Fish Physiol Biochem (2011) 37:273–284
DOI 10.1007/s10695-011-9495-y

EMG telemetry studies on upstream migration of chum salmon in the Toyohira river, Hokkaido, Japan

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Received: 25 November 2010 / Accepted: 13 December 2010 / Published online: 11 May 2011

Abstract The movements of 28 adult chum salmon, *Oncorhynchus keta* (Walbaum) tagged with electromyogram (EMG) transmitters were tracked along the Toyohira river, Hokkaido, Japan, in October of 2007 and 2008 to investigate and evaluate the upstream migratory behavior through the protection bed and fishway of ground sills. The approach time of fish that ascended successfully through the protection bed and fishway was shorter than that of unsuccessful fish. The unsuccessful fish were observed to swim in currents with high water velocity and shallow water depth at swimming speeds that exceeded their critical swimming speed (U_{crit}) during the approach to these structures. In consequence, unsuccessful fish frequently alternated between burst and maximum sustained speeds without ever ascending the fishway, and eventually became exhausted. It is important that fishway are constructed to enable chum salmon to find a passage way easily, so that they can migrate upstream rapidly without wasting excessive energy.

Keywords Ground sill · Protection bed · Fishway · EMG telemetry · Chum salmon

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Introduction

The upstream migration of salmon is energetically demanding because individuals have to pass a variety of natural and anthropogenic barriers including waterfall, rapid flowing water, weirs, hydroelectric facilities, and ground sill in their natal streams (Hinch et al. 2006). Slaney et al. (1996) reported that anthropogenic barriers impede or hinder the spawning migration routes of salmon and result in reducing the number and size of salmonid populations. To enable salmon to pass barriers, various designs of fishways have been developed and constructed (Roscoe and Hinch 2010). During their upstream migration, adult Pacific salmon tend to cease feeding prior to spawning migration, and have to rely on energy reserves to reach their spawning grounds (Hasler et al. 1978). Pacific salmon are semelparous (i.e., die following reproduction) and successful migration to their spawning grounds with adequate stored energy is therefore imperative to their lifetime fitness.

Electromyogram (EMG) is an indicator of the intensity of muscle activity in free-moving fish (Weatherley et al. 1982). EMG telemetry has been proven as an effective technique to examine the continuous swimming activity of sockeye salmon (*Oncorhynchus nerka*) (Hinch et al. 1996), pink salmon (*O. gorbuscha*) (Hinch et al. 2002), and chum salmon (*O. keta*) (Makiguchi et al. 2008). The swimming behaviors of migrating fish have been classified into three major categories: sustained, prolonged, and burst swimming (Hammer 1995). These swimming behaviors are used to control energy use during migration as an appropriate to environmental situation (Hinch and Rand 2000), and therefore the energy used during upstream migration is affected by the swimming patterns that they adopt (Hinch et al. 1996; Hinch and Rand 1998; Standen et al. 2002). Relationships between swimming performance, active metabolism, and EMG have been used to determine various swimming behaviors of fish. The critical swimming speed (U_{crit}) is defined as the quantification of the sub-maximum and largely aerobic swimming performance of fish, and is approximately the speed at which fish fatigue in an incremental velocity trial (Brett 1964, 1967; Hammer 1995). It is generally accepted that maximum oxygen uptake occurs at U_{crit} (Farrell and Steffensen 1987) and this allows us to estimate the maximum aerobic capacity (Hammer 1995).

The Toyohira river, in western Hokkaido, Japan, runs through the Sapporo city, and is known as an important river for chum salmon spawning. Several cross-sectional river structures called ground sills have been constructed in the Toyohira river in order to prevent from the lowering of the river bed. Although the protection bed and fishway were constructed for fish to pass through the ground sills, little is known about the upstream migrating behavior of chum salmon through these structures. The purpose of this study was to investigate and evaluate the upstream migratory behavior of chum salmon through the protection bed and fishway of ground sills in the Toyohira river using EMG telemetry technique and assess the effectiveness of the ground sill design.

Materials and methods

Study area

The Toyohira river drains an area of 904.8 km^2 (561.9 square miles), and runs through the cities of Sapporo and Ebetsu with a total length of approximately 72.5 km (Fig. 1). Our study area covered a distance between 13.0 km and 17.8 km from the river mouth. Six ground sills (#1, #3, #4, #5, #6/7, and #8) were built in the study area from 1950 to 1998 (Fig. 1). #2 ground sill were removed in 1990 when #3 ground sill were built. The protection bed and fish way of the #5 ground sill (Fig. 2a) and the fishway of #6/7 ground sill were renovated (Fig. 2b) on March 2008 and May 2009, respectively.

