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〈Original Article〉

Analysis of tail flip of the target prawn at the time of penetrating mesh in water flow by tank experiments

Yonghae KIM* and Malcolm S. GORDON[1]

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

The tail flip of the decapod shrimp is a main feature in escaping behavior from the mesh of the codend in the trawl. The characteristics of tail flip in target prawn was observed and analyzed in a water tunnel in respect of flow condition and mesh penetration by a high speed video camera (500 fps). The tail bending angle or bending time in static water was significantly different than in flow water (0.7 m/s) and resultantly the angular velocity in static water was significantly higher than in flow water when carapace was fixed condition. When escaping through vertical traverse net panel in water flow the relative moving angle and relative passing angle to flow direction during tail flip, it significantly decreases the number of shrimps escaping than the case of blocking shrimp. The bending angles of tail flip between net blocking and passing through mesh were not significantly different while the bending time of shrimp passing through mesh was significantly longer than when shrimp blocking on the net. Accordingly the angular velocity of passing through mesh was significantly slower than blocking on the net although the angular velocity of the tail flip was not significantly related with carapace length. The main feature of tail flip for mesh penetration was considered as smaller diagonal direction as moving and passing angle in relation to net panel as right angle to flow direction rather than the angular velocity of tail flip.

Keywords : Shrimp tail flip, Flow, Flexion time, Bending angle, Mesh penetration

Introduction

The shrimps were very important fishing target using various fishing gear such as trawl, trap, gill net etc. while shrimp aquaculture was sharply increased worldwide in recent years. The fishing selectivity of shrimp with fishing gear was very complex and difficult to analyze due to its morphological aspect as complicated cross-sectional shape and its dynamic movement totally different than fishes (Broadhurst, 2000; Catchpole and Revill, 2008). The selectivity of shrimp, prawn, lobster, etc. was investigated in relation to mesh size or codend type with by-catch reduction device in the trawl (Briggs, 1986; Broadhurst et al., 2015). From the earlier observation of shrimp in trawl tail flip was reported as relevant and main characteristics in relation to shrimp catch process, especially in front of the net (Newland and Chapman, 1989; Newland et al., 1992). However escape behavior of shrimp through the mesh of the codend was not fully observed or analyzed in relation to body shape and dynamic movements.

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

Tail flip as a startle escape response is a main feature in a decapod shrimps, crayfish and lobsters in relation to prey-predator (Wine and Krasne, 1972; Webb, 1979; Herberholz et al., 2004). The tail flip movements were investigated and analyzed in many aspects of static (Daniel and Meyhöfer, 1989; Arnott et al., 1998; Yu et al., 2009) and hydrodynamic for many species (Nauen and Shadwick, 1999; 2001; Arnott et al., 1999). However, there was no experiment or study on the tail flip of shrimp such as the bending time, the bending angle, the moving direction, etc. when water flow condition might affect selectivity (Broadhurst et al., 1999). From another behavioral study on shrimp penetrating through the mesh mimicking trawl codend in a water tunnel experiments the tail flip was a main response as an active passing response (Kim and Gordon, 2016).

In order to reveal the target prawn behavior when penetrating net referring to fish (Kim and Gordon, 2010) the tail flip was observed and analyzed as the body angle with flip time in net or without net by high speed video camera in static and flow water. Firstly tail flip movements such as tail bending angle with time were compared between static water and water flow conditions without net. Secondly tail flip was compared between when shrimp failed to pass mesh as blocking and penetrating mesh in several aspects of dynamic movement elements. As a result the tail flip in carapace fixed condition without net was different between in static water and flow water. Simultaneously the tail flip in net with the flow condition was different between when shrimp blocked in net and passing through the mesh.

