frac{\frac{S_L}{l}}{2t_M}$$

$\mathbf{S_L}$ = stride length

l = fish length (cm)

$\mathbf{t_M}$ = muscle contraction time (sec)

2.5.2. Continuous swimming performance

It is an aerobic type of swimming performance. This type of swimming is sustained for a long time (Gui et al., 2014). Duration of this swimming performance is longer than 20 sec and the longest was measured for 168h (Beamish, 1978; Langford, 1974). In this type of swimming fish uses mainly red musculature, but white musculature is used as well in difficult situations (strong or variable current) (Gui et al., 2014). Continuous swimming is differenced to two groups: steady and unsteady swimming performance.

2.5.2.1. Steady swimming performance

Steady swimming performance is a type of swimming when fish is exposed to a constant flow during a change. Then, fish uses mainly slowly oxidative red muscles. This type of swimming speed uses low power output to pass endurance swimming for long migration or routine activities of a day (Katopodis & Gervais, 2016). Duration measurement of this type of swimming is for longer period which is longer than 200 minutes (Beamish, 1978). It may be called cruising swimming speed or sustained swimming speed in some articles. For measuring swimming performance parameters of optimum cruising swimming speed and maximum sustained swimming speed are used (Gui et al., 2014).

Tab 1. Examples of swimming test settings in different fish species

Species	Body weight/ body length (g/cm)	Critical swimming speed	Experimental temperature	Type of swimming tunel	Acclimation
Danio rerio (wild-type)	0.54-1.41 g	56.0±4.8 cm/s_ 15.5 BL/s	28 °C	Brett-type	2 hours
Danio rerio (long-finned)	0.55-1.18 g	43.7±6.8 cm/s _ 12.5 BL/s	28 °C	Brett-type	2 hours
Danio rerio (no-tail mutant)	0.41-0.89 g	19.8±4.7 cm/s_ 6.9 BL/s	28 °C	Brett-type	2 hours
Seriola dorsalis (aquaculture)	18.63 ± 1.12 cm	4.16 ± 0.62 BL/s	17.64 ± 1.61 °C	Brett type (Loligo s.)	1 hour
Seriola dorsalis (wild)	19.31 ± 1.35 cm	4.80 ± 0.52 BL/s	17.64 ± 1.61 °C	Brett type (Loligo s.)	1 hour
Oncorhynchus mykiss (warm acly.)	446 ± 12 g	63.5 ± 1.9 cm/s	5.5-7 °C	Brett-type	day before
Oncorhynchus mykiss (cold acly.)	437 ± 12 g	59.6 ± 1.4 cm/s	5.5-7 °C	Brett-type	day before
Cyprinus carpio (transgenics)	73.19 ± 1.93 g	43.58 ± 1.79 cm/s	9.30 ± 0.37 °C	Brett-type	2.12 ± 0.04
Cyprinus carpio (control)	73.77 ± 0.82 g	53.09 ± 1.28 cm/s	9.30 ± 0.37 °C	Brett-type	2.26 ± 0.02
Poelicia reticulata (upper sword tail)	1.73 ± 0.05 cm	21.3 ± 0.65 cm/s	27-29 °C	very detaily in article	3 minutes
Poelicia reticulata (round tail)	1.76 ± 0.04 cm	22.6 ± 0.79 cm/s	27-29 °C	very detaily in article	3 minutes
Poelicia reticulata (flag tail)	1.75 ± 0.05 cm	23.7 ± 0.96 cm/s	27-29 °C	very detaily in article	3 minutes
Salvenilus alpinus	35.5 ± 1.2 cm	100.2 ± 3.0 cm/s	same as in the river	Brett-type	no informations
Prosopium williamsoni	30.4 ± 1.5 cm	42.5 ± 6.5 cm/s	same as in the river	Brett-type	no informations
Coregonus autumnalis	42.1 cm	80 cm/s	same as in the river	Brett-type	no informations
Notropis atherinoides	6.5 cm	59 cm/s	same as in the river	Brett-type	no informations
Percopsis omiscomaycus	7.2 cm	55 cm/s	same as in the river	Brett-type	no informations
Hiodon alosoides	22.5 cm	60 cm/s	same as in the river	Brett-type	no informations
Coregonus sardinella	29.5 cm	60 cm/s	same as in the river	Brett-type	no informations
Notemigonus crysoleucas	4.5 - 6.8 cm	35.8 ± 3.26 cm/s	21 - 23 °C	Brett-type (Blazka)	uncontroled
Notemigonus crysoleucas	4.5 - 6.8 cm	29.7 ± 2.92 cm/s	22 - 23 °C	Brett-type (Blazka)	uncontroled
Fundulus grandis	8.8 ± 0.6 g	35.7 ± 0.8 cm/s	23 °C	Kolok type	1.5 h in flow 20 cm/s
Fundulus grandis	8.2 ± 0.6 g	39.3 ± 1.1 cm/s	24 °C	Kolok type	1.5 h in flow 20 cm/s
Coryphaena hippurus	658 ± 26 g	2.67 ± 0.17 BL/s	26.3 ± 0.04°C	Brett-type (Loligo system)	4 hours
Coryphaena hippurus	658 ± 26 g	2.76 ± 0.13 BL/s	26.3 ± 0.04°C	Brett-type (Loligo system)	4 hours
Gasterosterus aculeatus	did't difere groups	0.88 (0.38 to 1.44)	17 ± 0.5 °C	Brett-type (Blazka)	no informations
Gasterosterus aculeatus	did't difere groups	−0.33 (−0.84 to 0.19)	18 ± 0.5 °C	Brett-type (Blazka)	no informations

Value of maximum sustained swimming speed shows the maximal steady speed which can fish withstand for a certain length during swimming time. Fish ends in fatigue (Gui et al., 2014). It is not a rule, that maximum sustained swimming speed is limited by the red muscles. Few fish species (mainly pelagic fish) swim sustainable at their maximum (Bone & Moore, 2008). Symbol of maximum sustained swimming is MSS.

Optimal swimming speed is defined as the speed when consumption of energy is minimal for specific distance (Webb, 1975). Symbol of optimal swimming speed is U_{opt} (cm. sec^{-1}) and formula is:

$$U_{opt} = U_f - \frac{1}{b}$$

U_f = speed of flow (cm. sec^{-1})

b = intercept and slope coefficients ($b < 0$)

2.5.3. Unsteady swimming

The duration of unsteady or prolonged swimming is shorter than in the case of sustained swimming, but it is longer than as for burst swimming. Duration range usually between 20 seconds and 200 minutes (Beamish, 1978). Fish can be exposed to varying speeds, that includes incremental swimming (rising) and decremental swimming (Gui et al., 2014). Separate sustained and unsteady swimming is difficult to practice because of variability in swimming speed expressed by fish even when it migrates, or it is in flocks (Beamish, 1978). Unsteady swimming is supplied by red muscles and is supported by fast white muscles. With a rising of a swimming speed fish started to use anaerobic metabolism too. Level of energy is gradually decreasing, and swimming ends in fatigue (Webb, 1984). There are two types of measurement for measuring unsteady swimming: critical swimming speed and maximum domed swimming speed.

Critical swimming speed is defined as the maximal flow velocity that can fish maintain for a time set period and it is the most important measurement to measure unsteady swimming performance (Brett, 1964; Gui et al., 2014). In this type of test fish is subjected to increase in a series of steps. Each step is maintained for a time set period. According to Brett (1964) duration of critical swimming speed was set to 60 minutes. U_{crit} is measured in cm/sec.

$$\mathbf{U_{crit}} = \mathbf{U_m} + \left(\frac{\mathbf{t_m}}{\mathbf{\Delta t}}\right)\mathbf{\Delta U}$$

$\mathbf{U_m}$ = highest velocity at which fish swam for the full-time interval (cm. sec^{-1})

$\mathbf{\Delta U}$ = incremental speed step (cm. sec^{-1})

$\mathbf{t_m}$ = fatigue velocity of fish

$\mathbf{\Delta t}$ = time for the incremental speed step

Maximum domed swimming speed is classified as a maximal tidal current velocity. It can be measured if fish can finish process of a half tidal period and becomes fatigued (Gui et al., 2014). After acclimatization intervals 20 – 60 min are normally used when water velocity rises between 1/4 to 1/9 of previously measured critical swimming speed of fish in pre – experiment (Gui et al., 2014).

