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〈Original Article〉

Penetrating behavior of target prawns (*Sicyonia penicillata*) contacting netting panels in an experimental water tunnel

Yonghae KIM* and Malcolm S. GORDON[1]

Institute of Marine Industry, College of Marine Science, Gyeongsang National University, Tongyoung, 53064, Korea
[1]Department of Ecology & Evolutionary Biology, University of California, Los Angeles, CA 90095, USA.

Capture efficiencies of commercial shrimp trawls may improve if their designs took into better account behavioral responses of wild shrimp to approaching cod-end of the trawls. Here we report results of water tunnel-based experimental studies of responses of wild California target prawns to several different near-realistic netting configurations over a range of water velocities (0.3–0.7 m/s). Netting panels were oriented at parallel to water flows (FP) on the bottom of test section, vertical (VT) or diagonal sloping backward (DG), bottom to top. Behavioral responses were recorded by video camera and analyzed frame by frame. Measured responses included rates of penetrating through netting by behavioral features and tail-flip frequencies. Frequencies of prawn passing through the nets increased with flow speed for both orientations and were higher at given speeds for sloped nets. Other behavioral features (e.g., passage head-or tail-first) also varied significantly with water velocities and netting orientation. Interactions of penetrating rates between netting orientations and flow speeds also were significantly dependent, except for prawn size. Additional studies are needed of other shrimp species and at higher water velocities more similar to actual field operations using trawls to improve size selectivity.

Keywords : Shrimp behavioral features, Flow speeds, Netting orientations, Penetration rates

Introduction

Size selectivity and capture efficiencies of commercial shrimp trawls might be improved if their designs took into better account behavioral responses of shrimp to approaching into cod-ends of the trawl. Trawl nets are the most widely used capture method for commercial harvesting of shrimp and other crustaceans as important as seafood by beam trawl (Kim, 2012) or otter trawl (He and Balzano, 2007). Little research has been done in recent years on capture process or efficiencies by application of shrimp behavior and trawl designs for these primary target species.

Most research related to management of shrimp fisheries is focused on by-catch of fin-fishes. There are many studies of by-catch reduction (Isaksen et al., 1992; Broadhurst, 2000; Catchpole and Revill, 2008) and mesh selectivity (Briggs, 1986; Tokai et al., 1990). By-catch reduction devices (BRD) in shrimp trawls are designed mainly to sort out the catch of unwanted fishes. This is done by using square mesh windows, grids of several types (Broadhurst, 2000; Loaec et al., 2006; He and Balzano, 2011), sieve nets and other gear modifications (Revill and Holst, 2004).

Size-sorting grids were also investigated for reducing

*Corresponding author : Yonghae@gnu.kr, Tel: +82-55-772-9183, Fax: +82-55-772-9189

the catch of small shrimp (He and Balzano, 2007). Other studies compared mesh selectivity by shrimp with respect to different netting materials (Deval et al., 2006), mesh shapes (Campos et al., 2002; Sala et al., 2015). The size selection in the cod-end with respect to net penetration seems determined by the size and shape of mesh openings in relation to shrimp morphology and penetrating behavior (Briggs, 1986; Broadhurst and Millar, 2011). *Nephrops* behavior in relation to fishing gear was observed and showed that the tail-flip of the shrimp has frequently occurred in the herding process near ground gear (Newland and Chapman, 1989). However, shrimp were infrequently observed in the mouths or cod-end netting of trawls in many field operations due to both small body sizes and technical limitations as indistinct images due to low contrast to background (Queirolo et al., 2012; Hannah and Jones, 2012). Mechanisms of mesh penetration by shrimp, such as control of body orientation, swimming or tail-flip were not clearly observed.

This paper is intended as a case study and template for laboratory-based experimental studies of the behaviors of commercially important shrimp species encountering or penetrating netting similar to types used in the cod-ends of commercial (beam or otter) trawls under a range of conditions similar to, but not exactly duplicative of, actual fishing operations in the field. We used a model system to observe shrimp behavior in relation to nets like those used in cod-end of commercial shrimp trawls. We studied body postures and body movements, including tail-flips, in relation to mesh penetrations as affected by net positions and water flow speeds. Using a precision water tunnel to control water velocities, we tested net panel positions based upon the three dimensions of the circular cylinder of the cod-end of a trawl.