Study animals and transmitter attachment procedures

In the Toyohira river, adult chum salmon carry out upstream migration from September to November in the Toyohira river. All chum salmon used in this study were captured using a catching net between 11.5 and 16.5 km from the river mouth and then transferred to outdoor tanks at the Sapporo Salmon Museum until the experiments took place. In 2008, nine males (fork length, 62.7–73.7 cm; body mass 2.3–4.6 kg) and seven females (fork length, 58.9–68.8 cm; body mass 1.9–2.9 kg) were used. In 2009, seven males (fork length, 47.5–70.4 cm; body mass 1.0–3.6 kg) and five females (fork length, 59.9–70.1 cm; body mass 2.1–3.6 kg) were used. Each fish was equipped with a cylindrical, epoxy-encased EMG transmitter (CEMG-R11-35, Lotek Engineering Inc., Newmarket, Ontario: 18.3 g in air, 16.2 mm in diameter, 53.0 mm in length) attached externally to the body surface positioned anterior to the dorsal fin. External attachment is suitable for short-term research, which allows us to reduce the handling stress of the fish (Bridger and Booth 2003). To attach the tag, experimental fish were anaesthetized using FA100 (eugenol; Tanabe Seiyaku Co. Ltd, Osaka, Japan) at a concentration of 0.5 ml l^{-1} in the Toyohira river water, and placed upright on a surgical table. Their gills were irrigated with water containing diluted FA100 to maintain sedation during the attachment procedure. Two stainless needles, large enough hold to restraining

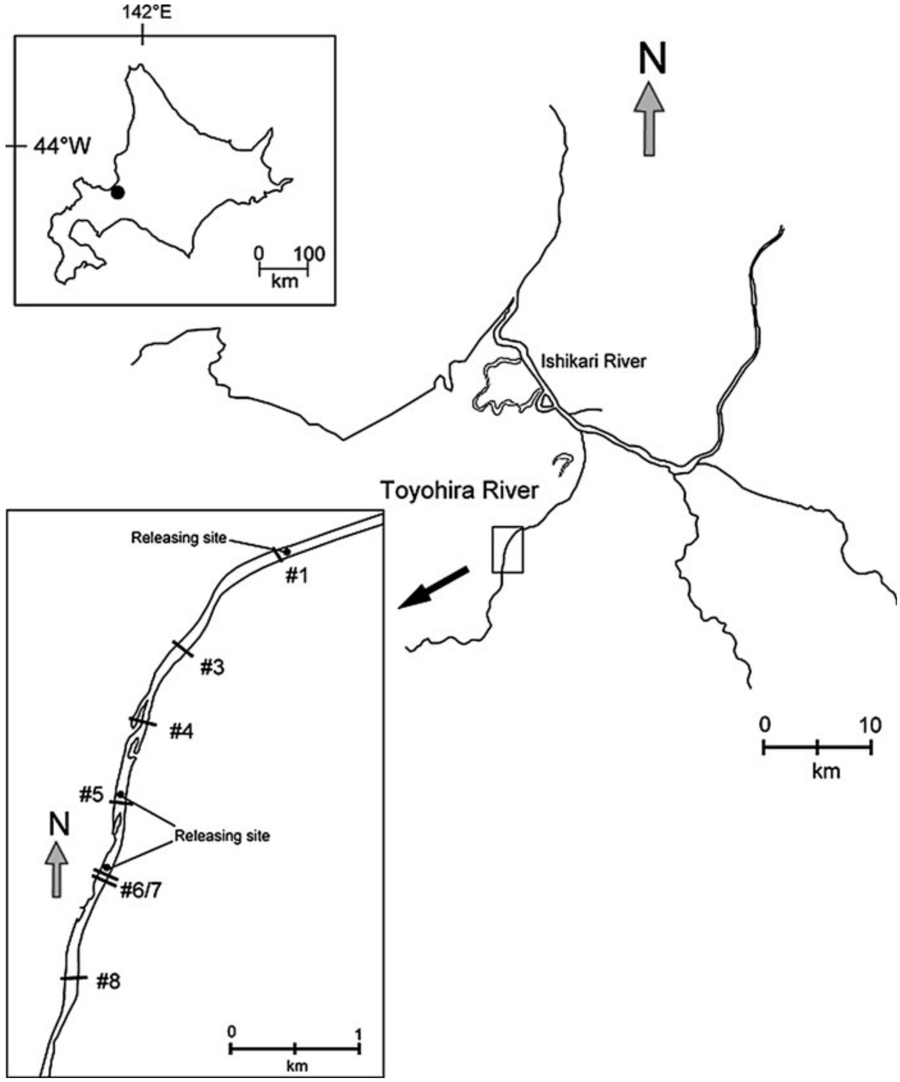

Fig. 1 Map of the study site showing the position of ground sills in the Toyohira river

nylon ties, were pushed through the dorsal muscle to secure the EMG transmitter which was sutured into place, using nylon ties and epoxy resin. Silicon pads were attached to minimize abrasion. The nylon ties were passed through the needles and tied on the opposite side (Bridger and Booth 2003).

