Efficient Undulating Locomotion Driven by a Decentralized Control That Fully Exploits Multi-articular Muscles

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Abstract: To clarify the mechanism of multi-articular muscles that contributes to the emergence of animal behavior, we focus on the locomotion of a snake. Analyses on the basis of the continuum model show that the body propels efficiently as the number of segments spanned by each muscle increases. On the basis of this result, we propose a decentralized control scheme for the efficient locomotion of a multi-articular serpentine robot, and we confirm its validity by simulations.

Keywords: Autonomous decentralized control, Multi-articular muscles, Serpentine robot

1. INTRODUCTION

Animals exhibit adaptive and efficient locomotion in real time under unpredictable real world constraints. A key mechanism underlying such functionality of animals is an autonomous decentralized control, whereby non-trivial macroscopic behavior or functionality emerges through the coordination of simple individual components. In particular, the design of the mechanical system (*i.e.*, body) in autonomous decentralized control systems is of significant importance, because highly intelligent behavior emerges through interactions between the body and the environment [1].

Although numerous biologically inspired robots was developed on the basis of the decentralized control, they could not fully reproduce the innate behavior of animals; one of its reasons is that the actuators in most robots act on single joints, whereas animals generally have multi-articular muscles that enable long-distant physical interaction. It was suggested that multi-articular muscles play a role in generating smooth, fine, and precise motions [2]; however, theoretical understanding of their functional role is currently at a rudimentary stage.

To address this issue, we focus on the locomotion of a snake that exploits its long muscle-tendon structures. Date and Takita showed using a continuum model that a snake propels efficiently when a bending moment proportional to the curvature derivative of the body curve is applied [3]. In this study, we extend their theory to investigate the effect of multi-articular muscles, and we show that the body propels efficiently as the number of segments spanned by each muscle increases. On the basis of this result, we propose a decentralized control scheme for the efficient locomotion of a multi-articular serpentine robot, and we confirm its validity by simulations.

2. CONTROL SCHEME BASED ON THEORETICAL ANALYSES

The adopted model is shown in Fig. 1. We consider two-dimensional motion. The body consists of a non-stretchable continuous backbone curve of length L and zero thickness. The backbone curve is parameterized by the arclength $s \in [0, L]$ from the head to tail. N rectilinear links of length $2r$ are aligned such that they are perpendicularly bisected by the backbone curve. The ith link intersects the backbone curve at $s = (i - 0.5)\Delta s[\equiv X_i]$, where $\Delta s = L/N$. n-articular muscles connect the tips of the links at $s = X_i$ and $s = X_{i+n}$ on the ipsilateral side. We disregard the viscoelastic property of muscles. We assume that the line density of the backbone curve ρ is uniform along the body, and that the weights of the links and muscles are negligible. The frictional coefficients in the longitudinal and latitudinal directions are assumed to be 0 and ∞, respectively. Furthermore, $n\Delta s \ll 1/\kappa(s)$ and $n\Delta s \ll L$ are assumed, where $\kappa(s)$ is the curvature of the backbone curve; owing to the former assumption, the angles between the longitudinal direction of the backbone curve at $s = X_i$ and the directions of the muscles attached on the ith link are found to be sufficiently smaller than unity, although the proof is not shown because of the page restriction.

Thus, the equations for the longitudinal force balance and momentum balance of a section of the backbone curve within the range of $[X_{i-\frac{1}{2}}, X_{i+\frac{1}{2}}]$, where $X_{i\pm\frac{1}{2}} \equiv X_i \pm \Delta s/2$, are expressed as

$$\begin{aligned}\rho\Delta s\alpha = \quad & f_s(X_{i+\frac{1}{2}}) - f_s(X_{i-\frac{1}{2}}) \\ & -[q(X_{i+\frac{1}{2}}) + q(X_{i-\frac{1}{2}})]\kappa(X_i)\Delta s/2 \\ & +F_r(X_{i-n}) + F_l(X_{i-n}) \\ & -F_r(X_i) - F_l(X_i), \qquad (1)\end{aligned}$$

and

$$\begin{aligned}0 \quad = \quad & [q(X_{i+\frac{1}{2}}) + q(X_{i-\frac{1}{2}})]\Delta s/2 \\ & -r[F_r(X_{i-n}) - F_l(X_{i-n})] \\ & +r[F_r(X_i) - F_l(X_i)], \qquad (2)\end{aligned}$$

respectively. Here, α is the longitudinal acceleration, $f_s(s)$ is the internal force along the backbone curve, and $q(s)$ is the shear stress. $F_r(X_i)$ and $F_l(X_i)$ are the forces