2.6. Effects of water velocity on growth of fish in intensive conditions

The vast majority of the newly built intensive fish farms utilize recirculation technology (RAS) of different designs with culture tanks of different shapes (Martins et al., 2010). Generally, these systems allow complete control of the process of production as optimization of important abiotic factors such as temperature, oxygen levels etc. which are fully automated. These systems are constructed to maximize growth (body weight) of fish, system productivity and lower running cost. However, usually these systems are primarily designed to provide water exchange in tanks (usually once per hour) to remove metabolites and provide them for biofiltration. Such operation results in relatively slow and constant water velocities inside the tank (Timmons et al., 1998). Generally, the effect of water velocity is underestimated in RAS based production of marketable fish. In fact, fish under intensive culture conditions are usually exposed to highly modified hydraulic regimes. In some cases, inducing of abnormal swimming behaviour due to high stocking densities or insufficient water velocity in rearing tanks was observed (Damsgård et al., 2006; North et al., 2006), what in turn may affect their fitness. It was already proven that fish with reduced fitness may exhibit reduced growth, survival or/and fillet quality. Optimal flow of water in intensive aquaculture is important for fish growth rate and welfare (Gorle et al., 2018). It was demonstrated that physical exercise promotes fish

growth rate by higher protein synthesis, improving cardiac system and higher oxygen capacity of fish blood (Belal, 2008). Leon (1986) came with an experiment where he explained that exercised fish eats more food than unexercised fish. That means that exercised fish are physiologically healthier - requiring less energy for activities and maintenance than unexercised fish. On the other hand, fish kept in fast water current have a lower growth rate compared to fish at slow or moderate water current. This results shows experiment measured by Solstorm et al. (2015) in Tab 2. It is obvious that optimal hydraulic conditions (water speed) are species-specific and size-specific.

Tab 2. Growth results from experiment by Solstorm et al. (2015) in slow (0.2 ± 0.02 BL.sec-1), moderate (0.8 ± 0.01 BL.sec-1) and fast (1.5 ± 0.02 BL.sec-1) water flow for salmon smolt

	Slow	**Moderate**	**Fast**
Weight (g)			
Start	98 ± 1	100 ± 1	98 ± 1
End	250 ± 3[a]	251 ± 3[a]	238 ± 3[b]
Length (cm)			
Start	22.3 ± 0.1	22.3 ± 0.1	22.2 ± 0.1
End	28.4 ± 0.1[a]	28.4 ± 0.1[a]	27.9 ± 0.1[b]
Condition factor			
Start	0.879 ± 0.003	0.885 ± 0.003	0.879 ± 0.004
End	1.079 ± 0.004	1.081 ± 0.005	1.086 ± 0.006

Davison (1997) came with a suggestion that the water speed can increase growth rate and decrease aggressive behaviour of several Salmonid species. In experiment made by Schram et al. (2009) is described that increase of a flow rate up to 4.7 tank volume in hour promote growth of turbot (*Scophthalmus maximus*). Such flow rate resulted in higher specific growth rate of juvenile turbot. Optimal set of flow rate positively improves growing and quality of flesh texture, which is very important in aquaculture industry (Belal, 2008).

2.7. Effect of water velocity on fish physiology in intensive conditions

Fish kept in low water velocity conditions had a higher total level of lipids compared with fish from the fast flow rates. That means that fish kept in a slow flow rate accumulate more energy than fish kept in fast flow rate (Solostorm et al., 2015). Rising level of protein and protein synthesis in white muscles is positively corelated to fish growth rate with increased water velocity (Houlihan & Laurent, 1987). There is no difference in the

level of ATP when fish kept in different flow rate are compared (McFarlane & McDonald, 2002). Level of glycogen in fish muscles decreased with increased water velocity (Solostorm et al., 2015) as is shown in Tab 3.

Tab 3. Muscle composition results from experiment by Solstorm et al. (2015) in slow (0.2 ± 0.02 BL.sec^{-1}), moderate (0.8 ± 0.01 BL.sec^{-1}) and fast (1.5 ± 0.02 BL. sec^{-1}) water flow for smolt - salmon

	Slow	Moderate	Fast
Protein			
Start	0.550 ± 0.009	0.544 ± 0.007	0.558 ± 0.009
End	0.543 ± 0.001^{b}	0.602 ± 0.001^{a}	0.607 ± 0.001^{a}
Lipids			
Start	0.087 ± 0.007	0.082 ± 0.005	0.092 ± 0.011
End	0.173 ± 0.007^{a}	0.151 ± 0.007^{b}	0.143 ± 0.008^{b}
Glycogen			
Start	117 ± 9	131 ± 9	126 ± 7
End	156 ± 8^{a}	138 ± 6^{a,b}	129 ± 4^{b}
Glucose			
Start	4.42 ± 0.42	4.26 ± 0.33	4.44 ± 0.37
End	3.41 ± 0.28	2.61 ± 0.21	2.84 ± 0.19
ATP			
Start	53.4 ± 2.4	55.0 ± 1.6	53.3 ± 1.1
End	51.6 ± 1.4	48.6 ± 1.0	51.5 ± 1.1
CrP			
Start	94 ± 11	108 ± 13	101 ± 11
End	107 ± 6^{b}	108 ± 5^{b}	130 ± 6^{a}

Stress behaviour can be caused by fast or slow flow velocity, that can have negative influence on fish welfare and swimming performance. Fish kept in moderate water velocity displayed a low value of stress and improved production characteristics (Solstorm et al., 2015). Flesh texture is improved and number of muscle fibres (important texture characteristics determinant of flesh quality) is increased by swimming exercises (Belal, 2008).

3. Materials and methods

Experiments were performed in Laboratory of controlled reproduction and intensive fish culture. Laboratory is a part of Institute of Aquaculture and Protection of Waters in South Bohemian University in the city České Budějovice. All experiments were performed in period from the beginning of January 2019 to the end of March 2019.

3.1. Swimming tunnel used during experimental work

For all experiments the Brett - type swimming tunnel produced by company Loligo Systems Inc. (Viborg, Denmark) was used. Total volume of used swim tunnel respirometer was 30 l. The whole system was construed from transparent plastic material (polyacrylate), except propeller and propeller shaft. System consisted of external water bath tank in which the swim tunnel chamber was placed.

Main part of the system was oval shape swim tunnel chamber, where all the experiments were performed. Water volume was 30l but experimental fish where placed into a test section (a test cabin) of size 14x14x55 cm. Water flow was created by propeller on the opposite side of the test section rotated by an electromotor. The electromotor and the propeller were connected by shafts. This equipment gives possibility to test water velocity rate from 5 to 175cm. s^{-1}. To produce similar flow in every part of test section plastic lamellas (honeycomb material) were used in inflow part of test section. In the front part of test section there were ports for connecting probes to measure temperature and oxygen.

An external bath served as a reservoir of water and protection of swim tunnel chamber from changing temperature. Swim tunnel itself was equipped with flush pump (40 l. s^{-1}) that was changing the water from the water bath to the chamber. The whole system was connected to the reservoir tank placed under the table. This tank was aerated by an aeration pump and the re-aerated water was pumped to the swim tunnel.

Whole system was controlled by software AutoResp ©. Rotation of propeller was spun by electromotor controlled by a control unit. The control unit was connected to a computer by Bluetooth power strip (the power strip was connected by Bluetooth with the computer) but there was a possibility of manual setting and controlling (for example direction of flow or rotation per minute). For measuring temperature and dissolved oxygen Witrox 1 system with probe fixed in port and connected with computer by Bluetooth was used. Fibre optic mini sensor was used for Witrox 1 measuring. For

wireless data acquisition and automated control of swimming tunnel software DAQ – BT instrument was used. Photos of swimming tunnel are shown from different points of view in Fig. 11, 12, 13.

Fig 11. Top view of swimming tunnel with European perch during measurement

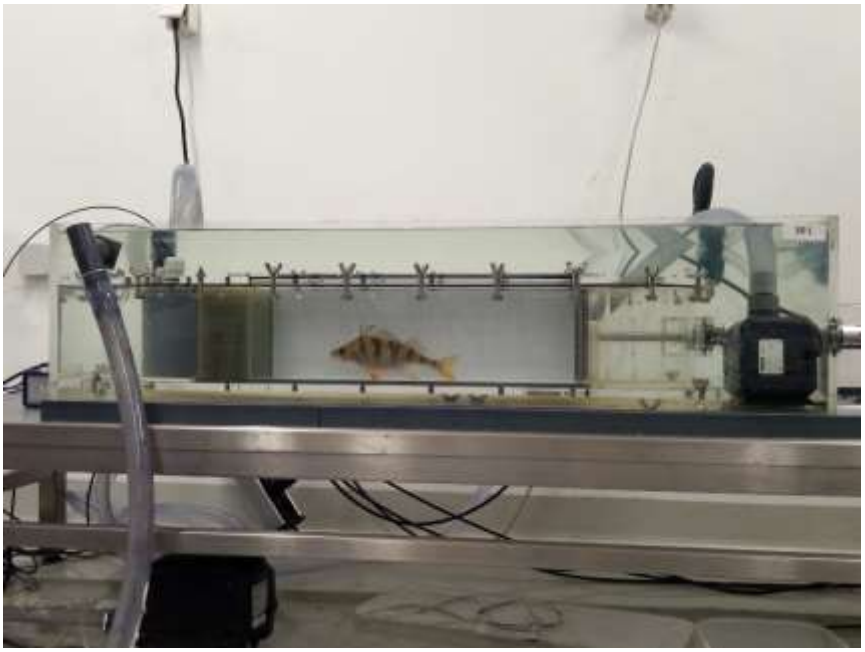


Fig 12. Side view of swimming tunnel with European perch during measurement

Fig 13. Detail view of European perch in test section (cabine) of swimming tunnel during measurement

3.2. Experiment 1. - Repeatability of swimming test in Eurasian perch

This experiment tested hypothesis that critical swimming speed will be influenced by repeated tests (effect of resting period). Three groups of fish were established as followed:

1. First test t 0, second test t 24 and third test t 48
2. First test t 0, second test t 48 and third test t 96
3. First test t 0, second test t 96 and third test t 192

Each group consisted of 5 fish in range of 83.7 to 140.9 g. Each fish group was kept in separate tank and fed by 2% of all biomass weight per day. Fish were starved to fed just one day before testing and at the day of testing. Fish were tested in swimming tunnel individually. Temperature in swim tunnel was about 23 °C. Fish were marked by passive integrated transponder (PIT tag, Loligo Systems Inc.) one month before swimming test. PIT tags were applicated intraperitoneally in area of right pectoral fin. It was necessary to do biometrics measurements of each fish. Especially fish total length, weight, width and depth. Applications of microchip and biometrics were made in anaesthesia (clove oil, 0.03 ml. l). Every information about fish was written down into the protocol.