The EMG transmitters consisted of an epoxy-coated transmitter package with a pair of Teflon-coated electrodes with brass muscle-anchoring tips (dimension 5 × 1 mm). The EMG electrodes were inserted subcutaneously using a hypodermic needle at about a 0.7 ratio of the body length on the left side of the fish. The electrodes detect electropotentials within the axial dark muscle composed by red muscle tissue, with the amplitude and frequency of these pulses being directly correlated to the level of muscle activity. Paired electrode tips were positioned approximately 10 mm apart, secured in the lateral red muscle toward the rear of the fish, which is primarily used in steady, nonbursting aerobic swimming activity (Beddow and McKinley 1999). EMG signals can therefore generally be related to swimming speed (Økland et al. 1997). The electrodes were sutured to avoid entangling vegetation and/or structure in the environment. An aminoglycoside antibiotic (Akiyama Seisakujyo Co. Ltd, Tokyo, Japan) was applied to the skin around the punctures and stitches. The CEMG model was equipped with a differential muscle probe, a signal conditioning circuit, a digitizer, a microcontroller, and a radio

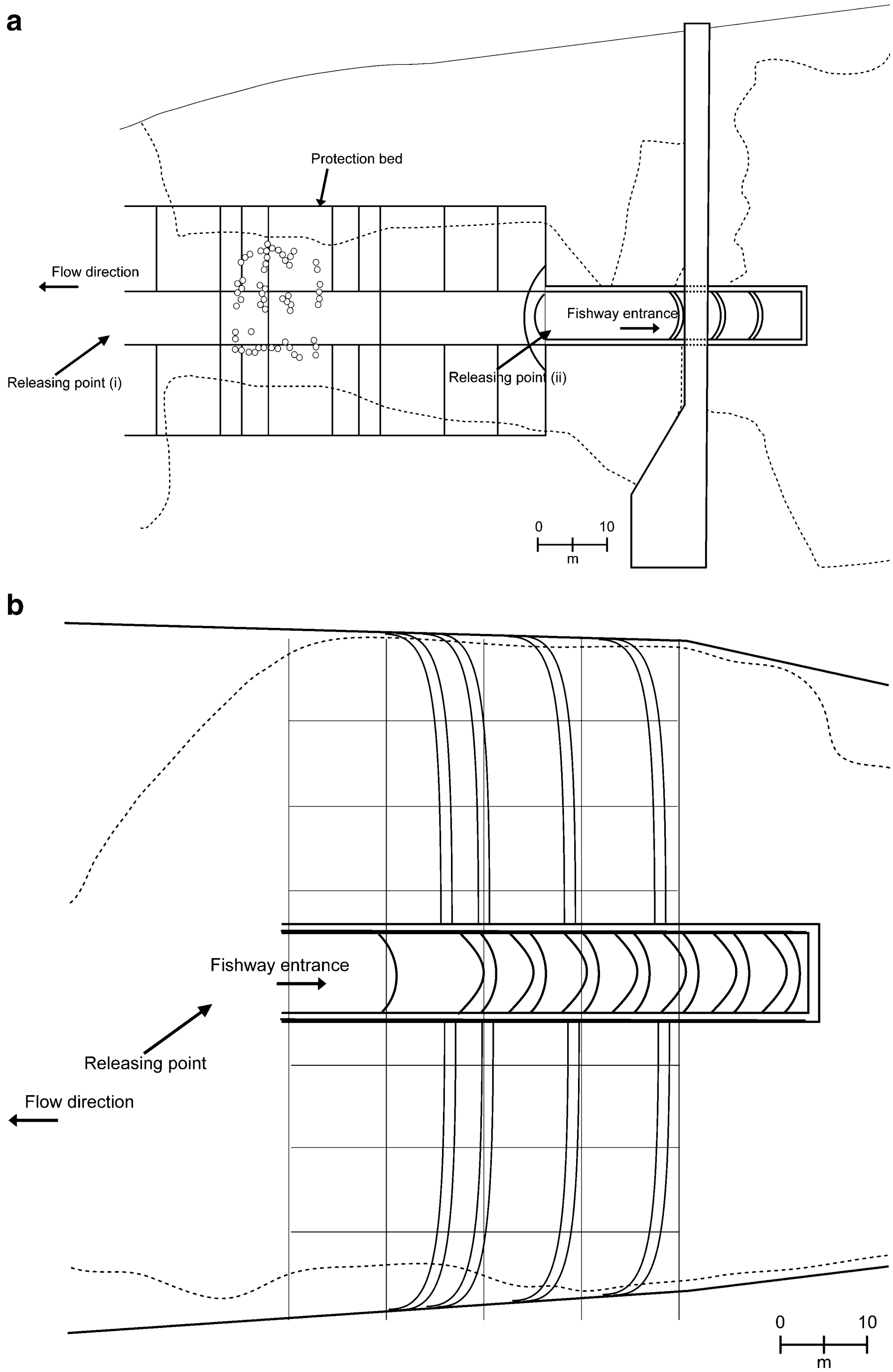

Fig. 2 Diagram of the protection bed and fishway of #5 ground sill (**a**) and the fishway of #6/7 ground sill (**b**). *Dotted line* represents edge of water. *Open circle* represents position of the sandbags on the protection bed

transmitter. The voltage corresponding to muscle activity was rectified and sampled from the beginning to the end of every 3 s time interval. Individual samples were summed and temporarily stored. At the end of the time interval, the mean value was calculated and assigned an activity level (EMG signal) ranging from 0 to 50 (no units) and then transmitted to a radio receiver (model SRX_600; Lotek Engineering Inc.). The attachment procedures usually required approximately 5 min to complete.

