Gait analysis of crawling locomotion of *Octopus Sinensis*

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1 Introduction

The octopus has eight long flexible arms and shows a variety of skillful movements by coordinating them. To control the hyper-redundant arms, the octopus has highly elaborated peripheral nervous system along each arm which can generate motor commands for reaching movement even if an arm is isolated [1]. The octopus shows crawling movement on the ground by coordinating arm movements; however, only a few studies have done about the gait pattern of the octopus crawling in spite of its importance for the understanding of their decentralized neural processing mechanism. Levy et al. [2] reported that octopuses can move toward various directions by pushing their body by elongating their arms but no periodicity was observed in their gait pattern. In this study, we analyzed the gait pattern of octopus crawling and tried to find some regularity in their arm coordination.

2 Materials and Methods

2.1 Experimental methods

Eight octopuses (*Octopus sinensis*) were used in the measurement experiments. Seawater was filled to a level of about half the animal's height in a transparent water tank and a waterway (120 x 30 cm) was prepared by using black plastic boards as walls in the tank. After putting each octopus in the water tank, crawling movement along the waterway was recorded by 50 fps using four high-speed cameras (GV200, Library co. Ltd.).

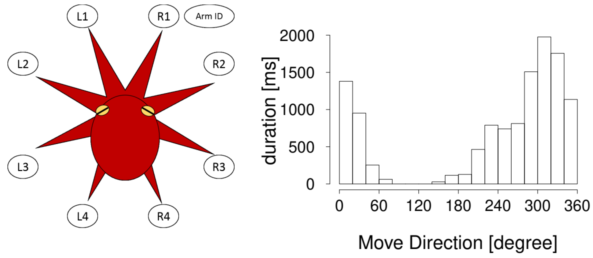
2.2 Data analysis

From the collected data we extracted 15 sessions of 6 octopuses in which they moved along the waterway without stopping. The trajectories of the mouth and the first sucker of the right forearm R1 (Fig.1(a)) were detected by a motion capture system (Move-tr/2D, Library co. Ltd.) and used to determine the direction of the animal's body and the moving direction. The locomotion speed was computed by the mouth trajectory using the Euler method. Optical flow was also computed by the Lucas-Kanade method to analyze the crawling motion.

3 Results

3.1 Locomotion direction

Fig. 1 shows the arm index and the distribution of moving direction. Octopuses preferred the fore-left direction between the arm L1 and L2, which corresponds to the report by Levy et al. [2], although the distribution was not symmetrical against their report. Locomotion toward various directions utilizing its radially symmetrical body structure was observed except right-rear direction (60-160 degrees).



(a) (b)

Figure 1: (a) Arm index of the octopus. (b) The total time of each locomotion direction in all sessions. The abscissa shows the clockwise angle from the front of the octopus.

3.2 Force production for crawling movement

The optical flow of the octopus during crawling showed that most of the whole body was continuously moving; however, a bend and an adherent part to the ground emerged in some arms (Fig. 2) and propagated toward the distal as if the adherent part pushes the body. In order to confirm this hypothesis, we tested whether the locomotion speed can be estimated by the existence of adherent parts in arms by multiple linear regression analysis:

$$v_e = \sum_{i \in A} k_i F_i, \tag{1}$$

where v_e shows the estimated speed, A is the set of arm indices, F_i is the binary value showing the existence of a adherent part in the i-th arm, and k_i is the regression coefficient. The result shows that the coefficients of determination were $R^2 > 0.7$ ($p < 0.01$) for all sessions, suggesting that the bend propagation along arms contributes to the force production of crawling.

Gutfreund et al. [3] reported that arm extension movements of octopuses were realized by the propagation of a bend from the base of the arm toward the tip. The bend propagation found in octopus crawling is similar to the arm extension movement; however, the bend often emerged from a middle part of an arm, which enables to generate propulsive force by front arms curving backward as shown in Fig. 2.

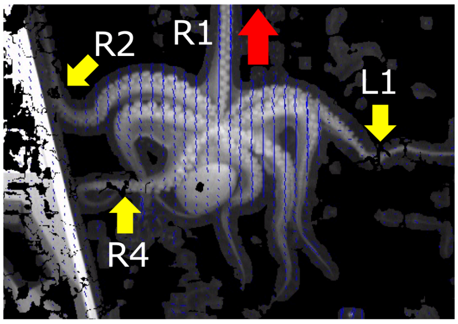


Figure 2: Optical flow of a crawling octopus. The pixels where no motion was detected are shown in black. The red arrow shows the locomotion direction, and short blue lines show the detected movement direction for each small region by the Lucas-Kanade method. Bends and adherent parts (indicated by yellow arrows) were observed in arms L1, R2, and R4.

