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Arm movements during crawling locomotion of *Octopus sinensis*

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1 Introduction

Octopuses have flexible eight arms by which they can perform a variety of movements, such as reaching and fetching. A highly developed peripheral nervous system is distributed in their arms and has been reported to generate some stereotypical arm movements, such as an arm extension [1]. Even in crawling locomotion, which requires coordinated movements of the eight arms, each arm may exhibit stereotypical movements. This study aims to identify the patterns of arm movements in crawling locomotion of octopuses and to reveal how each pattern is involved in the generation of propulsive force.

2 Method

We put an octopus (*Octopus sinensis*) without arm defects in an experimental tank (1200 × 450 × 450 mm) filled with artificial seawater and 20 mm deep and recorded the crawling movements with three high-speed cameras (Imaging Source, DMK 33UX273) at 1440 × 1080 dpi and 30 fps from directly below the tank.

The positions of the mouth, the mantle tip, and the $j = (4i+1)$th ($i = 0, 1, 2, \ldots, 10$) suckers (Fig. 1) were tracked using DeepLabCut, a markerless posture estimation software. Missing data were interpolated using data of adjacent frames by cubic spline interpolation. The trajectory data were low-pass filtered using a 5th-order Butterworth filter with a cut-off frequency of 3 Hz. The velocity at each position was obtained from the filtered trajectory data by the one-sided forward difference method and low-pass filtered in the same manner as the trajectory data. Suckers with a speed of less than ten mm/s were considered grounded.

3 Results and Discussion

3.1 Arm bending movement

The first typical movement pattern was to bend the arm toward the opposite direction of travel. Fig. 2 shows an example of the movement observed in R1. Fig. 3 shows the arm posture at $t = 0.5,\ 0.8,\ 1.2$ s in Fig. 2. During this period, the octopus moved toward the direction between L1 and L2 (left direction in Fig. 3). At $t = 0.5$ s, arm R1 was almost straight (Fig. 2 (b), Fig. 3 (a)), and many suckers of the arm were grounded (Fig. 2 (a)). Then, the suckers lifted off the ground from the proximal side (Fig. 2 (a)), and the bend of the arm propagated distally until $t = 1.2$ s (Fig. 2 (b), Fig. 3). During this period, the change in the distance between the mouth and the 33rd sucker is small (Fig. 2 (c)).

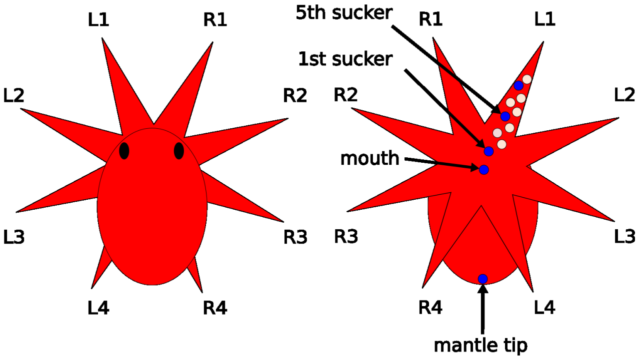

Figure 1: Octopus arm identifier and tracking positions.

3.2 Contribution of arm movement to propulsion

To investigate whether the bending movement is involved in the generation of propulsive force, we examined whether the acceleration $a(t)$ of the mouth can be predicted by multiple regression analysis from the grounding information of proximal (pr: $1, 5, \ldots, 17$th suckers) and distal (dt: $21, 25, \ldots, 41$st suckers) parts of each arm using the following equation:

$$a(t) = \sum_{i=1}^{8} \sum_{j \in \{\mathrm{pr},\mathrm{dt}\}} k_{ij} \bar{F}_{ij}(t) \tag{1}$$

where $\bar{F}_{ij}(t)$ is the moving average of $F_{ij}(t)$ with a time window of 0.1 s, which shows the grounding information of the part j of the i-th arm ($i = 1, 2, \ldots, 8$). $F_{ij}(t)$ is 1 when any sucker of the relevant site is grounded and 0 otherwise. If both the proximal and distal parts of the i-th arm are grounded, the $F_{i\mathrm{dt}}(t)$ was set to 0. k_{ij} is the partial regression coefficient. Model selection was also carried out using Akaike's information criterion. Fig. 4 is the result, showing that the time transition of the acceleration was well predicted ($R^2 \geq 0.65$). All the arms with positive and large absolute values of the partial regression coefficients showed a bending motion. This means that the bending motion is important for generating propulsive force, as suggested in the previous report [2].