Calibration of EMG signals to swimming speed

Following the recovery period, an individual calibration curve was developed to convert EMG signals from all 28 fish into swimming speeds. To quantify the relationship between swimming speeds and EMG signals, a swim chamber (West Japan Fluid Engineering Laboratory Co. Ltd, Nagasaki, Japan: 1.5 m length, 0.3 m width, and 0.3 m depth) in Hokkaido Campus of Tokai University was used. Water from the Toyohira river pumped into the chamber before each trial. Water temperature during the experiments ranged from 11.0 to 13.6°C in 2008 and 11.3 to 13.0°C in 2009, the same as in the Toyohira river. Water velocity was generated by a centrifugal pump whose motor frequency was controlled by a variable speed drive unit. Water velocities (up to 120 cm s^{-1}) at selected motor frequencies were verified using an impeller connected to a precalibrated frequency counter. Experimental fish were placed individually into the swimming section of the swim chamber and measured 10 EMG signals at 0 cm s^{-1} when the fish maintained a holding position. After this period, the trial was started at 30 cm s^{-1}, and water velocity was incrementally increased by 30 cm s^{-1} to measure 10 EMG signals at each increment. Fish readily swam against the current and rarely came in contact with the grid at the back of the swim chamber. The trial was finished at 120 cm s^{-1}. The relationship between swimming speed and EMG signal output from tagged fish was plotted, and a linear regression line was used so that swimming speeds of free swimming fish using the collected EMG signals could subsequently be calculated (McFarlane et al. 2004). Once the trial was completed, fish were transferred to a live-box and allowed to recover at the release point of the Toyohira river at least for 24 h prior to release.

Field study

In October of 2008 and 2009, chum salmon used in the EMG calibration experiment were individually released in the study area and tracked upstream on foot using a hand-held directional Yagi antenna (Table 1). Fish position was monitored using received signals from EMG transmitter by three SRX_600 radio receivers. The radio receivers recorded EMG signals at 3–5 s intervals. Migration time in each segment was measured for each fish by subtracting time of reach exit from reach entry. Ground speed was then calculated by dividing the segment length by the migration time. Cessation of swimming of chum salmon during their upstream migration was often observed, and more than 3 min of cessation of swimming during their upstream migration was defined as holding behavior. Calculation of swimming and ground speed did not include holding time. EMG signals were converted to swimming speed using equations established from the EMG calibration for each fish. During tracking, characteristics of habitat cover used by migrating chum salmon were also recorded. After tracking, water depth was measured at 0.2 m intervals in the water column, and water velocity was measured at 2–5 m intervals along the tracking area using an electromagnetic current meter (ES7603; Yokogawa Navi-tech Co. Ltd, Tokyo, Japan).

Table 1 Summary of tagged fish and release sites and number of unsuccessful and successful fish and percentage of successful pass at each structure

Year	Number of released individual (female)	Number of fish upstream migrating (female)	Successful individuals (female)	Releasing site	Releasing date	Number of fish downstream or entering the structure	Number of successful fish	Percentage of successful pass
2008	5 (3)	2 (2)	2 (2)	#1 ground sill	2008/10/6	2	2	100
	5 (2)	5 (2)	1 (0)	Protection bed of #5	2008/10/13	7	1	14
	4 (2)	4 (2)	2 (0)	Fishway of #5 ground sill	2008/10/29	4	2	50
2009	6 (3)	3 (2)	2 (0)	Protection bed of #5	2009/10/7	3	1	33
				Fishway of #5 ground sill		1	1	100
	6 (2)	5 (2)	1 (0)	#6/7 ground sill	2009/10/21	5	1	20

A relative energy index (EI) was calculated to estimate the potential energy extended by each fish in association with each ground sill based on the mean EMG signal and total time spent (h) at each location using the modified formula described by Scruton et al. (2007):

$$\mathrm{EI} = \text{Mean EMG values}_{\text{ground sill}\,X} * \text{slope}^{-1}_{\text{individual}\,X} \times \text{The total time spent}(h)_{\text{ground sill}\,X}$$

The mean EMG values were calculated and divided by slope of each individual regression line to compensate for the difference of the individual relationship between EMG signal and swimming speed.