Target prawns were chosen as model experimental subjects (Jensen, 2014). This species has a body shape similar to that of the ridgeback prawn (*Sicyonia ingentis*) which is one of the main shrimp species caught in commercial beam trawls in California, USA (Allen et al., 2005; Jensen, 2014). Here we report both behavioral and kinematic responses of target prawns as they penetrated differently oriented panels of mesh netting at relatively high speeds of water flow (up to 9 BL/s). We made quantitative analyses of their behavioral responses in addition to tail flips when penetrating mesh (Kim and Gordon, 2016). The results provide insight into how shrimp react to such situations. Those reactions may provide both gear designers and actual fishers with ideas as to how they might modify current practices to improve size selectivity and catch rates. Additional studies using water tunnels capable of operating at higher speeds are needed to obtain direct information relevant to present industry-standard practices.

Materials and Methods

Shrimps

Experimental shrimp were 103 target prawns, *Sicyonia penicillata* (mean carapace lengths (CL)=22±2 mm; mean total body lengths (TL)=79±7 mm), collected in shallow coastal California waters by divers 35 prawns on November 2015 and 68 prawns March 2016. They were first kept in the aquarium of Marinus Scientific Inc. in Long Beach, California, USA. They were delivered to the UCLA aquarium a day after collecting. Measurements were also made of body length (TL), carapace length (CL), carapace widths (CW) and carapace heights (CH) at the points of maximum cephalothorax cross-sectional areas. Small body sizes are defined as the lowest 25% (CL ≤ 20 mm), medium as the middle class 50% (20<CL ≤ 24 mm) and large as the upper class 25% (CL>24 mm).

Prawns were maintained in two acrylic aquaria (L1600×W760×D300 mm; L1570×W740×D600 mm; around 40000 mm^2 per prawn) that were integrated into re-circulating 30 litre/min with filters from a reservoir and water temperature controlled system at UCLA.

Natural seawater was maintained at controlled temperatures of 15-16°C, salinity 35 psu, pH 8.0 from December 2015 through April 2016. They were fed smelt purchased from a seafood market once each day. Photoperiod was 12:12 hours light-dark with room fluorescent lights controlled by a timer. Water tunnel experiments started at least one week after prawn began feeding normally. The study was carried out under a protocol approved by the UCLA Chancellor's Animal Research Committee.