Materials and methods

Shrimp

Experimental shrimp were 40 target prawn, *Sicyonia penicillata* (carapace length (CL) = 23.4±2.0 mm, total body length (BL) = 79.0±1.1 mm) (Jensen, 2014) ; purchased from the Marinus Scientific Inc. in Long Beach, California, USA on March 5, 2016. The target prawn is same genus of the ridgeback prawn which was main species caught in beam trawl (Allen et al., 2005). Measurements were made in mm for body width (W; mm) and height (H; mm) at the point of the maximum cephalothorax cross-sectional area when tail flexion as shown in Fig. 1.

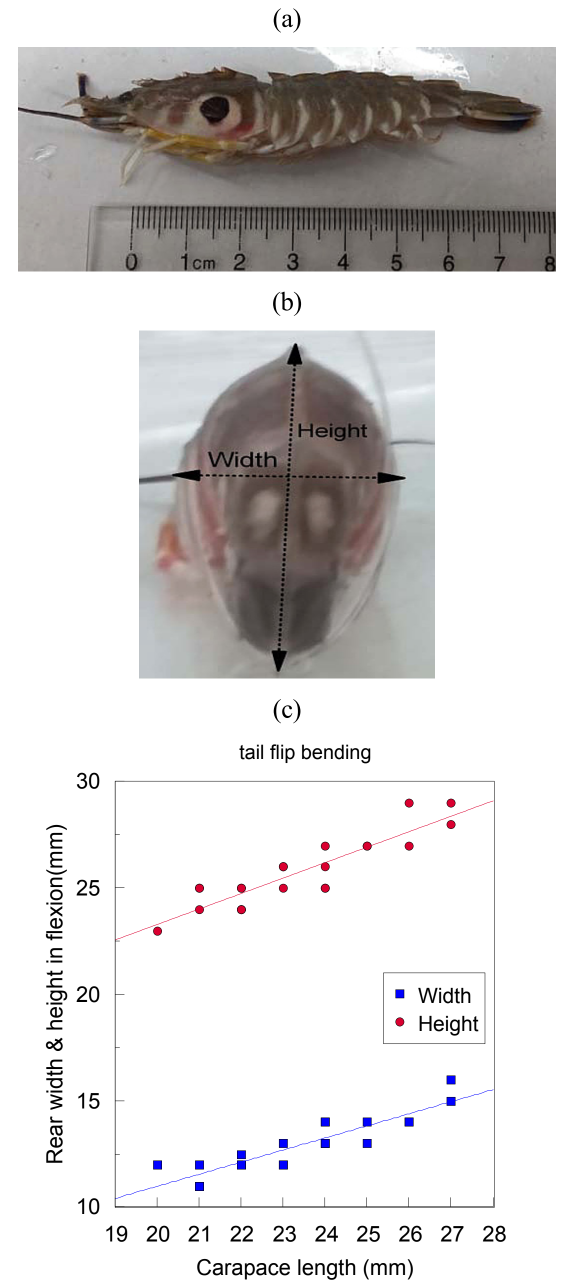
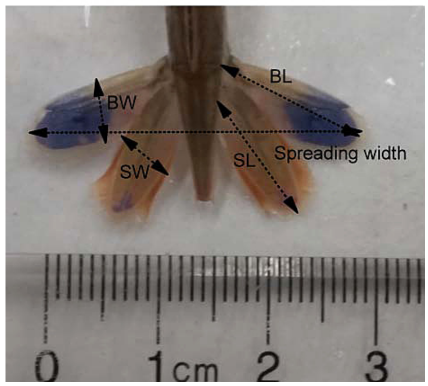


Fig. 1. The lateral view (a), rear view of the target prawn when tail flexion (b) and the relationship between the width or the height with carapace length (c).