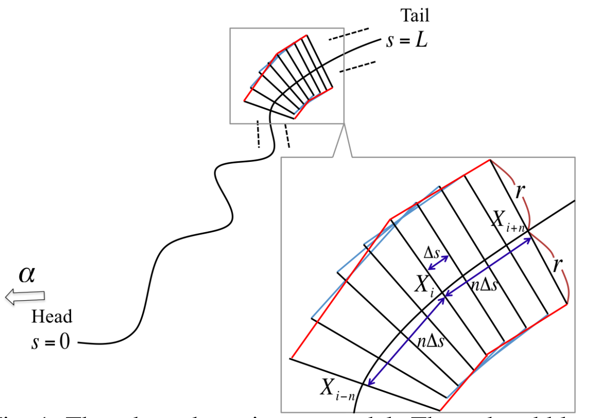

Fig. 1 The adopted continuum model. The red and blue lines denote multi-articular muscles.

generated by the muscles that connect the links at $s = X_i$ and $s = X_{i+n}$ on the right and left side, respectively. $q(X_{i\pm\frac{1}{2}})$ is eliminated from Eqs. (1) and (2), and the obtained equations are summed from $i = 1$ to N under the assumption of $f_s(0) = f_s(L) = 0$; furthermore, the summation is represented integrally. Then, we obtain

$$\rho L\alpha = \int_0^L ds \cdot nr[F_l(s) - F_r(s)]\kappa'(s). \tag{3}$$

For a given α, the optimal force distribution of muscles that minimizes the quadratic cost function $N^{-1}\sum_{i=1}^{N-n}(F_l^2(X_i) + F_r^2(X_i))$ can be derived using the Lagrange multiplier method with continuum approximation as

$$\begin{aligned} F_l^*(s) &= \mathrm{Max}[K\kappa'(s), 0], \\ F_r^*(s) &= \mathrm{Max}[-K\kappa'(s), 0], \end{aligned} \tag{4}$$

where $K = \rho L\alpha[\int_0^L ds \cdot rn\kappa'^2(s)]^{-1}$. Thus, $F_l^*(s)$ and $F_r^*(s)$ decrease as n increases, which implies that the body can locomote via small actuation forces when n is large.

On the basis of this result, we design a decentralized control scheme of a multi-articular serpentine robot in which rigid links of length Δs are concatenated one dimensionally. As $\Delta s \to 0$, $(\phi_{i+n} - \phi_i)/n\Delta s$ corresponds to the curvature derivative $\kappa'(X_i)$ in the continuum model, where ϕ_i is the ith joint angle; hence, from (4), we design the force generated by the muscle that connects the ith and $i + n$th link on the right and left side, $F_{r,i}$ and $F_{l,i}$, respectively, as follows:

$$\begin{aligned} F_{l,i} &= \mathrm{Max}[-k(v_d - v)(\phi_i - \phi_{i+n}), 0], \\ F_{r,i} &= \mathrm{Max}[k(v_d - v)(\phi_i - \phi_{i+n}), 0] \end{aligned} \tag{5}$$

for $2 \le i \le N - n$, where k is the control gain and v_d is the desired longitudinal velocity. Note that $F_{r,1}$ and $F_{l,1}$ are arbitrarily manipulated by the robot controller.

3. SIMULATION RESULTS

We conducted simulations to investigate the validity of the control scheme described above. We designed a simulation course with a curved sulcus, along which the robot locomoted. Fig. 2 shows the snapshots at $t = 400$ when $n = 1$ and 5. It is clear that the forces generated by the muscles when $n = 1$ are larger than those when $n = 5$. Fig. 3 shows the plots of the time averages of the velocity and the total force generated, $\bar{v}$ and $\bar{F}_{total}$, respectively, when n is varied. We find that $\bar{v}$ approaches v_d while $\bar{F}_{total}$ decreases as n increases. This result strongly suggests that multi-articular muscles play a pivotal role for enhancing locomotion efficiency.

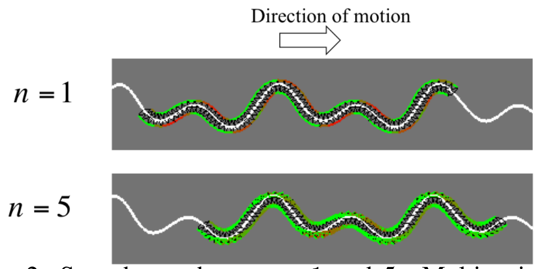

Fig. 2 Snapshots when $n = 1$ and 5. Multi-articular muscles are denoted by red color when they generate forces and by green color otherwise. White curve denotes a sulcus along which the robot locomotes.

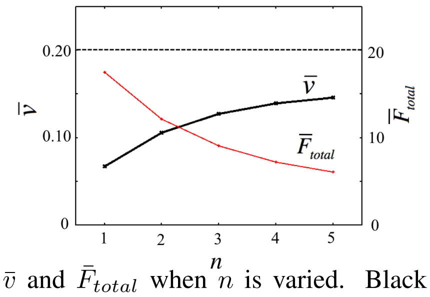

Fig. 3 $\bar{v}$ and $\bar{F}_{total}$ when n is varied. Black and red lines denote $\bar{v}$ and $\bar{F}_{total}$, respectively. The dashed line denotes the desired velocity v_d.

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