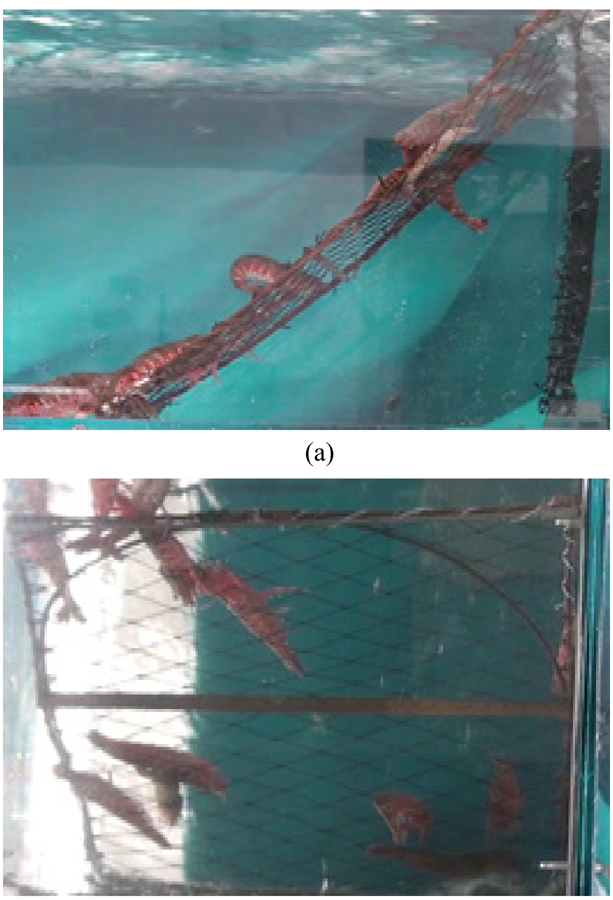
Nettings

Netting used was dark brown in color, made of 9 ply polyethylene (PE) twine in diamond mesh (stretched mesh sizes 27 mm and 50 mm). Net hanging ratios were 90% (openings 24 mm and 45 mm respectively), comparable to real cod-ends of shrimp trawls. Flat panels of netting were positioned in three directions in the working section of the water tunnel (Fig. 1). Three orientations of net panels were selected to represent different panels of cod-ends occurring during fishing operations:

1) vertical transverse (VT) to flow as the standard protocol, mounted in a 300×380 mm acrylic frame with mesh size 50 mm, positioned 200 mm forward of the rear outlet of the working section;

2) slope up (diagonal) (DG) to flow at 45 deg, mounted in a 420×300 mm wooden frame with mesh size 50 mm connected to an acrylic frame that fit the width of the working section;

3) flat (horizontal) parallel (FP) to flow, like the lower net panel of the cod-end of a shrimp trawl, mounted in a 290×570 mm acrylic frame positioned 80 mm (the mean body length of prawn) above the bottom of the working section; two mesh sizes of 27 mm and 50 mm were used in a frame.



(a)

(b)

Fig. 1. Netting panels set as diagonal (DG) and vertical transverse (VT) under flow from left to right. (a) is lateral view and (b) is a simultaneous mirror image as ventral view from below the working section.

Water tunnel

The water tunnel used was also used for carp penetration in mesh by Kim and Gordon (2010). It was a computer controlled, thermally regulated, high precision, low turbulence Model 503, manufactured by Engineering Laboratory Design, Inc., Lake City, MN, USA. It had a 300×300 mm cross-section, 1000 mm long transparent acrylic working section. The tunnel was filled with the same natural seawater used to maintain the prawn. Water temperatures were regulated at 15-16°C by two automatic water chillers. To maintain pH≈8.0 water in the tunnel was circulated at low flows of 0.1 m/s through marble sand and coral when the tunnel was not in use for experiments. Room lighting was 12×100W fluorescent ceiling lights. The upper and rear sides of the working section, except the front window, were covered in blue fabric and the floor under the working section was covered by blue painted cardboard to diminish the light reflection and to mimic sea color in video recordings.

Experiments

Endurance of prawns at different flow speeds was tested using horizontal 27 mm and 50 mm mesh netting (FP). Flow speeds were increased from 0.3 to 0.7 m/s with increments of 0.1 m/s by1min interval for 6 min. Numbers of prawn maintaining their positions (not moving backwards by either walking on the mesh or swimming) were counted at 1 min intervals. Endurance rates were represented as fractional rates of prawn numbers maintaining position for every min at different flow speeds.

Experimental trials consisted of placement in the working section of one of the netting panels or the grid in one of the orientations listed above. For each trial a group of 10-13 prawn sampled randomly from the maintenance aquarium was introduced into stationary water in front of the netting panel. They were held in place for 5 min separated from the netting panel or grid by a wire screen. Water flow was then started at speeds of 0.3, 0.5 or 0.7 m/s up to 9 BL/s. The wire screen was removed and the number of prawn that passed through the mesh was counted after 5 min of steady flow at the selected speed. Most combinations of conditions were tested 10 times each by turns of several trials until all prawns used in a day.

Responses of the groups of prawn to the netting panel were recorded as lateral and ventral views of 1,920×1,080 pixels by a digital video camcorder (Sony HDR-CX560, Tokyo, Japan) positioned 1,200 mm from the front surface of the working section (Kim and Gordon, 2010). For rear images a PC-controlled and recorded underwater endoscope USB camera (dia. 6 mm, length 50 mm, frame speed 30 fps, 1,280×720 pixels) was fixed at the left upper corner of the screen frame in the working section. Illumination levels were measured by Lux-meter (Dr. Meter, LX1330B, Qingdao, China) as 15 lx in the horizontal direction and 10 lx in each of the vertical and rear directions under normal room light.