The fish was moved into the test section and closed well during the measurement. Then the flush pump was switched off, because the respirometry test was set as a closed respirometry. Biometric data including body length (mm), body width (mm) and body depth (mm) of each fish were set into the software. Fish were allowed to acclimatize, that was set to 20 min in flow of 5 cm. sec^{-1}. Testing started after acclimatization. The test was set to rising velocity 2 cm. sec^{-1} per minute. Start water velocity was 5cm. sec^{-1} and final velocity was when fish got fatigue.

3.3. Experiment 2. – Effect of culture system on critical swimming speed in European perch

For this experiment two groups of European perch were used as follows:

- intensively aquacultured fish (RAS)
- pond-reared fish.

Fish were kept in tanks in laboratory before the testing. This experiment was based on hypothesis that pond reared European perch will have better swimming performance when compared with fish from RAS systems. Biometric parameters (fish length, width and depth) were measured under anaesthesia. Fish weren't marked by microchip, because they were measured just once. Water temperature was set to 18 - 20 °C. Fish were starved one day before test. During measuring procedure each fish was moved into the test section and closed well. Then the flush pump was switched off, because respirometry test was set as a closed respirometry. Biometrics data of each fish were set into software in the computer. Acclimatization period was set to 20 min in flow of 5 cm. sec^{-1}. Test started after acclimatization using rising velocity 2 cm. sec^{-1} per minute. Starting water velocity (adaptation) was 5cm. sec^{-1} and final velocity was when fish got fatigue.

3.3.1. Intensively reared fish

Fish were obtained from pond aquaculture at age about 5 months. Then the fish were moved to the aquarium room in laboratory, where they were reared for another 1 year. To be able feed fish by pellets co-feeding with *Chironomus* larvae in intensive conditions were applicated at the start of rearing. The fish were kept in tanks with volume of 600l. The tanks were part of RAS system with parts: tanks (600l), BIO filter (plastic medium), sedimentation tank, aerators with air pump and flush pumps. 3mm pellets Biomar Effico

Sigma 8700 (proteins 42%, fat 22% and energy 18.4 MJ/44008 kcal) was used as a feed. Daily feed ratio was progressively decreased from 4.5 to 1.5% of all biomass in tank during the rearing.

Fish were kept in system with stable water quality during growing period. Especially pH at 6.5 – 7.5, temperature 23 ± 1 °C and level of oxygen on the effluent were higher than 60%. Water flow was set to 600l. h^{-1}providing water exchange once per hour.

3.3.2. Pond-reared fish

Pond-reared fish were obtained from a company owned by Mr. Hojdánek near to České Budějovice after spring pond catching. Forty fish were selected in the range from 100 to 200g. fish were medicated by peracetic acid (25 ml. m^3) for 30 minutes because of as a preventive treatment before testing. Fish were fed by frozen *Chironomus* larvae and before test they were placed into tank outside the aquarium room with water temperature 8 °C (same temperature as in the origin pond). Fish were acclimatized to temperature about 20 – 22 °C. Tank with water (same temperature as outside) was moved into the laboratory. After few days (approx. 3-4) water temperature was stabilized to 20 – 22 °C as it was inside the building.

3.4. Experiment 3. – Effect of fish size on critical swimming speed in Eurasian perch

This experiment was based on hypothesis that there will be differences in critical swimming speed between three groups of weight 100 ± 10g, 200 ± 10g and 250 ± 10g. Biometrics of fish – fish length, width and depth was done before testing. Biometrics was made in anaesthesia (clove oil 0.03 ml. l^{-1}). Fish weren't marked by PIT tag, because they were measured just once.

Each fish group was kept in separate tank and fed by 2% of all biomass a day. Fish were starved to feed just day before testing and at the day of testing. Measurement of critical swimming speed was carried out on individual basis. Temperature in swim tunnel was kept at 23 °C.

Fish was moved into test section and closed well during the measurement procedure. Then the flush pump was switched off, because the respirometry test was set like the closed respirometry. Biometrics data of each appropriate fish were set into the software.

Acclimatization period was set to 20 min in flow of 5 cm. sec^{-1}. Test started after acclimatization using rising velocity of 2 cm. sec^{-1} per minute. Start water velocity was 5 cm. sec^{-1} and final velocity was when fish got fatigue.

3.5. Experiment 4 – Testing of relationship between fillet yield, somatic indexes and swimming performance

This experiment was based on hypothesis that fish with higher swimming performance will have higher fillet yield or differences in somatic indexes. Fish were kept in RAS system consisted of rearing tanks (600l), biofilter (plastic medium), sedimentation tank, aerators and pumps. Fish were fed 2% of biomass in a tank by pellets.

Critical swimming speed of individually marked (PIT tag, Loligo Systems, Inc.) fish in swimming tunnel was determined before measuring of somatic indexes and fillet yield. Than the fish were killed by blowing to head and then weight all body (±0.01g), measured total length and body length. Abdominal cavity was opened and heart, liver, spleen and total perivisceral fat were dissected. Each organ and all perivisceral fat were weight separately (± 0.01g). Then carcass weight of fish with and without head as well as fillet weight of each individually marked fish were determined (±0.01g). Obtained data were used for calculation of hepatosomatic, cardiosomatic, splenosomatic index and index of perivisceral fat using followed formulas:

$$Hepatosomatic\ index = \frac{Liver\ weight}{Body\ weight}\ 100$$

$$Cardiosomatic\ index = \frac{Heart\ weight}{Body\ weight}\ .100$$

$$Splenosomatic\ index = \frac{Spleen\ weight}{Body\ weight}\ .100$$

$$Index\ of\ perivisceral\ fat = \frac{Perivsceral\ fat\ weight}{Body\ weight}\ .100$$

3.6. Methodology of data evaluation

Statistical analyses were performed using STATISTICA 12.0 (StatSoft, Praha, Czech Republic). Data are presented as mean ± SD. The effects of critical swimming speed on BW, TL, SR, K, SH, and SGR were analysed by one-way ANOVA with stocking density as fixed variable. Differences were considered significant at $p < 0.05$. All data were tested for homogeneity of variance using the Cochran, Hartley, and Bartlett test, and for normality with the Shapiro-Wilk normality test. The parametric Tukey test was used for assessing differences among groups in BW, TL, SR, SH, K, and SGR.

Linear regression was used to describe the relationship between the critical swimming speed somatic indexes and yield parameters. Results are reported as mean ± SD and significance accepted as $P<0.05$. Correlation coefficients were very low indicating a weak correlation for all evaluated yield parameters and indexes in every groups.

4. Results

4.1. Experiment 1 – Repeatability of swimming test in Eurasian perch

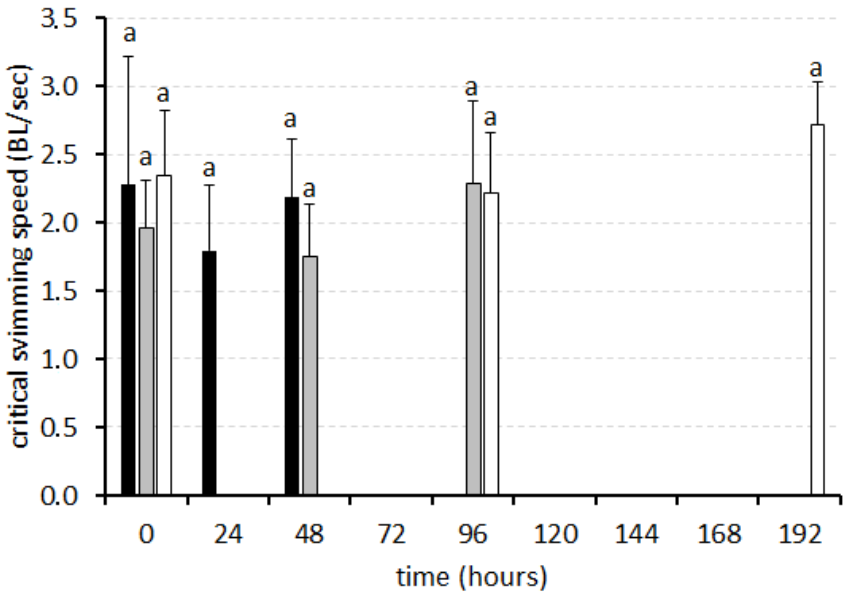


Fig 14. Critical swimming speed (mean ±S.D.) at different time during repeated swimming tests in intensively cultured European perch (*Perca fluviatilis*). Values with different letter on the top of column are significantly different ($P < 0.05$, $n = 5$)

Tab 4. Body weight, total body length, body width and body height of fish used in test.