(a)



(b)

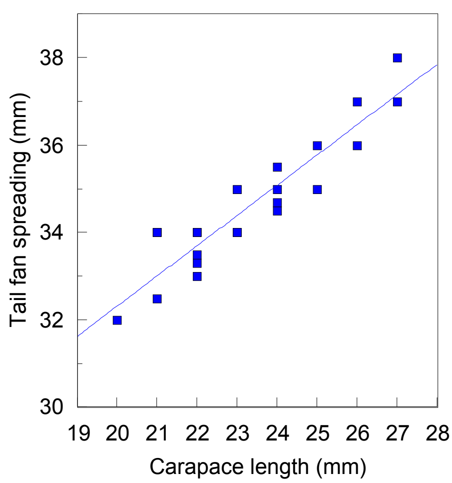


Fig. 2. The tail of the target prawn (a), the spread of the exopod with carapace length (b). (BW: width of exopod, BL: length of exopod, SW: width of endopod, SL: length of endopod)

$$W = 0.57\ CL - 0.41 \qquad (n = 22,\ r = 0.9) \qquad (1)$$

$$H = 0.73CL + 8.65 \qquad (n = 22,\ r = 0.9) \qquad (2)$$

The tail of the shrimp as a major part in tail flip is consisted with telson and uropod that has two parts as exopod and endopod as shown in Fig. 2. The maximum spread of the tail fan (S; mm) between the outer ends of the exopods was plotted with the carapace length as following regression equation.

$$S = 0.69\ CL + 18.5 \qquad (n = 22,\ r = 0.93) \qquad (3)$$

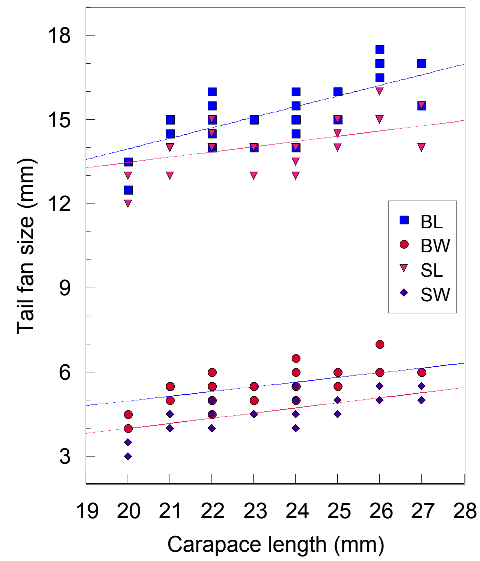


Fig. 3. The length (BL, SL) and width (BW, SW) of exopod and endopod (Fig. 2 (a)) respectively with carapace length of the target prawn.

A pair of exopod and endopod of a shrimp was represented as their length and width with the carapace length as shown in Fig. 3 with relatively lower co-relationships ($0.54 < r > 0.74$).

Experimental shrimps were maintained in an aquarium (L160×B76×D30 cm) that were integrated into a single re-circulating and water temperature control system in the Aqua-room of the UCLA. Seawater condition of the aquaria was controlled temperatures of 15-16°C, salinity 35 psu, PH 8.0 during March and June 2016. They were fed smelt purchased from a seafood market once each day and photoperiod was 12 hours light-dark with room fluorescent lights controlled by a timer.

Water tunnel

The water tunnel used, located in Department of Ecology & Evolutionary Biology, UCLA, 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 30×30 cm cross-section, 100 cm long transparent acrylic working section (Kim and Gordon, 2010). The tunnel was filled with seawater reserved in the seawater tank and adjusted salinity by dechlorinated Los Angeles tap water. Water temperatures were regulated at 15-16°C by automatic two water chiller. Water in the tunnel was circulated as low flow 10 cm/s through marble sand and coral mainly during night time when the main observation end each day. Room lighting was and a 500 W halogen lamp.

The upper, the rear and lower bottom side of the working section, except front window towards the video camera were covered in blue fabric to diminish the light reflection and to mimic the sea color in video recordings. Illumination was measured by Luxmeter (Dr. Meter, LX1330B) as 15 lx at lateral direction of the camera to observing front window and 10 lx at dorsal and rear direction under 12×100 W fluorescent ceiling lights. Illumination with a 250 W halogen lamp under room lights was 600 lx at the lateral direction and 400 lx at the dorsal direction. The noise level measured by smart phone (Samsung SM-G530T, Noise level by Pineapple4) was 56 dB when flow speed 0.7 m/s in experimental conditions when chillers off.