For more accurate postures of prawn bodies during tail-flipping a PC-controlled high speed video camera (Redlake PCI500, Red Lake Falls, USA) was used at 1,500 mm from the front of the working section to take lateral views for 2s at 500 fps (320×280 pixels) (Kim and Gordon, 2016). Experiments for each net panel were done once a day for about 20-40 prawn for 45 days. Each prawn was repeated 16 trials as 12 times for net panel test and 4 times for endurance test at least two days interval respectively.

Image analyses

Maneuvers and body positions recorded by the Camcorder and the mini endoscope were digitized and analyzed frame by frame using Window Gom Player. We measured multiple parameters related to net penetration by the prawn: prawn size, partial penetration, passing head- or tail-first, the stimuli for tail-flips that resulted in net penetration and numbers of tail-flips. Prawn sizes were defined as small, medium and large by CLs as mentioned previously. Netting panel areas penetrated by prawn were divided into thirds in both VT and DG experiments. Three stimulus situations evoking net penetration were: self-induced tail-flip (voluntarily without contact with other prawn), tail-flip followed by contact with other prawn and no tail-flip (passive penetration). Numbers of consecutive tail-flips during net penetrations were counted from the start of abdomen flexion to the end of the body coming out of the net. Passive penetrations with no tail flip were recorded as zeroes. Consequently no tail flip in stimulus source and zero tail flip in number of tail flips represents passive penetration by flow speed while the other cases represents actively self penetration by tail flip mainly.

Statistical analysis

Data for fractional rates of prawn penetrating nets for trials of different netting panels at different flow speeds were tested for 115-125 prawn by two-factor ANOVA (Zar, 1996). Other parameters (e.g., body size, sections of netting penetrated, stimuli, numbers of tail flips as fractional rates) for each 10 trials were statistically tested by Chi-square method. Penetration rates through grids at different flow speeds were tested by one-factor ANOVA. Regression equations for sustaining rates on horizontal netting (FP) are least squares linear estimates and sustaining rates on netting with different mesh sizes were tested by paired t-test.

Results

Fig. 2 shows the relationships between morphometric parameters for 65 prawns used in this study. Least squares linear regression equations relating carapace heights (CH, mm), carapace widths (CW, mm) and body length (TL, mm) to carapace lengths (CL, mm) are:

$$TL=2.77CL+19.1 \quad (r^2=0.91) \quad (1)$$

$$CW=0.63CL-0.3 \quad (r^2=0.83) \quad (2)$$

$$CH=0.77CL-0.4 \quad (r^2=0.83) \quad (3)$$

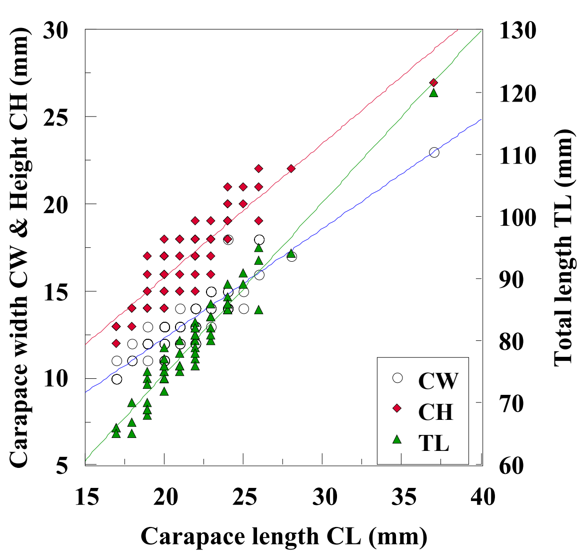


Fig. 2. The relationships between carapace lengths (CL), carapace width (CW) and carapace height (CH) of target prawn. Carapace lengths and total lengths (TL) were normally distributed.