3.3 Arm contraction movement

The second typical pattern is a contraction movement observed in an arm straightly extended toward the crawl-

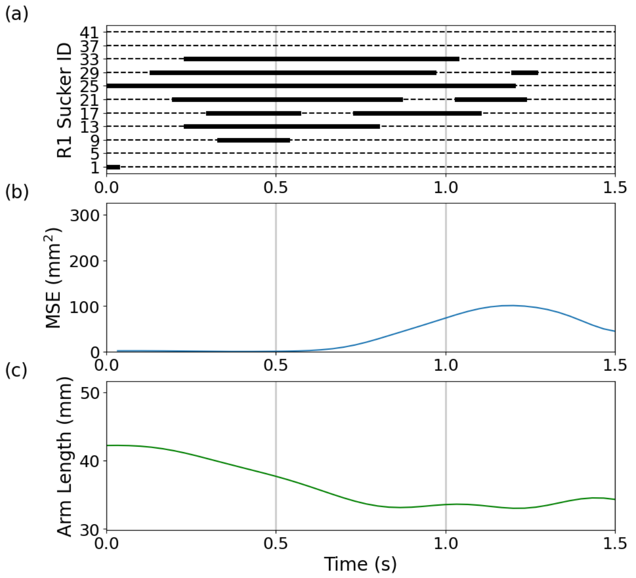

Figure 2: Time profile of the arm bending movement observed in arm R1. (a) shows the grounding sequence of suckers, (b) shows the mean squared error of the linear regression analysis for the 11 tracked sucker positions, and (c) shows the distance between the mouth and the 33rd sucker.

ing direction. Analysis of an arm in this type of movement showed that the arm was initially extended with the non-proximal suckers grounded. Then, the arm gradually contracted while keeping a straight shape. However, the result of the multiple regression analysis (eq. (1)) indicated that this contraction movement might not contribute to the propulsive force or may be involved in deceleration.

3.4 Arm extension movement

The third typical pattern is the extention movement observed in the arm oriented in the opposite direction to travel. The arms that exhibited this movement were often characterized by the gradual propagation of the grounded suckers from the proximal to the distal. Although this movement was suggested to contribute to propulsion [3], the result of the multiple regression analysis (eq. (1)) suggested a small contribution.

4 Conclusion

Three typical arm movement patterns were identified in the crawling motion: arm bending, arm contraction, and arm extension. Among them, the arm bending movement contributes significantly to the propulsive force. This movement is similar to the stereotyped movement generated by the peripheral nervous system reported by Sumbre et al. [1]. Therefore, the experimental results suggested that even in crawling locomotion, individual arm movements are generated by the peripheral nervous system.

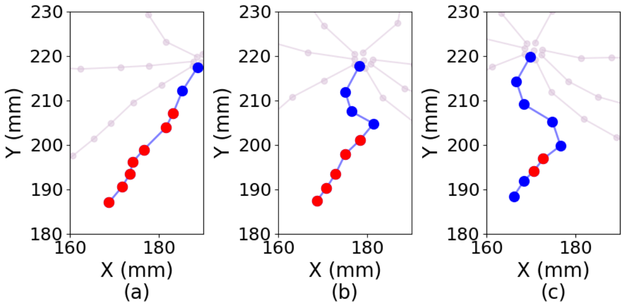

Figure 3: An example of the arm bending movement. (a), (b), and (c) show the arm postures of arm R1 at $t = 0.5, 0.8, 1.2$ s in Fig. 2, respectively. The octopus is moving toward the left and the circles show the sucker positions ($1, 5, 9, \ldots, 41$th suckers from top). Red and blue circles express grounded and ungrounded suckers, respectively.

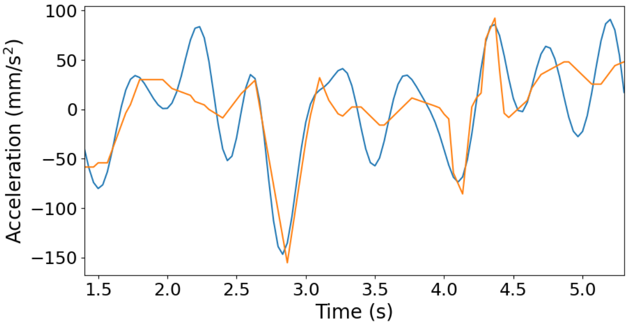

Figure 4: Time profile of the acceleration of an octopus. The blue and orange lines show the observed value and predicted value by multiple regression analysis, respectively.

5 Acknowledgments

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