Experiments

Tail flip experiments were carried out as two stages; tail flip in carapace fixed without net and tail flip in the net penetration. The carapace of a shrimp was fixed by rubber band attached with ring of electric line (PP coating, dia. 3 mm) firmly connected upper frame and hanged middle of working section (Nauen and shadwwick, 2001). The tail flip of a shrimp was observed one by one in static water and then water flow 0.7 m/s. The tail flip was evoked by electric line as sudden touching head (Wine and Krasne, 1972; Newland et al., 1992). High speed video camera (Redlake PCI500) was framed for 2 s of tail flip by PC controlled image capture at 1.5 m from front working section by 500 fps (320×280 pixels) under room light (shutter speed 1/500 s) or add with a 250 W halogen lamp (shutter speed 1/1000 s). Experiments for each head fixed condition or net passing were done once a day for about 40 available shrimps.

Netting used was dark brown in color, made of 9 ply polyethylene (PE) twine in diamond mesh of stretched size 50 mm. Net hanging ratios were 90% (openings 45 mm respectively) close to real codend of fish gear rigging. Flat panels of netting were positioned in vertical transverse to flow, mounted in a 298×380 mm acrylic frame, positioned 20cm forward of the rear outlet of the working section of the water tunnel. For tail flip in net, two shrimps were introduced in the front of the net panel at static water and then by water flow increased until 0.7 m/s, shrimp flew back to the net positioned parallel on the flat net (Kim and Gordon, 2010). When shrimp shown tail flip either blocking on the net or passing through mesh, high speed video camera was framed for 2 s by PC controlled activation.

When the abdomen flexion of a shrimp was occurred from straight state to tail bending, the body position and body posture were changed as shown in Fig. 4. The tail

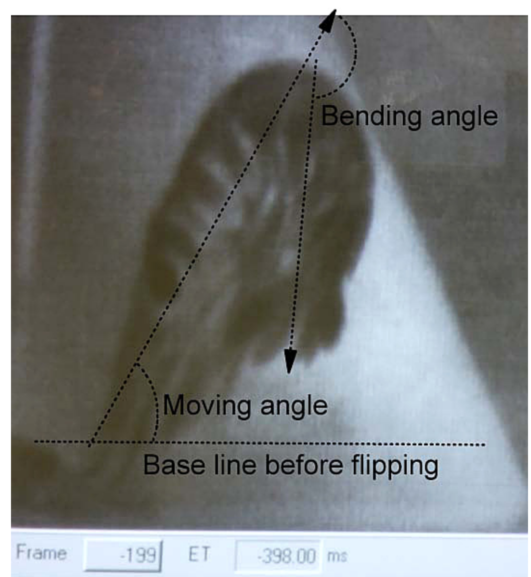


Fig. 4. The relative moving angle and bending angle when maximum flexion of a shrimp.

flip of shrimp as fast flexion of abdomen and tail considered as a quick movement was analyzed by frame by frame of 500 fps by the PC image analyzer (Redlake, Motion Scope PCI) taken from high speed camera in unit of 2 ms. The moving angle of a shrimp was measured between straight body line before tail flip and straight cephalothorax line when maximum tail bending (Daniel and Meyhöfer, 1989). The bending angle was defined as an angle between the straight cephalothorax line and the straight line of posterior abdomen and tail (Arnott et al., 1998). The bending angle was measured as an initial bending angle before tail flip and maximum bending angle during tail flexion in video image of the monitor. The relative passing angle in net was defined as a lateral angle between a horizontal line of water flow and the straight cephalothorax line either blocking or passing through the net.