Behavior at different flow speeds

Under slow flow conditions on horizontal netting (FP) prawns gradually moved backwards by either walking on the mesh or swimming. As flow speeds increased prawn facing forwards on the netting let go one by one and drifted back. Resultantly none of prawns were passing down through FP meshes. The fractional rates of prawn numbers maintaining position (endurance rates) for 1 min at flow speeds from 0.3 to 0.7 m/s increased by increments of 0.1 m/s were significantly different between 27 mm and 50 mm mesh netting (paired t-test, $p<0.001$) (Fig. 3 and Table 1). At the highest flow speed (0.7 m/s, about 9 TL of mean body length), the sustaining rate on 27 mm netting was nearly double the rate on 50 mm netting. The relationships between flow speeds (V; m/s) and fractional endurance rates (ER) are described by the following exponential regression lines:

$$\text{27 mm mesh:} \quad ER=102.2e^{-2.48V} \quad (r^2=0.96) \quad (4)$$

$$\text{50 mm mesh:} \quad ER=113.2e^{-4.02V} \quad (r^2=0.95) \quad (5)$$

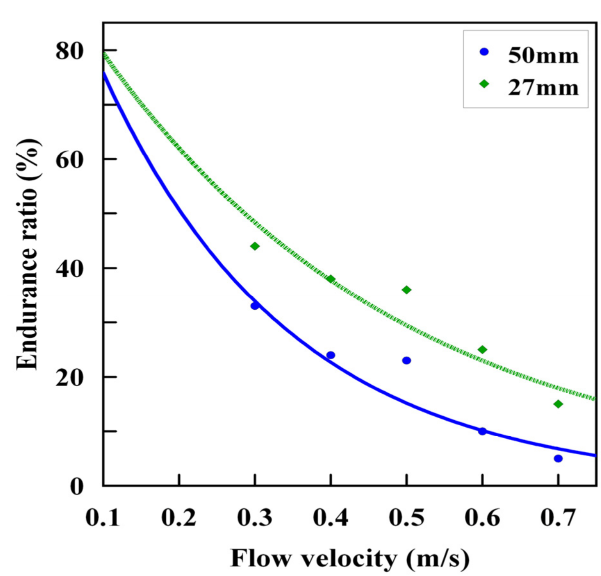


Fig. 3. Relationships between fractional endurance rates (ER) and flow velocities (V; m/s) with FP netting position.

Net penetration rates

With VT netting position prawn drifting back under flow stopped when they reached the netting. They initially were blocked but then passed through. Some smaller prawn quickly passed through the mesh either head- or tail-first. Other prawn tried to tail flip, moving non-directionally on the front surface of the net. A few prawn passed through by tail flip in the backward direction.

Table 1 shows absolute and relative numbers of prawn in all body size categories passing through netting panels in the VT and DG positions at different flow speeds. The Table 2 also shows numbers of prawn holding as endurance on to netting in the FP position for 1 minute at different flow speeds.

Passing rates at all flow speeds were significantly higher (tested by two-factor ANOVA) when nets were positioned diagonally rather than vertically ($p<0.003$). For each net position passing rates also increased significantly at higher flow speeds ($p<0.001$). There was no significant interaction between net position and flow speed ($p>0.47$). Passing rates through the grid at different flow speeds increased significantly only at the highest speed (tested by one-factor ANOVA, $p<0.05$). Endurance rates for flat panels (FP) were significantly higher for the smaller mesh size at all flow speeds.

Table 1. Numbers of prawn and passing rates for all body size groups through netting panels in VT (vertical transverse) and DG (diagonal) positions

Flow speed (m/s)	VT			DG		
	Total	Pass	Mean (%)	Total	Pass	Mean (%)
0.3	125	34	27±14	118	50	42±8
0.5	125	65	52±13	116	72	62±6
0.7	115	83	72±10	113	89	79±6

Table 2. Endurance rates as remaining numbers of prawns on FP (flat parallel) netting of two mesh size at variable flow speeds

Flow (m/s)	Mesh size 27 mm		Mesh size 50 mm	
	Number	Rate (%)	Number	Rate (%)
0.0	130	100	136	100
0.3	57	44	45	33
0.4	49	38	33	24
0.5	47	36	31	23
0.6	33	25	14	10
0.7	20	15	7	5