Group	Body weight (g)	Total body length (cm)	Body width (cm)	Body height (cm)
t 0, 24 and 48	101.7 ±19.6	20.6 ± 1.1	2.8 ± 0.3	4.7 ± 0.3
t 0, 48 and 96	126.8 ± 15.3	21.8 ± 0.8	3.2 ± 0.2	5.3 ± 0.2
t 0, 96 and 192	107.8 ± 13.0	20.7 ± 0.5	2.9 ± 0.2	5.0 ± 0.3

In this experiment no significant differences were found between groups in critical swimming speed (Fig. 14). The data on critical swimming speed in each group and on different days after the first test were similar. For the first group the average critical swimming speed was the following: 0h – 2.28 ± 0.93 BL. sec^{-1}, 24h – 1.80 ± 0.47 BL. sec^{-1} and 48h – 2.18 ± 0.43 BL. sec^{-1}. For the second group measured average critical swimming speed was: 0h 1.96 ± 0.35 BL. sec^{-1}, 48h 1.75 ± 0.38 BL. sec^{-1} and 96h 2.28 ±

0.61 BL. sec^{-1}. For the third group of fish, the average critical swimming speed was: 0h – 2.35 ± 0.48 BL. sec^{-1}, 96h – 2.21 ± 0.44 BL. sec^{-1} and 192h – 2.71 ± 0.31 BL. sec^{-1}. Variability in swimming speed is shown in Fig 15. and 16 whereas variability in oxygen consumption is depicted in Fig. 17.

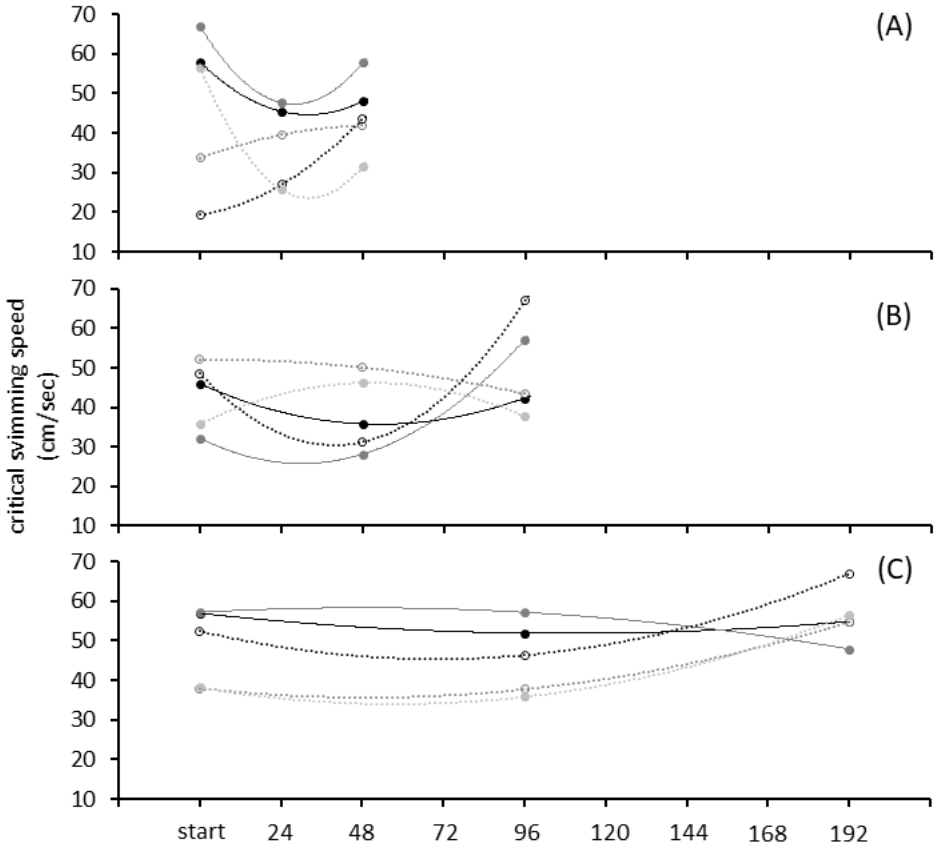


Fig 15. Variability in critical swimming speed of individually marked intensively cultured European perch (*Perca fluviatilis*) during repeated swimming tests. Groups of fish measure at time 0h, 24h and 48h (A). 0h, 48h and 96h (B) and 0h, 96h and 192h (C).

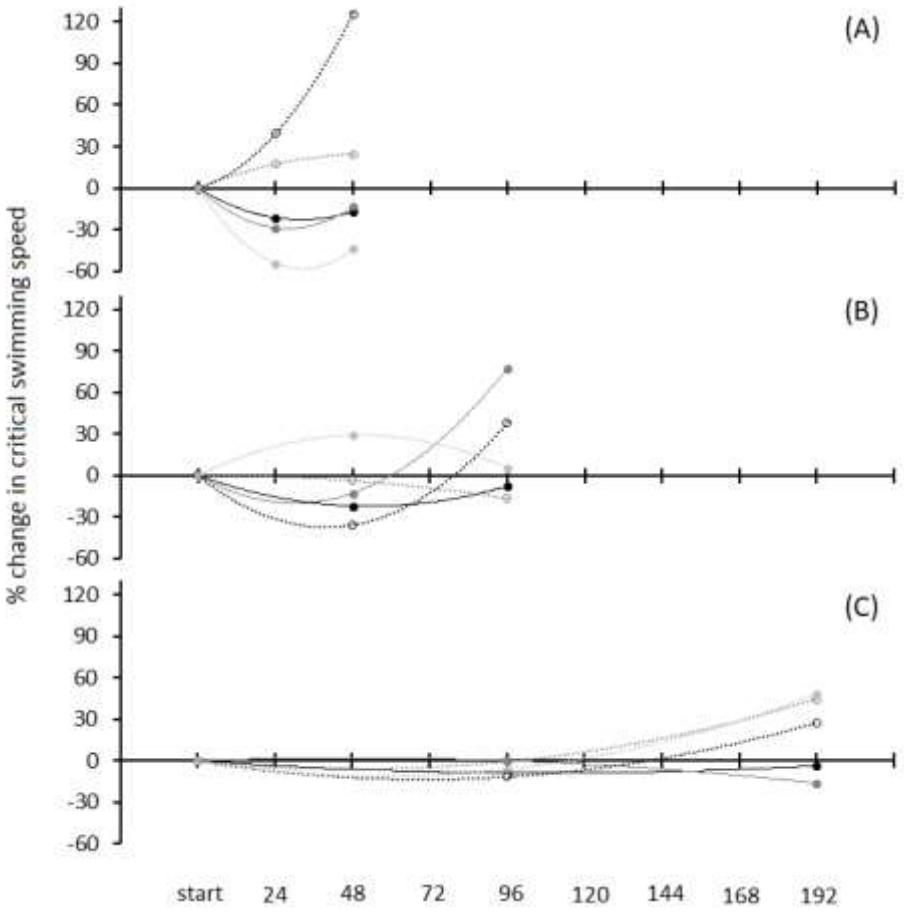


Fig 16. Variability in percentage change of critical swimming speed of individually marked intensively cultured European perch (*Perca fluviatilis*) during repeated swimming tests. Groups of fish measure at time 0h, 24h and 48h (A). 0h, 48h and 96h (B) and 0h, 96h and 192h (C).