The initial tail flexion was defined as abdomen bending just before the tail flip between the abdomen and the cephalothorax (for example of bending angle 0 deg in Fig. 1(a)) with measured tail flip time by an image frame 2ms. Then the angular velocity of abdomen bending was estimated as maximum bending angle minus initial bending angle divided by total flexion time as radian unit. Because of lateral view was recorded by one high speed camera, measuring error of the angles was estimated as 5 deg. Therefore 30-32 events of shrimps for a free state, blocking and passing net were carefully selected respectively as nearly parallel movements of the body to minimize the conversion error.

The data of tail flip time, bending angle and angular velocity between static water and flow water without net, or between blocking and passing cases in net penetration were tested by one-way ANOVA or by a student t-test (Zar, 1996).

Results and discussion

The tail flips of the target prawns were observed by a high speed video camera in static water of free state in carapace fixed state in static water and water flow and in blocking state or passing through the mesh in the vertical flat panel net as shown in the examples of Fig. 5.

(a) Blocking on the net

(b) Passing mesh

Fig. 5. Examples of blocking on the net (a) and passing through mesh (b) by tail flip of target prawn.

The distribution of bending angle for the target prawn when carapace fixed condition was compared between tail flip in static water and flow water as shown in Fig. 6. The maximum tail bending angle as 163±15 deg (Fig. 6(b))

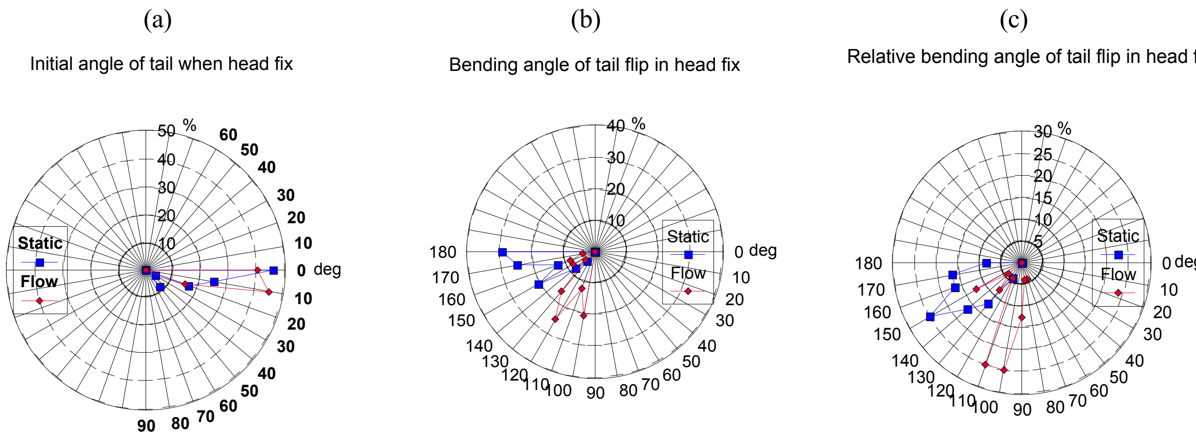


Fig. 6. The comparison between tail flip in static water and flow water in initial tail bending angle before tail flexion (a), maximum tail bending angle (b) and relative bending angle when carapace fixed condition.

and relative bending angle as 152±16 deg (Fig. 6(c)) in static water were significantly higher than as 125±21 deg and as 110±22 deg in flow water respectively ($n=24$, $p<0.00001$). However initial tail bending angle before tail flexion (Fig. 6(a)) was not significantly different by T-test ($n=24$, $p>0.3$).