Critical swimming speed trials

In 2008, U_{crit} trials were conducted on individual fish using the swim chamber at the same time as the EMG calibration trial in order to determine the swimming speeds (i.e., EMG levels) at which fish exceeded their maximum aerobic capacity. Thirteen adult chum salmon (fork length, 63.5–70.0 cm; body weight 2.4–3.9 kg) were used to estimate U_{crit}. Five fish were used for the swimming performance tests. Initial and final water temperatures were monitored for each trial and temperature did not increase more than 2°C during the course of any individual trial. Mean temperature values ranged from 11.0 to 13.6°C for the trials. Fish were placed individually into the swimming section of the swim chamber. In all cases, fish were acclimated for an hour at 30 cm s^{-1} before use in all U_{crit} trials to minimize handling effects. After this period, water velocity was increased to 60 cm s^{-1} and fish was swum for 15 min. At the completion of each 15 min period, the water velocity was increased by an additional 30 cm s^{-1} and was maintained at the new speed for 15 min or until the fish became fatigued and was unable to swim against the current. The water velocity and the point of fatigue within the 15 min period were used in the calculation of U_{crit}. After each trial was completed, body mass, fork length, width, and depth were determined. Water velocities were corrected for the solid blocking effects (Gehrke et al. 1990) as described by Bell and Terhune (1970). U_{crit} was calculated, after correction for blocking effects, in relative (normalized for body length [BL]) units, using the formula described by Beamish (1978) as:

$$U_{\text{crit}} = U_p + \left(T_p T_i^{-1}\right) \times U_i$$

where U_p is the velocity at which the fish last swam for the full period, U_i is the velocity increment (30 cm s^{-1}), T_p is the length of time in minute that the fish was able to swim against the water velocity which produced fatigue, and T_i = the time between velocity increments (15 min).

Regression analysis was performed by simple regression of EMG signals on swimming speed. Correlation coefficients were obtained using simple regression analysis (Excel software). Statistical significance was determined using Welch's t test, and achieved when $P < 0.05$. Values are presented as means ± standard deviation or standard error of mean.

Results

Calibration of EMG signals and swimming speeds

There were no clear differences in muscle activity between females and males in the present study. The activity levels were significantly correlated with swimming speed (average of 16 chum salmon in 2008 $r^2 = 0.947$, average of 12 chum salmon in 2009 $r^2 = 0.914$; all $P < 0.05$), and were individually used to convert EMG signals of the field study to each fish's swimming speed. The U_{crit} ranged from 1.43 to 1.68 BL/s (mean ± SE 1.55 ± 0.10 BL/s, 1.03 ± 0.07 m/s, $N = 5$).

Behavior of tagged fish around the ground sills

Tagged fish were intermittently tracked from approximate 1 to 2 days. The proportion of fish passing through obstacles varied among structures (Table 1). Of seven and three tagged fish released at the protection bed of the #5 ground sill, one fish (14% and 33%) ascended through the fishway of #5 ground sill in 2008 and 2009, respectively. Of four and one tagged fish released at the fishway of #5 ground sill, two (50%) and one (100%) fish ascended through the #5 ground sill in 2008 and 2009, respectively. Of the five tagged fish released at the fishway of #6/7 ground sill, one individual (20%) ascended through the #6,7 ground sill. The percentage of success fish which passed through the protection bed of the #5 and the fishway of #6/7 ground sill were lower than that through the #1 and the fishway of #5 ground sill, suggesting that these structures were arduous passage for upstream migrating chum salmon in the Toyohira river.

We were able to collect EMG data of three and ten fish that migrated successfully and unsuccessfully through these structures, respectively, in the approach to the protection bed of #5 and the fishway of #6/7 ground sills. Table 2 shows that mean approaching time was shorter for fish that passed successfully through the protection bed of #5 ground sill (43.0 min, $N = 2$) than for those that were unsuccessful (224 ± 65 min, $N = 6$). The relative energy index (EI), which integrates both EMG value and approaching time, was greater for fish that passed unsuccessfully through the protection bed of #5 ground sill ($1{,}379 \pm 507$, $N = 6$) than for those that were successful (237, $N = 2$). We pooled data of mean swimming speed, maximum speed, approaching time, and EI in the protection bed of #5 ground sill and the fishway of #6/7 ground sill, and compared those values between successful and unsuccessful fish (Table 2). Mean swimming speed and mean maximum speed were not significantly different between successful and unsuccessful fish. However, mean approaching time was significantly shorter and EI was significantly greater for fish that passed successfully through these structures than for those that were unsuccessful ($P < 0.01$).

Figure 3 shows cross-sectional water depth (a) and water velocity (b) around the protection bed and fishway of #5 ground sill. Relatively shallow water depth and high water velocity were observed the protection bed of #5 ground sill. Figure 4 shows typical pattern of temporal swimming speed and migration paths of successful (a) and unsuccessful individuals (b) at the protection bed of #5 ground sill. Successful fish made one trial for upstream migration, swam relatively at constant speeds, and showed high swimming speed over U_{crit} several times (Fig. 4a). In contrast, very different swimming patterns were observed for the unsuccessful fish (Fig. 4b). Unsuccessful fish tried to make upstream migration nine times, and swam high speed over U_{crit} frequently.