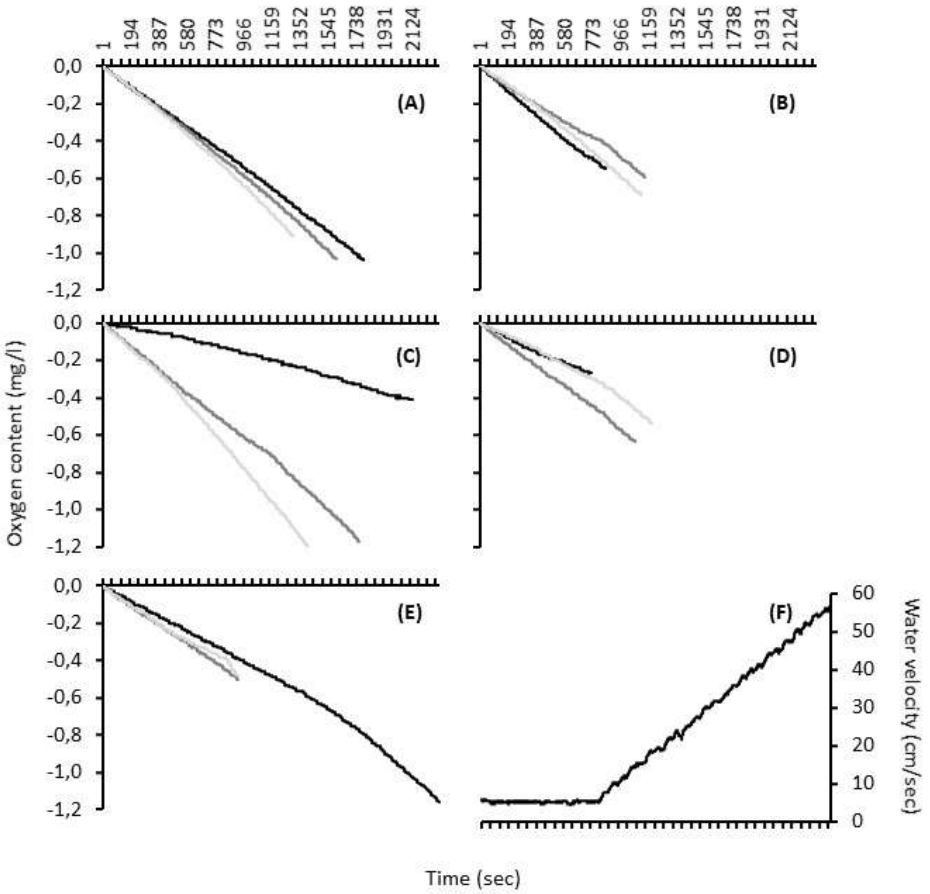


Fig 17. Variability in oxygen consumption of individually marked intensively cultured European perch (*Perca fluviatilis*) during repeated swimming tests. Group of fish measure at time 0h (black line), 24h (dark grey line) and 48h (light grey line).

4.2. Experiment 2 – Effect of fish size on critical swimming speed in Eurasian perch

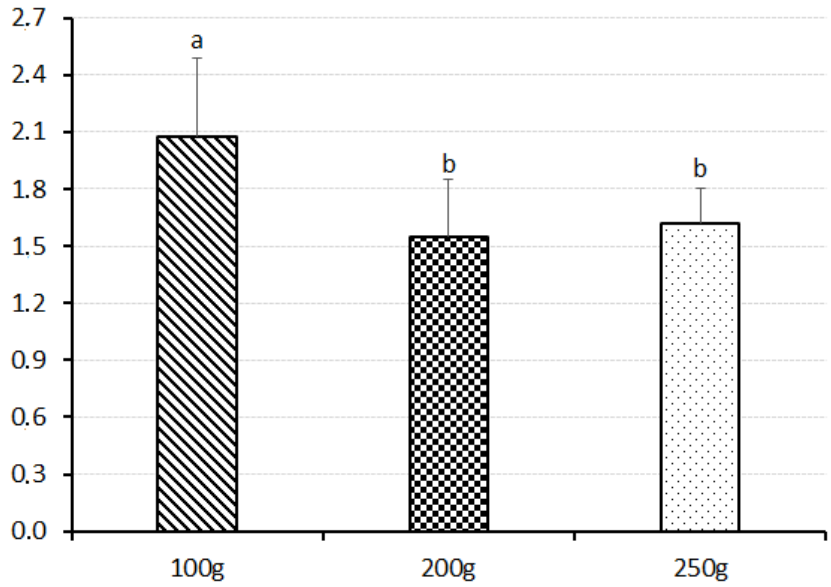


Fig 18. Critical swimming speed (mean ±S.D.) in different size categories of intensively cultured European perch (*Perca fluviatilis*). Values with different letter on the top of column are significantly different ($P < 0.05$, $n = 10$)

Tab 5. Body weight, total body length, body width and body height of fish used in test.

group	body weight (g)	total body length (cm)	body width (cm)	body height (cm)
100g	100 ± 10	21.4 ± 0.4	2.8 ± 0.2	5.1 ± 0.1
200g	200 ± 10	25.5 ± 0.6	3.7 ± 0.3	6.6 ± 0.3
250g	250 ± 10	26.6 ± 0.6	3.6 ± 0.3	7.3 ± 0.4

Significant differences were found in critical swimming speed between fish of body weight 100 ± 10 g and two groups with body weight of 200 ± 10 g and 250 ± 10 g, respectively in this experiment (Fig. 18). There was no significant difference between fish with body weight 250 ± 10 g and 200± 10 g. Average critical swimming speed of 100 ± 10 g group was 2.08 ± 0.41 BL. sec^{-1}. 200 ± 10 g group of fish had average critical swimming speed of 1.55 ± 0.3 BL. sec^{-1} and 250 ± 10 g group 1.62 ± 0.19 BL. sec^{-1}.

4.3. Experiment 3 - Effect of culture system on critical swimming speed in European perch

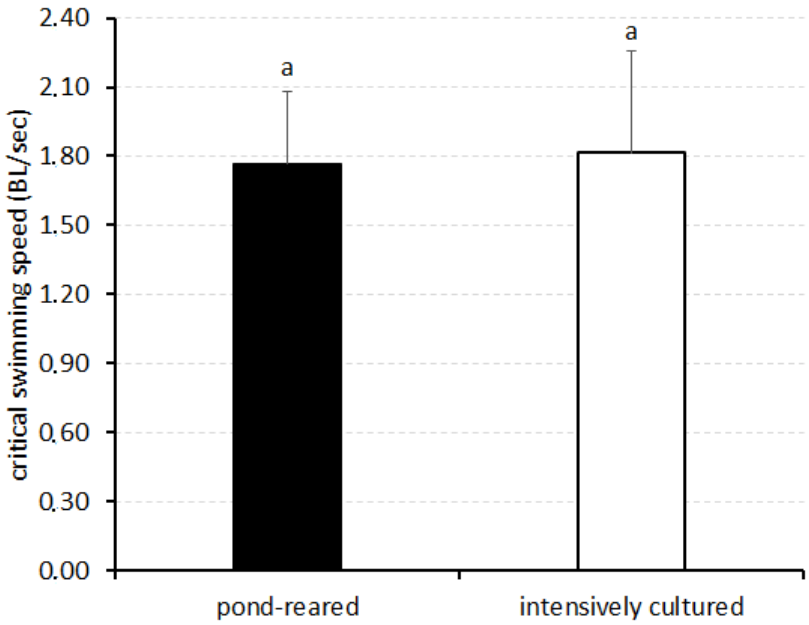


Fig 19. Critical swimming speed (mean ±S.D.) in pond-reared and intensively cultured European perch (*Perca fluviatilis*). Values with different letter on the top of column are significantly different ($P < 0.05$, $n = 20$)

Tab 6. Body weight, total body length, body width and body height of fish used in test.

group	body weight (g)	total body length (cm)	body width (cm)	body height (cm)
RAS	150.0± 60.0	23.4 ± 2.2	3.3± 0.7	5.9 ± 1
pond cultured	121.4 ± 32.1	20.3 ± 1.5	3.4 ± 0.5	5.7 ± 0.6

No significant differences were found when comparing pond reared (wild) and intensively reared fish (RAS) in Fig. 19. Average of critical swimming speed of wild fish was 1.77 ± 0.32 BL. sec^{-1} and average critical swimming speed of intensive reared fish (RAS) was 1.81 ± 44 BL. sec^{-1}.

4.4. Experiment 4 - Testing of relationship between fillet yield, somatic indexes and swimming performance

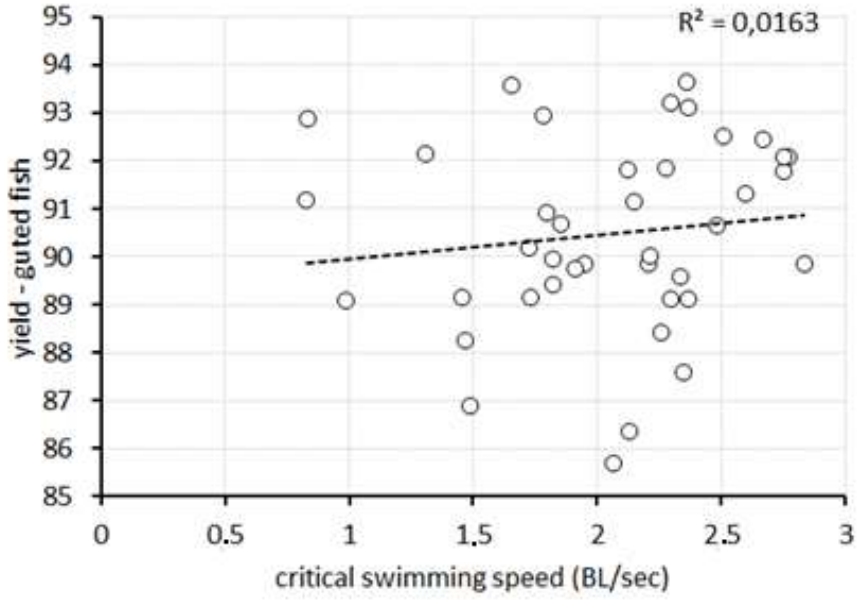


Fig 20. Relationship between yield of gutted fish and critical swimming speed in intensively cultured European perch (*Perca fluviatilis*) (n = 40)

There figures plot data on critical swimming speed of intensively cultured perch against yield of gutted fish during this experiment. Weight of used fish ranged from 85.7 g to 93.6g and the average body weight was 90.5 ± 2 g. Critical swimming speed ranged from 0.83 BL. sec^{-1} to 2.83 BL. sec^{-1} with average value of 2.04 ± 0.51 BL. sec^{-1}. No significant relationship between swimming performance and yield of gutted fish was found (Fig. 20).