Net penetration behavioral parameters

Net penetration behavioral parameters (i.e. body size, section of netting, head-first or tail-first as body part when passing; stimulus sources, numbers of tail flips) were noted for prawn penetrating under the different experimental conditions (i.e., netting orientation VT and DG, 3 steps of flow speed). Then penetrating number was divided by the total numbers of prawn penetrating as penetrating rate. The penetrating rates by lower, middle and upper sections of netting are shown in Fig. 4. The penetrating rates by which body part first (head or tail) passing are shown in Fig. 5. The penetrating rates by stimulus sources (voluntary without stimulus, without tail flip or other prawn) are shown in Fig. 6. The penetrating rates by numbers of tail flip are shown in Fig. 7. Comparisons of rates for each behavioral parameter with different netting orientations, and varying flow speeds were tested by Chi-square methods and two-factor ANOVA as shown in Table 3.

With the exception of only a marginally significant effect of flow speed or netting orientation on body size categories Table 3 shows that the other behavioral parameters varied statistically (Chi-square methods) significantly between different test conditions. Each parameter except prawn size varied significantly for each netting orientation and for different flow speeds. Interactions (by ANOVA) between netting orientations and flow speeds also were dependent significantly, except for prawn size. More prawn passed through the upper section of the diagonal netting (DG) than passed through the upper section of the vertical netting (VT) due to rolling upwards on the slope. Passing through tail-first and active passing with tail-flips were more

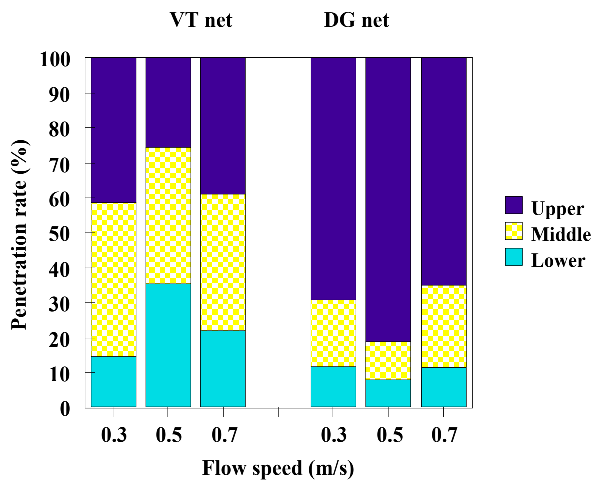


Fig. 4. Fractions of prawns penetration through each of the three net sections (upper, middle and lower) for vertical (VT) and diagonal (DG) netting panels at different flow speeds.

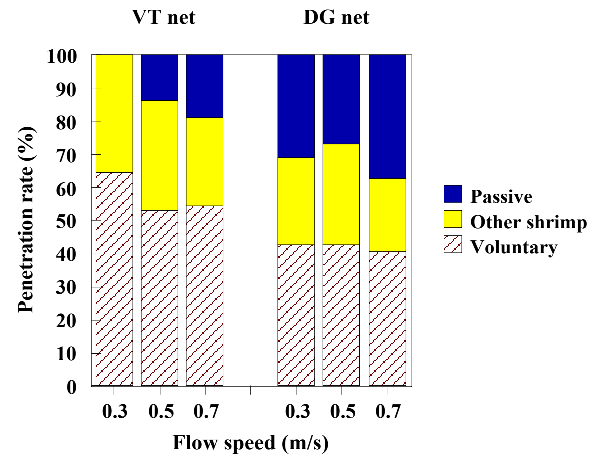


Fig. 6. The penetrating rates by stimulus sources (voluntary with tail flip, other prawn or passively with flow) for vertical (VT) and diagonal (DG) netting panels at different flow speeds.