Table 2 Mean swimming speed, maximum speed, resident time, and energy index of successful and unsuccessful fish at each structure

Ground sill	Swimming speed (BL/s)*		Maximum speed(BL/s)*		Approaching time (min)*		Energy Index(EI)*	
	Successful	Unsuccessful	Successful	Unsuccessful	Successful	Unsuccessful	Successful	Unsuccessful
Protection bed of #5	0.43 (2)**	0.59 ± 0.10 (6)	2.31 (2)	2.86 ± 0.210 (6)	43.0 (2)	224 ± 65.1 (6)	237 (2)	1,379 ± 507 (6)
Fishway of #6 ground sill	0.56 (1)	0.77 ± 0.05 (4)	1.85 (1)	3.32 ± 0.820 (4)	39.9 (1)	285.9 ± 24.9 (4)	449 (1)	1,760 ± 459 (4)
Pooled data	0.47 ± 0.18 (3)	0.64 ± 0.07 (10)	2.16 ± 0.810 (3)	2.93 ± 0.270 (10)	41.97 ± 7.57 (3)	241 ± 39.4 (10)	308 ± 85.7 (3)	1,529 ± 322 (10)
P value	0.45		0.44		<0.01		<0.01	

* Values represent mean ± standard error

** Data in parentheses are fish number

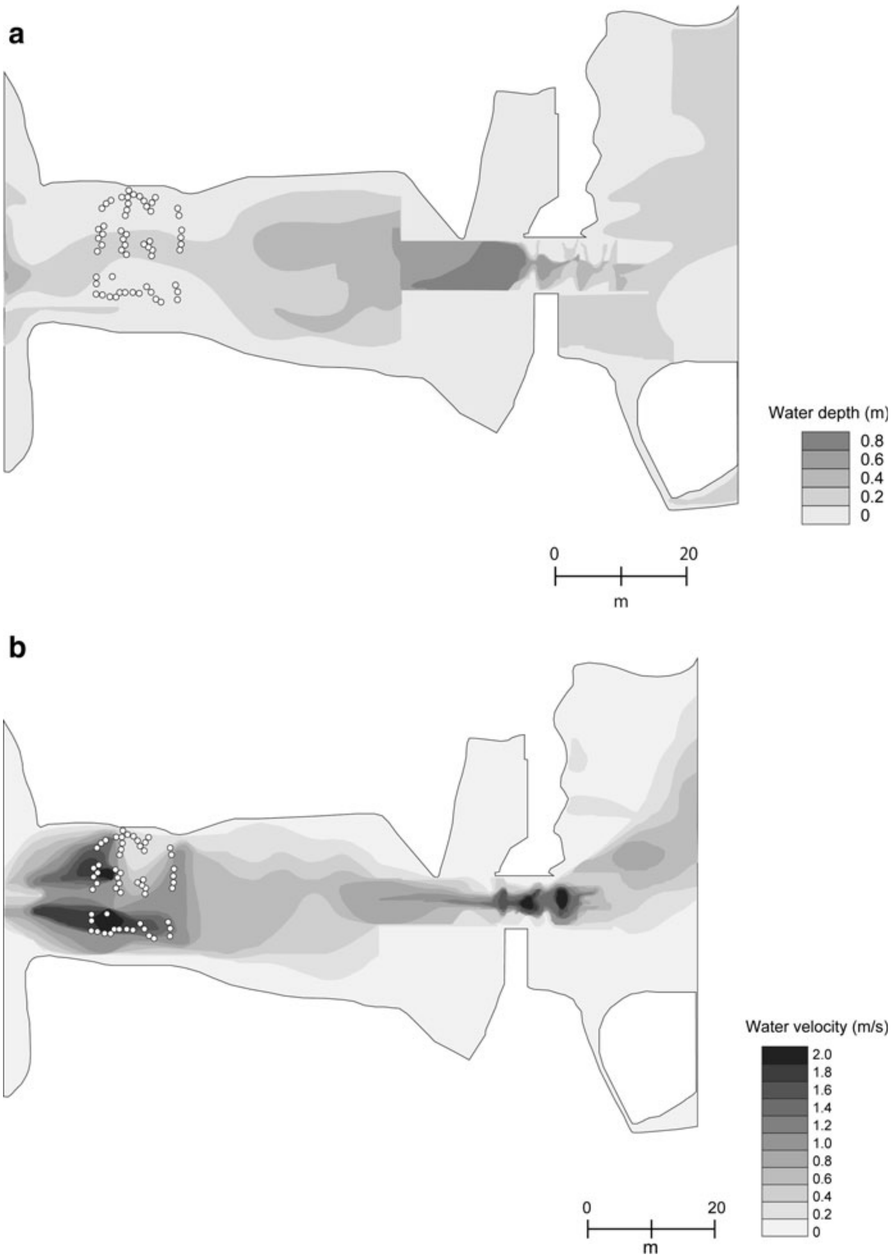

Fig. 3 Two-dimensional water velocity (**a**) and water depth (**b**) in the protection bed and fishway of #5 ground sill. *Open circle* represents position of the sandbags on the protection bed

Water velocity in the migration paths through the protection bed of #5 ground sill tended to be higher for unsuccessful fish (Fig. 4b) than those for successful fish (Fig. 4a). Table 3 shows that water velocity and water depth in the migration paths at the protection bed of #5 ground sill and the fishway of #6,7 ground sill in all successful and unsuccessful fish, respectively. Water velocity was significantly higher for unsuccessful fish than for successful fish, and water depth was significantly shallower for unsuccessful fish than for successful fish at these structures.