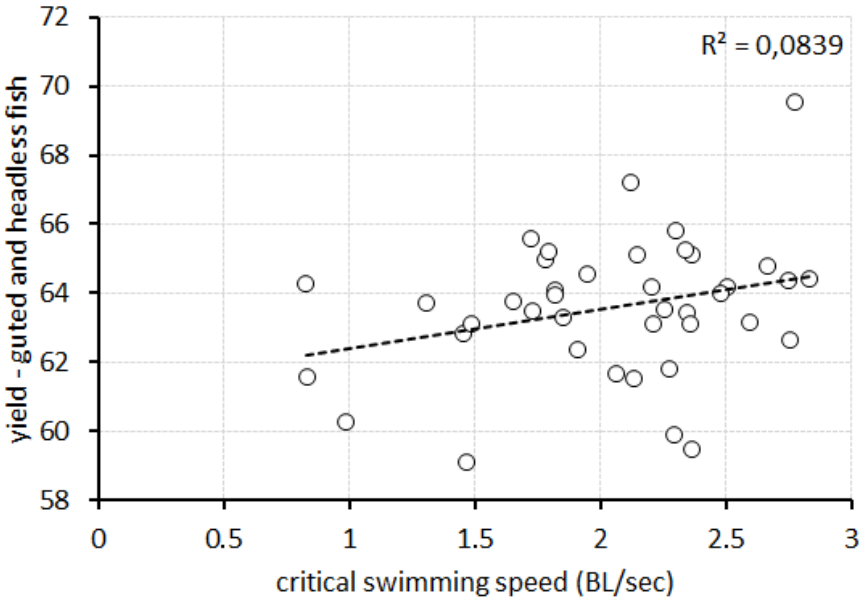


Fig 21. Relationship between yield of gutted and headed fish and critical swimming speed in intensively cultured European perch (*Perca fluviatilis*) (n = 40)

Moreover, swimming performance data (critical swimming speed) were plotted against yield of gutted and headed fish. No significant relationship between swimming performance and yield of gutted and headed fish was found (Fig. 21).

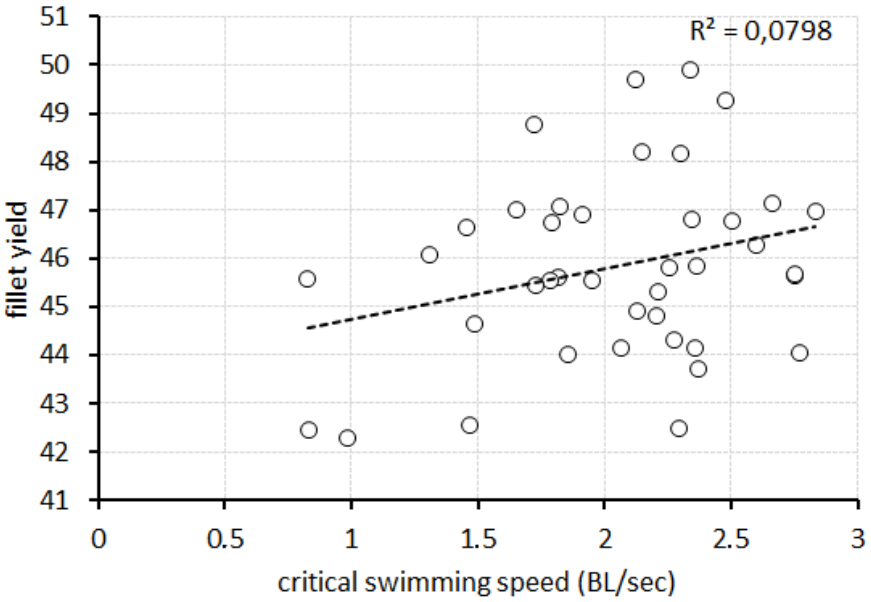


Fig 22. Relationship between fillet yield and critical swimming speed in intensively cultured European perch (*Perca fluviatilis*) (n = 40)

In another comparison, swimming performance data (critical swimming speed) were plotted against fillet yield of intensively cultured perch. No significant relationship between swimming performance and fillet yield was found (Fig. 22).

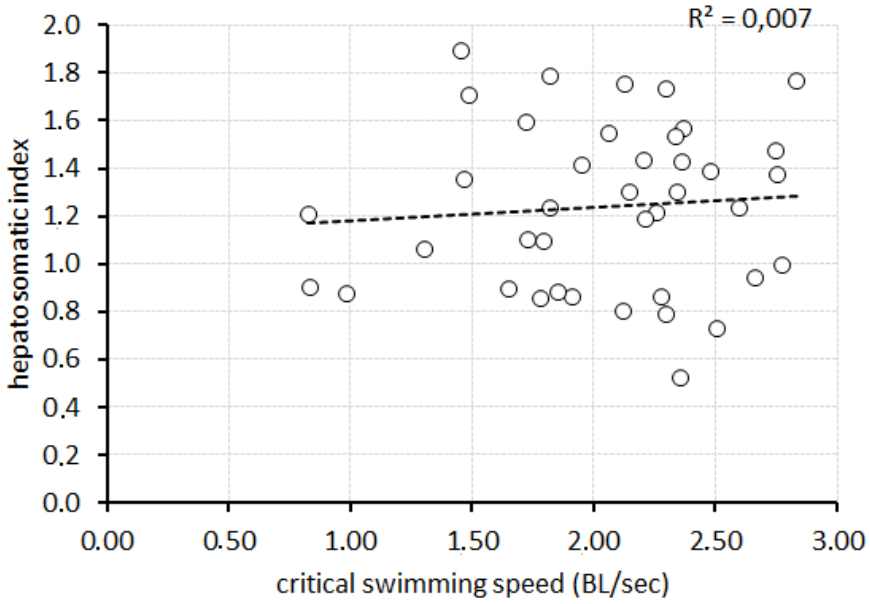


Fig 23. Relationship between hepatosomatic index and critical swimming speed in intensively cultured European perch (*Perca fluviatilis*) (n = 40)

In addition, swimming performance data (critical swimming speed) were plotted against hepatosomatic index of intensively cultured perch. No significant relationship between swimming performance and hepatosomatic index was found (Fig. 23).

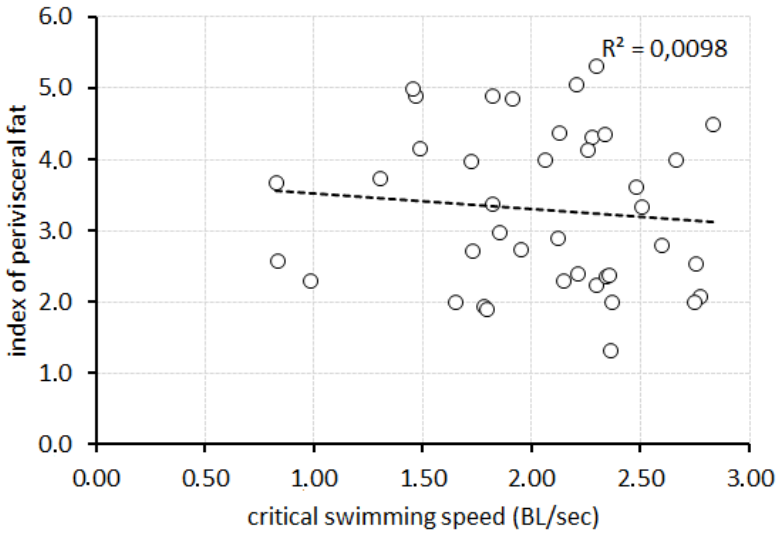


Fig 24. Relationship between index of perivisceral fat and critical swimming speed in intensively cultured European perch (*Perca fluviatilis*) (n = 40)

Another relevant parameter was perivisceral fat index. Swimming performance data (critical swimming speed) were plotted against perivisceral fat index of intensively cultured perch. No significant relationship between swimming performance and perivisceral fat index was found (Fig 24).