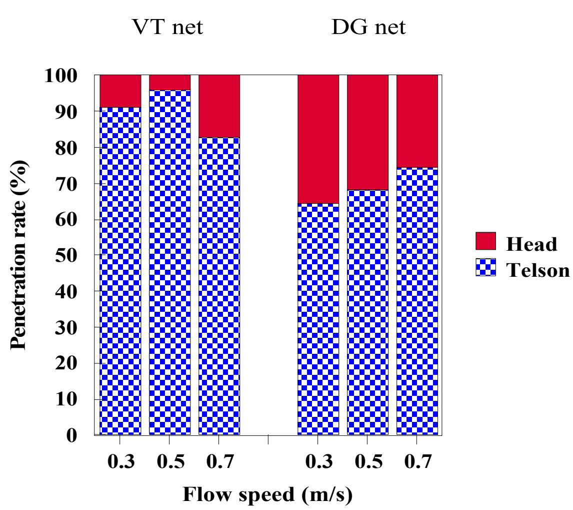


Fig. 5. Fractions of prawns penetration through each of body part (head-first and telson-first) for vertical (VT) and diagonal (DG) netting panels at different flow speeds.

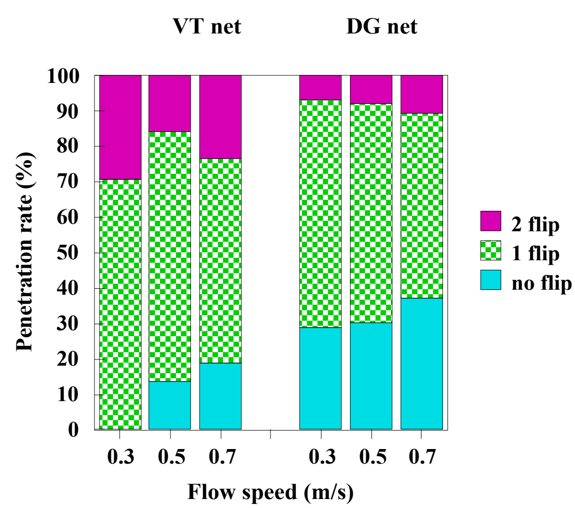


Fig. 7. The penetrating rates by numbers of tail flip for vertical (VT) and diagonal (DG) netting panels at different flow speeds.

Table 3. Chi-square and 2-factor ANOVA tests of variations in behavioral parameters of prawn penetrating netting

Behavioral Parameters	Test probability			
	Chi-square	Chi-square		2-factor ANOVA
	Each parameter for whole	Nettings (VT:DG)	Flow (m/s) (0.3:0.5:0.7)	Interaction (Netting:Flow)
prawn size	0.257	0.307	0.040	0.925
Net section	0.001	0.001	0.023	0.001
Body part	0.001	0.001	0.052	0.003
Stimulus source	0.001	0.001	0.004	0.004
Tail flip numbers	0.001	0.001	0.004	0.008

frequent on VT netting than on DG netting at slow flow speeds. Accordingly passive penetrating as forced by flow was increased significantly up to 35 % in diagonal netting at higher flow speed.

Discussion

Model experiments in a water tunnel

These laboratory experiments are intended to serve as a case study and model of shrimp/net interactions. They provide knowledge and understanding of behavioral phenomena that are very difficult to observe in field fishing experiments. There are significant possibilities for improving both size selectivity and collecting efficiency of commercial shrimp trawls with respect to both mesh orientations and cod-end design. The geometry of cod-ends can vary from flat bags to bulbous semi-spheres (O'Neill et al., 2003) depending on cod-end design, towing speed and catch accumulation.

Towing speeds for commercial shrimp trawls are usually 1.5~2.2 k't for beam trawls (Kim, 2012) and 2.3~2.4 k't for otter trawls (He and Balzano, 2007; 2011). Both ranges are well above the maximum flow speed of 0.7 ms^{-1} available in this study. However, flow speed inside codend was far slower than towing speed (Kroeger, 1984; Pichot et al., 2009). Our study prawns were significantly smaller in size than many shrimps captured in the field. Scale effect by animal size in behavioral test is very difficult to apply to field behavior while scale effect in hydrodynamics of net test was well established. However movements or swimming speed can be deduced as multiply of body size BL/s (Videler and Wardle, 1991) if model animal was optimally selected.