The comparison of the bending times when carapace fixed condition as from start of tail flexion to 90 deg bending, from 90 deg to the maximum bending and total bending time was shown in Fig. 7. The posterior bending time as 40±11 ms and total bending time as 68±14 deg in static water were significantly shorter than as 26±9 deg and as 56±12 deg in flow water respectively ($n=24$, $p<0.0017$) while initial 90 deg bending time was not significantly different by T-test ($n=24$, $p>0.2$). The resultant force in lobster tail flip was highest as thrust power when 90 deg of bending angle (Nauen and Shadwick, 2001). Generally in natural static water maximum bending angle of crayfish (Webb, 1979) or shrimp (Daniel and Meyhöfer, 1989) was 180 deg around. However, the bending angle in flow water in this study was smaller than in static water due to water drag by body orientation as flow direction from rostrum to telson. The effect of water flow as strong as about 9 BL/s in tail flip of shrimp in this study was considered as the first report as authors known until now.

The angular velocity of tail bending when carapace fixed condition estimated by bending angles (Fig. 6) and bending times (Fig. 7) were represented between static water and flow water as shown in Fig. 8. The angular velocity in static water was significantly higher than in flow water by T-test for initial 90 deg bending ($n=24$, $p<0.027$), for posterior bending ($n=24$, $p<0.0061$), and total bending ($n=24$, $p<0.027$) respectively.

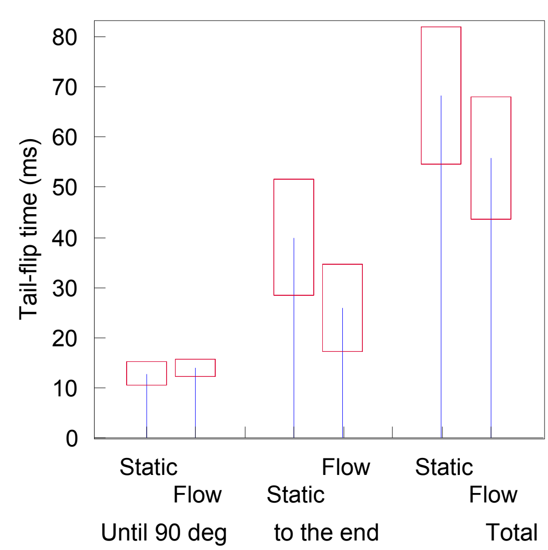


Fig. 7. Comparison of tail flip time between static water and water flow in carapace fixed condition.

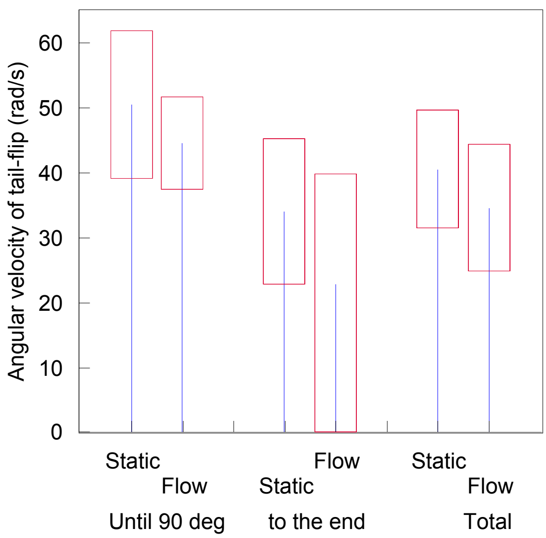


Fig. 8. Comparison of angular velocity of tail bending between static water and flow water when carapace fixed condition.

Comparison of body moving angle and relative passing angle to flow direction between shrimp blocking in the net and passing through the mesh were shown in Fig. 9. When shrimp blocking by net moving angle by tail flip 72±11 deg was significantly higher than as 42±22 deg when shrimp passing through mesh (n=32, $p<0.00001$). Similarly relative passing angle to flow direction by tail flip when shrimp blocking by net 73±27 deg was were significantly higher than as 38±21 deg when shrimp passing through mesh by T-test (n=32, $p<0.00001$). In crayfish or lobster moving angle by the lateral giant-fiber tail flip by telson tapping was higher than the medial giant-fiber tail flip by rostrum tap (Wine and Krasne, 1972; Newland et al., 1992). Consistently when shrimp blocking by net moving angle by tail flip 72 deg was similar with tail flip of the Carridean shrimp in static water (Daniel and Meyhöfer, 1989).