Discussion

The present study revealed that only a small percentage of tagged fish could pass through the

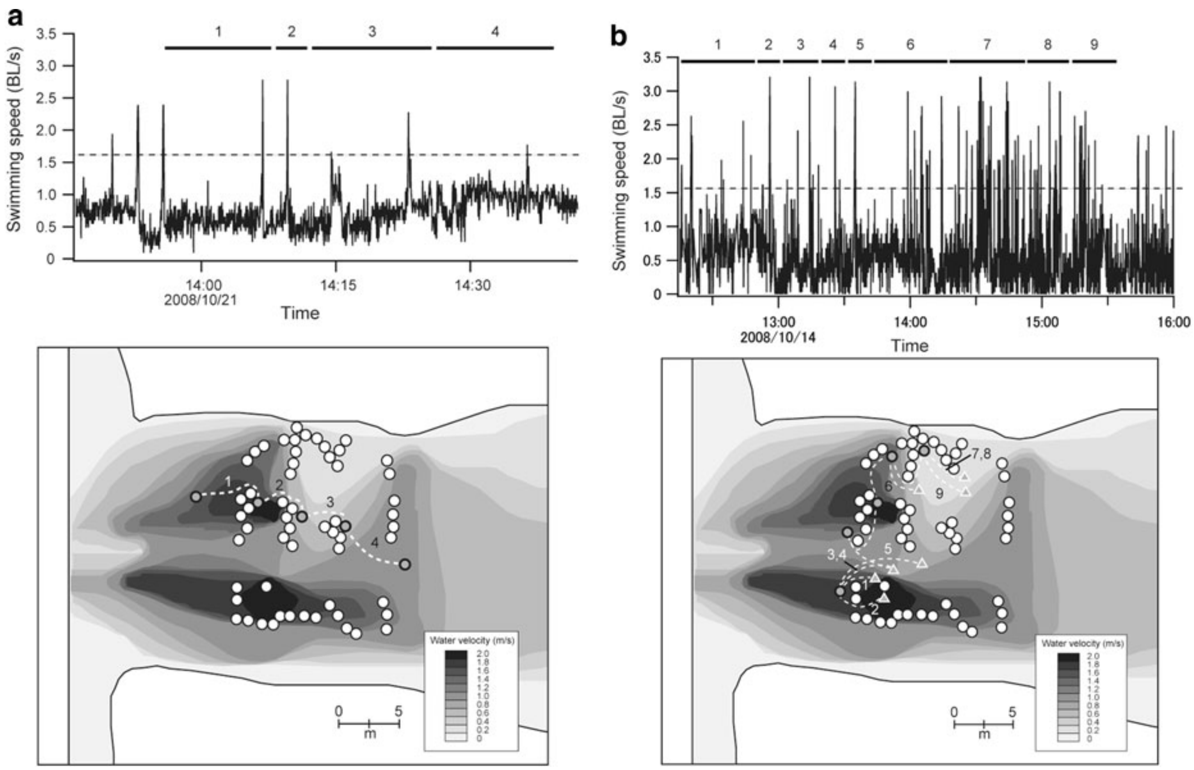

Fig. 4 Time-series plots of swimming speeds of successful (**a**) and unsuccessful (**b**) chum salmon and dotted line represent a mean critical swimming speed (1.55 BL/s) (*upper figure*). Swimming path (*white dotted line*) of successful (**a**) and unsuccessful (**b**) chum salmon and two-dimensional water velocity in the protection bed of #5 ground sill (*lower figure*). Numbers on the *upper figure* correspond to the lower figure, respectively

Table 3 Water velocity and water depth of successful and unsuccessful fish at each structure

	Protection bed of #5		Fishway of #6 ground sill	
	Water velocity (m/s)	Water depth (m)	Water velocity (m/s)	Water depth (m)
Successful	1.16 ± 0.149* (6)**	0.27 ± 0.050 (6)	0.408 ± 0.032 (5)	0.57 ± 0.116 (5)
Unsuccessful	2.63 ± 0.20 (21)	0.177 ± 0.018 (21)	1.184 ± 0.214 (10)	0.166 ± 0.02 (10)
P	<0.01	0.03048	<0.01	0.01951