Weak swimming ability resulted in target prawns as a model shrimp like other shrimps (Yu et al., 2009) gradually being pushed backward by flow (under up to 9 BL/s) when on horizontal net panels. At different flow speeds they sustained their positions for longer times on smaller mesh netting. These are responses that might occur on the bottom panels of trawls from their mouths to their cod-ends (Newland and Chapman, 1989; Queirolo et al., 2012). Based on these results the endurance of position holding on horizontal flat netting, most of edible shrimp in the trawls in the field at common towing speeds (ex. 2.0~2.5 k't ≈ 1.0~1.3 m/s ≈ 9 BL/s (when BL ≈ 110~140 mm)) can be expected to be flow backward shorter than a few min (Fig. 4). However vitality of the shrimp could be varied by species, size, flow speed etc. Further studies of different shrimp species, different flow regimes and different trawl designs are likely to better define parameters that could lead to optimization of performance and increases in income by operators.

Net penetration parameters

Mesh penetration behavior of shrimp, which could result in their escape from a trawl, was varied and complex (Broadhurst et al., 2015). The main feature in mesh penetration was the tail flip, which also occurs in front of the ground ropes of trawls (Newland and Chapman, 1989). Mesh penetration by shrimp occurs both passively, produced mainly by water flow, and actively, mainly resulting from more or less well-directed tail flips (Broadhurst et al., 1999).

There were two main types of passive escape by flow speed:

1) Smaller prawn pushed backward by water pressure with their bodies parallel to flow, then pushed through the mesh.

2) Larger prawn pushed backward by flow, then entangled or blocked on the netting, had their heads or tails pushed into the mesh. Water pressure then gradually pushed more of their bodies into the mesh until the whole body passed through without any voluntary body movements.

Active escape as voluntary penetrating also divided into two categories:

1) When the 2nd type of passive entanglement occurred some prawns made tail flips. These often pulled the ends of their tails out of the mesh, their bending abdomens also came out of the mesh, and their entire bodies passed through.

2) Prawn in transverse positions in front of netting often made tail flips. They bent their 4th abdominal segments in the directions of openings in the mesh and moved backwards in the direction of flow. The cross sectional areas of the bent abdomens were smaller than the mesh openings and the bodies passed through. If contact with the netting caused resistance in the middle of a tail flip a stronger second tail flip often resulted in penetration.

As mentioned in the Introduction to this paper target prawns are similar taxonomically, morphologically and behaviorally to many commercially important shrimp species. Thus they can reasonably be considered good models for the responses of *penaeid* shrimp generally to commercial shrimp trawls. Our water tunnel experiments are not exact replications of real conditions existing in commercial shrimp trawl fisheries. We believe, however, that our results are reliable demonstrations of the major biomechanical and behavioral responses of shrimp to netting properties, netting orientations and water flow conditions. A new concept of cod-end construction as multi-section by diagonal net panel or escape bent (referring from Fig. 7) can be possibly tried to passing more small shrimp in real trawls as operated in real fisheries. These results can serve as at least part of the basic capture process for evidence based future developments in both trawl design and operation.

Mechanisms of net penetration by tail flip

Tail flipping durations and angular velocities of body bending were both affected by flow pressures as shown by Kim and Gordon (2016). Abdominal flexion times in static water were similar to those occurring in other shrimp (Daniel and Meyhöfer, 1989; Arnott et al., 1998). Directions of tail flips resulting in net penetrations were nearly parallel to flow. Directions of tail flips when prawn held onto the netting were mostly normal to flow. Longer durations of tail flips that resulted in net penetration indicated that movement by tail flips could be obstructed by bars of mesh.

The maximum power of tail flips could be related to the energy needed to stretch mesh openings. Maximum power of tail flips was shown to peak at 90 deg of abdomen bending in caridean shrimp (Daniel and Meyhöfer, 1989) and in spiny lobster (Nauen and Shadwick, 2001).

Tail flip durations in our experiments were not related to body size (Kim and Gordon, 2016). This result is different from those found in similar studies of brown shrimp using 200 fps video in free static water (Arnott et al., 1998). Mechanisms used by shrimp for penetration of nets need further observation using higher speed video tools to clarify the relationships between tail flip movements and mesh stretching over time as well as for measurements of thrust forces.

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