Comparison of bending angle between shrimp blocking at the net and passing through the mesh were shown in Fig. 10. The bending angles such as in initial bending angle, absolute bending angle and actual bending angle as (b)-(a) of tail flip between blocking by net and passing through the mesh were not significantly different respectively (n=30, $p>0.31$).

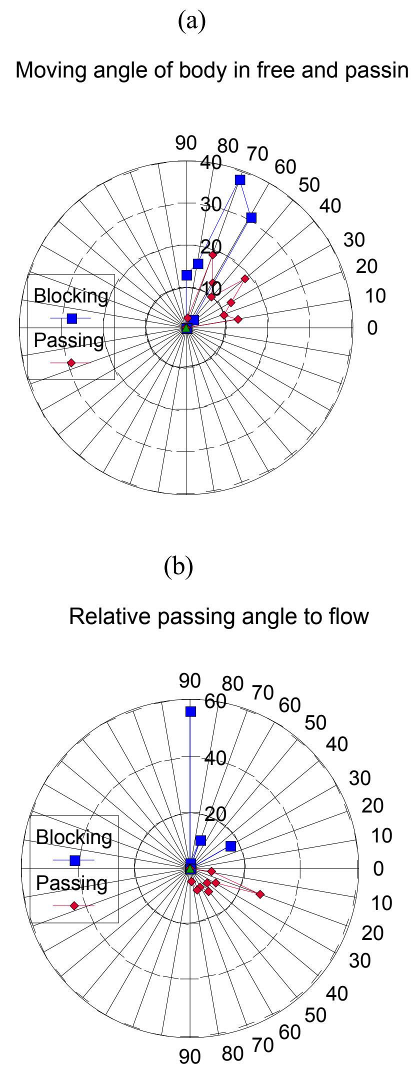


Fig. 9. Comparison between shrimp blocking in the net and passing through mesh in body moving angle (a) and relative passing angle to flow direction (b).

The comparison of the bending times when shrimp in the net as from start of tail flexion to 90 deg bending, from 90 deg to the maximum bending and total bending time was shown in Fig. 11(a) and resultant bending angular velocity in Fig. 11(b). The posterior bending time and total bending time when shrimp blocking net were significantly shorter (n=30, $p<0.03$) than when shrimp passing through mesh respectively while by T-test.

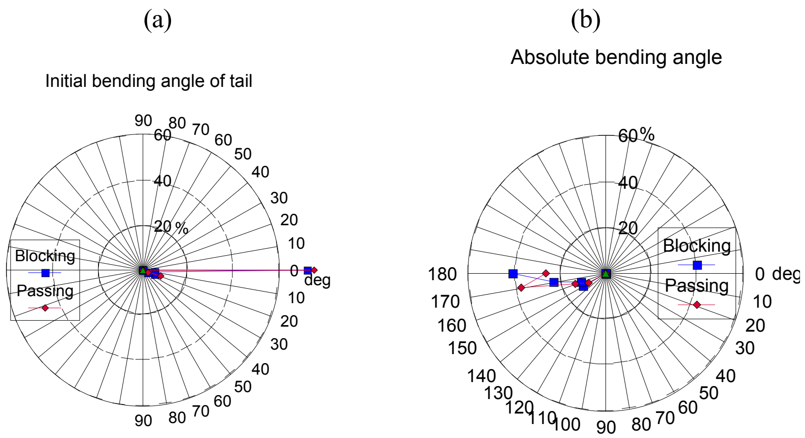


Fig. 10. Comparison between shrimp blocking in the net and passing through mesh in initial bending angle (a), absolute bending angle (b) and actual bending angle (c) as (b)-(a).