* Values represent mean ± standard error

** Data in parentheses are fish number

protection bed of #5 ground sill and the fishway of #6/7 ground sills, suggesting that these structures were obviously arduous for upstream migrating chum salmon in the Toyohira river. Individuals that successfully passed through these structures showed several characteristics. First, successful fish had relatively short approaching times that resulted in low EI compared with those of unsuccessful fish, indicating that they could make rapid forward progress by selecting relatively deep water depth and low water velocity. In contrast, unsuccessful fish exhibited an approaching time approximately five times longer, which resulted in higher EI than those of successful fish. Second, unsuccessful fish swam for prolonged periods at speeds exceeding U_{crit} at the protection bed of #5 ground sill and the fishway of #6 ground sill. Hinch and Bratty (2000) investigated swimming speed and passage success for sockeye salmon through Hell's Gate in the Fraser river, British Columbia using EMG telemetry, and found that unsuccessful fish relatively swam faster at speeds above their U_{crit} and had relatively longer approaching times than successful fish. Our results were concordant with these findings. Aerobic metabolism predominates in salmonids (i.e., red muscle activity) at swimming speeds up to 70–80% of the U_{crit}, but anaerobic metabolism is initiated during swimming at 80% of the U_{crit} (Webb 1971) and may contribute to salmon energy budgets as swimming speeds approach and exceed U_{crit} (Hammer 1995). Adult salmon swim below and above U_{crit} during upstream migration, using burst swimming (Hinch and Bratty 2000; Hinch and Rand 2000; Hinch et al. 2002). Makiguchi et al. (2008) found that chum salmon during upstream migration consistently showed holding behavior following high swimming speed exceeding U_{crit} and indicated that the swimming behavior prior to holding represent exhaustive swimming. Therefore, unsuccessful fish were likely experiencing levels of fatigue and stress during their passage at the protection bed of #5 ground sill and the fishway of #6/7 ground sill. Salmon tend to cease feeding prior to spawning migration and rely on the fish's limited energy reserves and engage in spawning events (Hasler et al. 1978; Brett 1995; Rand and Hinch 1998). Extensive delay of the passage may prevent fish from spawning because of gamete resorption (Shikhshabekov 1971) and depletion of energy, and could lead to premortality of chum salmon in the Toyohira river.

We compared EI per hour calculated by dividing the average approaching time by EI between successful and unsuccessful fish. Values of EI per hour were similar between successful (0.1223) and unsuccessful fish (0.1057), suggesting that EI per unit time was the same between successful and unsuccessful fish. High approaching time and a burst-then-sustained speed pattern of unsuccessful fish indicated that they were actively seeking upstream passage and seemed to frequently alternate between burst and maximum sustained speeds. In addition, unsuccessful fish were observed to swim at relatively high water velocity and shallow water depth in the protection bed and fishway of ground sills. It is generally considered that a fish passage system should be designed to minimize the energetic cost of migrating fish under most flow conditions (Bunt 2001). However, high water velocity and turbulence diminish the success of migrating fish in locating and passing through fishways (Barry and Kynard 1986). Thus, our results suggest that it is important for the successful migration of salmon to find passage upstream rapidly and easily without wandering. Migrating Atlantic salmon (*Salmo salar*) sometimes fails to locate the entrance to a pool and orifice fishway, and appear to be attracted by tailrace and turbine flows (Gowans et al. 1999). Fish are positively rheotactic but avoid the highest velocity flows (Banks 1969). Bunt (2001) proposed the effective fishway entrance design to mitigate the blocking of barrier in cases where there is a waterfall or other migratory obstruction. In contrast, successful fish might utilize reverse flow field through the fast flows during upstream migration. Fish have the ability to use reverse flows or upwelling created by structure downstream of the dams, which may have helped to minimize swimming efforts (Pon et al. 2009a). Such behaviors have previously been observed in upstream migrating sockeye salmon (Hinch et al. 2002). Pon et al. (2009b) tracked adult sockeye salmon during upstream migration using EMG radio telemetry at a fishway on the Seton river, British Columbia, Canada and found no differences in initial plasma physiology such as plasma lactate, glucose and cortisol levels, and energy state between successful and unsuccessful fish, indicating that passing failure may not related metabolic acidosis. It is still unclear why some fish found passage for in a relatively shorter period while others did not.

The present study provided basic information on the protection bed and fishway that could improve passage efficiency for chum salmon in the Toyohira river. It is important to improve the efficiency of fishways and to minimize the impact of the ground sills passage for fish. Furthermore, this study showed that telemetry tracking may be necessary to identify potential effects of migrating fish through the protection bed and fishway of the ground sill.

Acknowledgments We thank the following for their help and cooperation: Mr. Y. Okamoto (Sapporo Salmon Museum) for providing experimental animals and Prof. K. Tsumura and Prof. K. Yano for providing the swimming chamber and facilities in Hokkaido Campus of Tokai University. This study was supported in part by a Research Fellowship for Young Scientists to Y. M. (195295) from the Japanese Society for the Promotion of Science (JSPS) as well as Grant in-Aid for Scientific Research (A) (18208017) from JSPS, and the Foundation of Riverfront Improvement and Restoration to H. U.

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