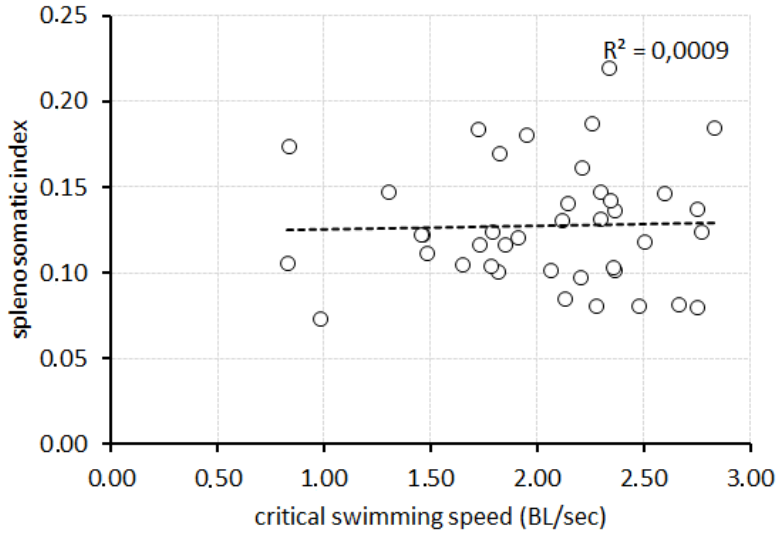


Fig 25. Relationship between splenosomatic index and critical swimming speed in intensively cultured European perch (*Perca fluviatilis*) (n = 40)

Comparison was performed also for splenosomatic index. Swimming performance data (critical swimming speed) were plotted against splenosomatic index of intensively cultured perch. No significant relationship between swimming performance and splenosomatic index was found. (Fig. 25).

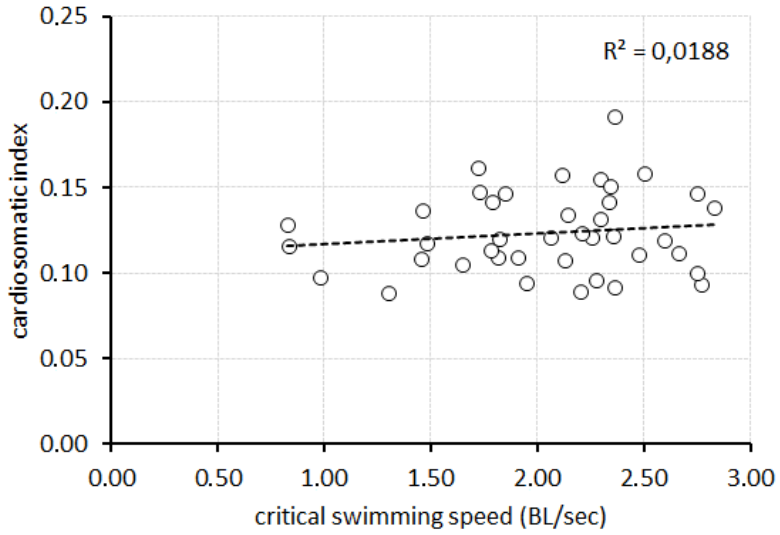


Fig 26. Relationship between cardiosomatic index and critical swimming speed in intensively cultured European perch (*Perca fluviatilis*) (n = 40)

The last comparison was made for cardiosomatic index. Swimming performance data (critical swimming speed) were plotted against cardiosomatic index of intensively cultured perch. No significant relationship between swimming performance and cardiosomatic index was found (Fig. 26).

5. Discussion

5.1. Experiment 1. - Repeatability of swimming test in Eurasian perch

The first part of this study was dedicated to an experiment focused on repeatability of swimming performance tests and possible effects of regeneration (recovery). This experiment aimed to finding out how quickly fish can regenerate after a swimming test that ends in fatigue. It was hypothesised that the value of critical swimming speed will decrease in terms of every measurement in each group (most significantly in the first group). The alternative hypothesis stated that fish will get used to swimming performance testing (rising U_{crit}). The results of the present study showed that there is no significant difference in critical swimming speed between groups and days of measuring performed. A similar pattern was found in all groups of fish. The lowest measured values of every group were obtained during the second measuring (first group after 24h, second after 48h and third after 96h) and then the values of third measuring were slightly higher than those of the second and higher than during the first measuring, except for the first group of fish. One cloud think that fish regenerated after few hours and were no longer feeling stressed due to being in the tunnel. Overall during the third measuring values for critical swimming speed were obtained higher than during the first and second measurements. That can indicate that fish get used to higher flow or eliminate stress after the two previous measurements. In future testing, it is necessary to form more groups and verify whether the same patterns hold. Results from this study could be used in future tests of individually marked fish and effects of a wide range of factors (treatments) on swimming performance.

There was no similar experimental setup found in the current literature, which did not allow comparing results with different fish species. The results of perch swimming behaviour could be influenced by fish activity or personality. Fish can be classified in terms of the level of their activity as proactive or reactive fish (and intermediate). Proactive fish are defined with a risk reaction towards individuals, activity in risk situation or less flexible or less flexibility behaviour during environmental change (Wilson and McLaughlin, 2007; Wilson and Stevens, 2005). Reactive fish are classified as individuals that do not seek conflicts and that avoid danger by predators. Reactive fish are more flexible in behaviour (Ruiz – Gomez et al., 2011). The heterogeneous results in swimming performance in this experiment could be explained by the fact that both categories of fish were used in the experiment. Very different types of fish behaviour were

observed as a result of the measurements. A few fish did not swim at all and those needed to be eliminated from the experiment whereas some other fish started swimming immediately after acclimatization started. Most of the fish started to swim during test in water flow about 10 – 25 cm. sec^{-1}. The possibility of measuring together these two groups could influence the data of the present experiment.

In measuring oxygen consumption there was found that oxygen consumption during repeated tests is highly variable. Mostly the first measurement has lower oxygen consumption and third measurement the highest. These results shown that fish did not acclimated to swimming in a tunnel, or maybe because of bad regeneration between testing days.

5.2. Experiment 2. - Effect of fish size on critical swimming speed in Eurasian perch

The second part of this study was focused on comparing critical swimming speed in different weight categories and the influence of body weight on swimming performance. This experiment confirmed a difference between 100 g and 200g group as well as between 100g and 250g group. It was expected that with rising body weight, the values of critical swimming speed in BL. sec^{-1} will decrease, but they will rise with total water velocity (cm. sec^{-1}). In size categories of 200 and 250g no difference or a decreasing trend was found in the levels of critical swimming speed (BL. sec^{-1}). Similar experiments were done with many species. Those experiments confirmed that critical swimming speed decreased with rising size (weight or length).

Remen et al., (2016) measured three weight groups of Atlantic salmon (*Salmo salar*). The first group has body weight 80 ± 1 g, the second 289 ± 9 g and the third 1750 ± 175 g. Level of critical swimming speed rose with weight, but in value BL. sec^{-1} decrease. The first group of salmons has 80.6 ± 0.5 cm. sec^{-1}, the second 90.9 ± 1.2 cm. sec^{-1} and the third 99.5 ± 3.7 cm. sec^{-1}.

Fry and Cox (1970) presented a study where results showed that with rising of body weight of rainbow trout (*Oncorhynchus mykiss*) critical swimming speed (in BL. sec^{-1}) decreased. For 10 g fish it was measured approximately 9 BL. sec^{-1}, for 100 g fish was measured approximately 5.5 BL. sec^{-1} and for 1000 g fish was approximately measured 3 BL. sec^{-1}.

In this experiment was measured that bigger fish handle higher flow better and swam more constantly, but compared to the group of 100 g, lower critical swimming speed was observed. This is in agreement with the study made by Tolley and Torres (2002) and Turnpenny and Bamber (1983). Comparing the total length of fish and critical swimming speed fish of the 100g group with those of the larger and heavier fish, the 100 g group can swim in higher water velocity. There may have been better experimental design to use 3 groups with same distance 100g – that means 100 g, 200 g and 300g. Such an experiment was not possible because of limitations of fish available in size category 300 ± 10 g.

5.3. Experiment 3. - Effect of culture system on critical swimming speed in European perch

The third part of this study was dedicated to comparing differences in swimming performance aquaculture (RAS) fish and pond reared fish. This experiment was conducted to find out if fish from aquaculture (RAS) have lower swimming performance than fish from wild environment. The measured values for critical swimming speed was similar to previous experiments. This experiment did not provide evidence in favour of significant differences between wild fish and aquaculture (RAS) fish. Mean critical swimming speed was1.77 BL. sec^{-1} and 1.81 BL. sec^{-1} for pond reared and RAS fish, respectively. In comparison with similar experiments (comparing wild and intensively cultured fish), this experiment found overall that wild fish have better potential for swimming performance than aquaculture fish. For example, Wegner et al. (2018) conducted an experiment where they compared swimming performance of California yellowtail (*Seriola dorsalis*). The experiment used approximately 80 g fish. Brett – type tunnel was used for measuring fish. In water with the same temperature there was measured critical swimming speed of wild fish 4.80 ± 0.52 BL. sec^{-1} and for aquaculture RAS fish 4.16 ± 0.62 BL. sec^{-1}. In this experiment there were used 10 fish from aquaculture and 7 wild fish. In the experiment made in this thesis 20 aquaculture fish were used and 19 pond reared fish, which means that this experiment is more precise than experiment made by Wegner et al. (2018).

Another experiment made by Basaran et al. (2007) evaluated the differences between wild and aquacultured sea bream (*Sparus aurata*). In this experiment there was used approximately the same weight fish (wild – 99.3 ± 1.6 cm, aquaculture – 95.9 ± 4.3 cm).