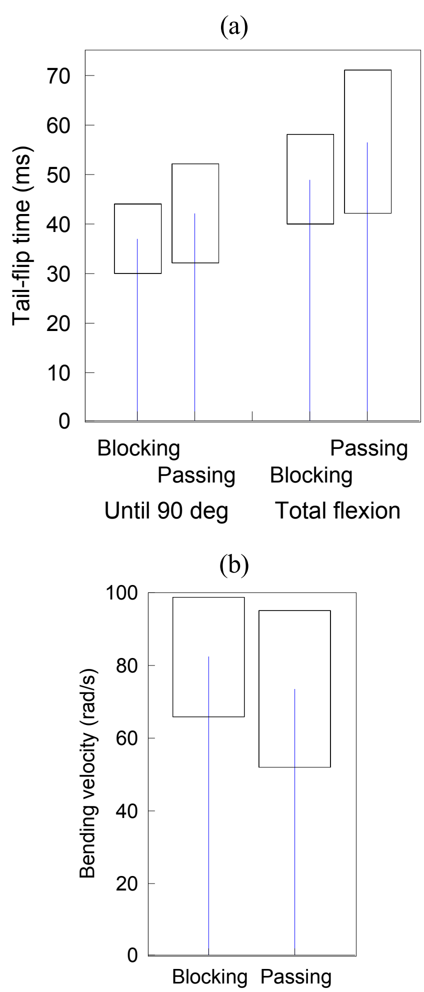


Fig. 11. Comparison of the tail flip times as just before uropod folding and total time when blocking and passing mesh.

The angular velocity when blocking the net was significantly higher than when passing through the mesh by T-test respectively (n=30, $p<0.04$). The angular velocity of the tail flips when blocking or passing was not significantly related with carapace length ($p>0.46$). The angular velocity of the tail flips in the net was greater than in carapace fixed condition due to restricted body state as a main reason. The angular velocity of the tail flip of the target prawn in the net under flow condition was revealed similar with tail flip of brown shrimp which was related to a shrimp size inversely (Arnott et al., 1998). Furthermore the angular velocity of tail flip in a lobster of bigger body size was shown slower than smaller shrimps (Nauen and Shadwick, 1999). The kinematic performance of the tail flip might be varied by physiological activation by giant fiber, ecological prey-predator or habitat, and environmental flow, temperature etc. (Zhang et al., 2011; Yu et al., 2009). The main factor of the shrimp by tail flip for mesh penetration was considered as moving direction, number of tail flip, mesh opening etc. in relation to flow direction. Therefore 3-D observation for tail flip in mesh penetration could be necessary using high speed camera in the near future.

Conclusion

The main feature of escape through the mesh of the codend in a shrimp trawl was considered as tail flip and its kinetic performance was investigated in the water tunnel. The first trial of comparison in tail flip of the target prawn under the carapace fixed condition was observed and analyzed the tail flip time and bending angle between static water and flow water. The tail bending angle or bending time in static water was significantly different than in flow water (0.7 m/s) and resultantly the angular velocity in static water was significantly higher than in flow water when carapace fixed condition.

The second trial of the tail flip was observed and analyzed between shrimp blocked front of the net and passing through mesh of vertical traverse net panel in flow velocity of 9 BL/s around. The bending time when shrimp passing through mesh was significantly longer than when shrimp blocking net due to hindered by mesh bar. Accordingly the angular velocity when passing through mesh was significantly slower than when blocking the net. However the relative moving angle and relative passing angle to flow direction during tail flip when passing through mesh was significantly smaller than when shrimp blocking. The main feature of tail flip for mesh penetration was considered as an optimum diagonal direction to net panel as the rotational passing body angle of tail flip in relation to flow direction rather than the angular velocity of tail flip. This result could be helped to understand shrimp escaping mechanism from net of trawl and apply for codend design in order to reduce smaller shrimp by-catch as well.

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