3.3 Arm pairs frequently used for propulsion

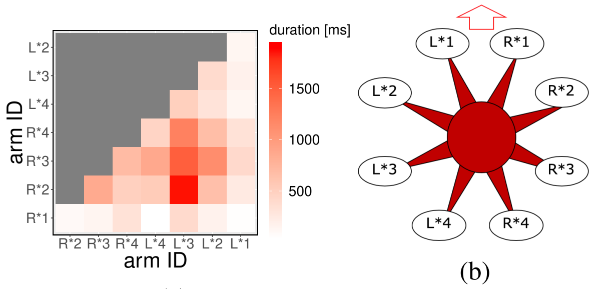
Fig. 3 shows the total time of each arm pair used together for propulsion in all sessions. In this analysis, the arm index was defined based on the locomotion direction (Fig. 3(b)). This result shows that the preferred arm pairs for force production were the (L*3, R*2), (L*3, R*3), (L*3, R*4), (L*2, R*3), and (L*4 and R*3). Assuming that each arm generates the same amplitude of propulsive force, these arm pairs can move the body toward between L*1 and R*1. Hence, this result suggests that the octopus often uses contralateral arm pairs with respect to the locomotion direction simultaneously. Levy et al. [2] reported that the octopus moved by pushing the body by stereotypical elongation of arms and four hind arms were used for the propulsion. However, our results suggest that arm pairs perpendicular to the locomotion direction, such as (L*3, R*2) and (L*2, R*3), and even foreside arm pairs, such as (L*2, R*2), also contribute to the propulsion by curving the arms toward the backward (Fig. 2).

3.4 Sequence of arms used for propulsion

Fig. 4 is the frequency map that shows the transition of pushing arms in the left (a) and right (b) side with respect to the locomotion direction. The transition was judged by the timing of the start of the formation of an adherent part in each arm. The abscissa and ordinate represent the arm indices of pre-transition and post-transition, respectively. The results show that frequent transitions were from the arm 4 to 3, 3 to 2, 2 to 4, and 3 to 4 for both left (L*) and right (R*) sides, i.e., from the hind to the fore or to the hindmost, and the foremost arms, L*1 and R*1, were not used frequently.

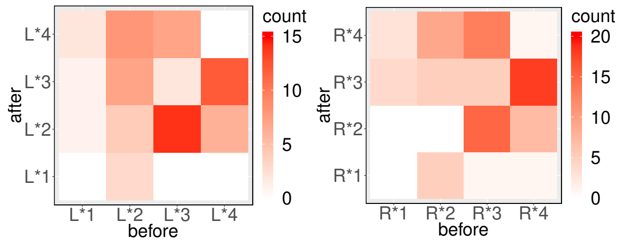
4 Conclusion

In this study, we obtained the following characteristics of the gait pattern of octopus crawling movements. Propagation of a bend was observed in arms and a distal part nearby the bend was adherent to the ground, which would generate propulsive force. Contralateral arm pairs to the locomotion direction were often used to push the body. Not only hind arms but also fore arms contribute to the propulsion by bending toward the backward. The arm movements for propulsion tended to propagate from the hind to fore arms. The octopus seems to change the interarm coordination dynamically and to generate gait pattern according to the moving direction, which enables the locomotion toward various directions by utilizing its radially symmetrical body design.



(a) (b)

Figure 3: (a) Total time of each arm pair used together for propulsion in all sessions. The abscissa and ordinate show the relative arm indexes with respect to the locomotion direction as shown in (b).



(a) (b)

Figure 4: The frequency map showing the order of arms used for propulsion. (a) and (b) are the results for left and right arms with respect to the locomotion direction, respectively.

References

[1] G. Sumbre, et al., "Control of octopus arm extension by a perioheral motor program," Science, **293**(5536), 1845-1848, 2001.

[2] G. Levy, et al., "Arm coordination in octopus crawling involves unique motor control strategies," Cur. Biol., **25**(9), 1195–1200, 2015.

[3] Y. Gutfreund, et al., "Organization of octopus arm movements: a model system for studying the control of flexible arms," J. Neurosci., **16**(22), 7297–7307, 1996.