Wild fish was obtained from a sea and aquaculture fish from a farm. In this experiment results show that there is no difference between wild and aquaculture fish, which agrees with the present study on European perch. For wild fish were measured 4.52 ± 0.05 BL. sec^{-1} and for aquaculture 4.20 ± 0.04 BL.sec^{-1}. In this experiment there were used 13 aquacultured fish and 36 wild fish, that is in wild fish more than in this thesis experiment.

In experiment made by Dunmall and Schreer (2003) on Atlantic salmon (*Salmo salar*) no significant difference between wild and farmed fish was found. They used 16 farmed fish and 13 wild fish. The number of measured fish is mostly similar to the experiment in this thesis.

A question why there were results from this experiment different from similar experiments arose within this experiment? Pond reared fish for the presented study were obtained from pond aquaculture after spring pond harvesting. One possible explanation is that fish from pond are not used to living in higher flow conditions, probably in lower flow, than is normally set up in RAS systems. Another possible explanation of such results is that fish could have been under higher stress during the experiment than fish from RAS, which are quite frequently handled. Therefore, there is assumption that RAS fish were used to stress made by people and unnatural environment. Because of stress, wild fish did not eat the same volume of feed as RAS fish and further there was difference in feed type during the acclimatisation period, which could be another factor. In an experiment made by Basaran et al. (2007) there were used for wild and aquaculture fish different feed (sardine and pellets).

It will be reasonable to measure a bigger group of wild fish as well as to measure them with and without transport and without acclimation to temperature to obtain knowledge on these effects in future setting of similar experiment. Also, maybe better to acclimate aquaculture fish to lower temperature, than wild fish to higher temperature in a short period as it was used in this experiment.

5.4. Experiment 4. - Testing of relationship between fillet yield, somatic indexes and swimming performance

The last part of the study was focused on an experiment testing the hypothesis whether there could be a relationship between critical swimming speed and parameters such as fillet yield and somatic indexes. For this experiment only aquacultured fish were used. No relationship between swimming performance (in particular critical swimming

speed) and somatic indexes and fillet yield was confirmed in this experiment. The expected results were that fish with different swimming performance will be presented by different values in somatic indexes and fillet yield. It was expected that fish with lower critical swimming speed could have higher perivisceral fat index and lower fillet yield. On the contrary, there was a hypothesis that fish presented by higher critical swimming speed will have lower perivisceral fat index and higher fillet yield. One possible bottleneck of presented study is the low number of measured fish (n= 40).

A similar study was not found in the literature, but in an experiment made by Solstorm et al. (2015) provides results that fish kept in fast water flow had got 15% higher cardiosomatic index than fish kept in slow water velocity and 10% higher than fish kept in moderate velocity. Plans for future work with salmon are to select fish according to their cardiosomatic index. This method is tested on salmon, because problems of cardiovascular system of this intensively farmed species were documented.

One of the biggest expectations was that fish with higher critical swimming speed will have lower perivisceral fat, but results were quite similar to fish with lower critical swimming speed. This could have been influenced by the rearing in RAS since juvenile stadium or the genetics background of the population used. For experiment based on this method maybe it will be better to do comparison between population reared in RAS and from open waters (rivers/streams with higher water velocity). If the hypothesis is confirmed in the next set of experiments (not presented in this study), there can be possibility of selecting fish according to their swimming performance as minimum-invasive method. Selected group of fish can prove better growth rate or fillet yield.

The reason why the hypothesis was not confirmed can be because only one measurement was selected. The hypothesis could be tested in groups from different tanks where water velocity was set to two different levels, but to the same level and quality of feed.

6. Conclusion

The first experiment hypothesised that there will be differences between the three groups (with different day distance of measuring) measured repeatedly with different intervals of resting. All results of this experiment showed that there is not significant difference between days of measurement both within and across groups. An interesting observation given these results is the same tendency in each group. In every group the lowest values were measured in the second measurement and the highest in the third and last measurement. This method has recently become a new method to measure swimming performance with potential for expanding such testing in the future. It is also a possible to repeat measurement of fish after any process (anaesthesia, pollution, application of microchip) without distorted data.

The second experiment did not confirm any relationship in terms of critical swimming speed in the three different weight categories of perch. There were differences between first (100g) and second (200g) but no difference between the second and the third (250g) group. The third experiment did not confirm differences in critical swimming speed between wild and RAS fish. The result of this experiment showed, that wild and RAS perch display the same level of critical swimming speed.

The purpose of the last experiment was to find if there are any relationships among levels of critical swimming speed and body indexes or fillet yield. No relationship was found in this experiment because of fish genetics, nutrition, unknown influence or other unknown factors. Similar methods can be used in the future to select fish and can improved economics of perch fish farms in the future.

It can be concluded that by comparing each group of fish in each particular experiment there none of the original hypotheses were confirmed. Similar experiments were conducted for the first time at the Faculty of Fisheries and Protection of Waters, but no one has ever measured in swim tunnels or with this settings of experiments. The present thesis has generated the first data for critical swimming speed measured in intensive farming of European perch as well as it has delivered a new approach for fitness testing. In the future will be possible to set a wider range of experiments. Experiments with repeatability or testing the context of swimming speed with yield are new methods for measuring swimming performance. The results of this thesis also bring new data of high importance for percids aquaculture as there is lack of knowledge as far as swimming performance is concerned.

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8. Abstract

Critical swimming speed and swimming performance in relation with different factors were tested in this thesis in groups of European perch (*Perca fluviatilis*) with focus to utilize these results in intensive aquaculture.

Thesis is consisted of four different experiments performed in swimming tunnel. In the first experiment there weas tested, if there are any differences in day distances of measuring between three groups of fish. Each group was measured three times. The first group was measured in time (t) 0, 24 and 48 h, the second group was measured in time (t) 0, 48 and 96 h. Finally, the third group was measured in time (t) 0, 96 and 192 h. The second experiment was set to compare critical swimming speed in three weight categories of a fish. Weight categories of 100g, 200g and 250g were tested. In the third experiment pond reared fish and aquaculture (RAS) reared fish were tested. Results were compared together, if there are any differences. The last experiment was set to find out if there is any relationship between level of critical swimming speed and somatic indexes or fillet and caraccas yield.

No one of experiments performed confirms expectations of results. In the first experiment there was found that there is no effect of repeated swimming tests on critical swimming speed as well as no effect of different recovery period (from previous test). In comparison of different weight categories there were measured the highest levels of critical swimming speed in 100g group without decreasing trend in for bigger size categories (200 and 250 g). Pond and intensively reared fish had the same level in critical swimming speed. Moreover, the fourth experiment did not confirm influence level of critical swimming speed to somatic indexes or fillet yield.

The results of presented thesis can contribute on better technical design of rearing units for this gastronomically and economically interesting species in intensive aquaculture, mainly in RAS systems.

Key words: fitness, oxygen consumption, swimming performance, swimming tunnels, intensive aquaculture

9. Abstrakt

V práci byly testovány různé faktory ve vztahu ke kritické rychlosti plavání u různých skupin okouna říčního (*Perca fluviatilis*) se zaměřením na využití těchto výsledků v podmínkách chovů intenzivní akvakultury.

Celá práce se skládá ze čtyř různých pokusů provedených v plavacím tunelu. První pokus byl nastaven tak, aby bylo možné porovnat skupiny individuálně značených ryb, zda se liší naměřené hodnoty plavání s rozlišným odstupem opakovaných měření. Každá skupina byla změřena 3 x po sobě. První skupina byla měřena v čase (t) 0, 24 a 48 h, druhá skupina byla měřena v čase (t) 0, 48 a 96 h. Třetí skupina byla měřena v čase (t) 0, 96 and 192 h.

V druhém pokuse byly porovnány rozdíly v kritické rychlosti plavání u třech váhově rozdílných skupin. Váhové kategorie 100 g, 200 g a 250 g byly testovány. Třetí pokus porovnával rozdíly kritické rychlosti plavání mezi rybami pocházejícími z intenzivní akvakultury (RAS) a rybami z rybniční akvakultury. Cílem posledního čtvrtého pokusu bylo zjistit, zda má hodnota kritické rychlosti plavání vztah k somatickým indexům nebo výtěžnosti ekonomicky zajímavých částí rybího těla.

V žádném z provedených pokusů nebyly potvrzeny předešlé očekávání. U prvního experimentu bylo zjištěno, že hodnoty měřené kritické rychlosti plavání nejsou ovlivněny opakovaným provedením testu a rovněž nebyl potvrzen vliv délky zotavení z předchozího testu. Při porovnávání váhových kategorií byly měřeny nejvyšší hodnoty kritické rychlosti plavání u 100 g skupiny, ale bez následného sestupného trendu u dalších skupin. Porovnání kritické rychlosti plavání u ryb z intenzivních a rybničních podmínek neprokázalo významné rozdíly. Rovněž bylo zjištěno, že kritická rychlost plavání nemá vztah k somatickým indexům a výtěžnosti filet.

Zjištěné a naměřené hodnoty mohou posloužit v budoucnu ke zlepšení podmínek chovu tohoto ekonomicky a gastronomicky zajímavého druhu v podmínkách intenzivní akvakultury, zejména v systémech RAS.

Klíčová slova: fitness, spotřeba kyslíku, schopnost plavání, plavací tunely, intenzivní akvakultura