Muscles Can be Brakes: the Work Loop Technique for Stable Muscle-like Control

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1 Introduction

Using virtual Hill-type muscles with reflex is a promising bio-inspired model to emulate biological (e.g., biped) locomotion [1]. However, it requires an optimization of many (e.g., 74 in [2]) variables (e.g., PD control variables \( K_p \) and \( K_d \)) for a specific speed, and each optimization takes about many (e.g., 12 in [2]) hours. Although adding feed-forward mechanisms could reduce optimization efforts [3], it is still unclear to numerically determine the contributions of the feed-forward and feedback mechanisms in locomotion. Moreover, the feed-forward muscle-reflex models are difficult to be applied to high degree-of-freedom (DOF) bio-inspired (e.g., insect) robot locomotion owing to higher optimization efforts.

To address this problem, we used the work loop technique to analyse and determine the PD control variables \( K_p \) and \( K_d \) of a simplified muscle-reflex (SMR) model [4]. Interestingly, the result has shown that various muscle-like functions (e.g., brakes) can be emulated by using the SMR model and the work loop technique. The technique is used in muscle physiology to evaluate the mechanical work output of skeletal muscle contractions via in vitro muscle testing [5]. A plot of force and length yields a work loop, if the force and length could be back to their initial states at the end of each stimulated cycle. For instance, as a motor the muscle yields positive work characterized by the counter-clockwise muscle work loop, while a muscle acts as a brake resulting in a clockwise work loop. More muscle functional roles (e.g., struts) can be seen at [6]. This abstract presents a novel application of the work loop technique to analyse properties and determine parameters of a muscle-reflex model. More importantly, the determined parameters can facilitate high DOF bio-inspired robot learning control.

2 Method

In one joint control, a virtual agonist-antagonist mechanism (VAAM) consists of the virtual muscle-like mechanisms \( M1 \) and \( M2 \) modeled by the contractile and parallel elements (see Figure 1(a)) producing active and passive forces, respectively [4]. VAAM produces active and passive forces using its contractile and parallel elements (CEs and PEs, see Figure 1(b)). The joint actuation relies on CEs, while PEs govern joint compliance. Here we show that an insect-like muscle function results only from PEs and the reflex force \( f^{\text{ref}} \) while CEs are cancelled out, i.e., \( N_j = 0 \). The SMR model of VAAM is given by:

\[
I \ddot{\theta} = \frac{f^{\text{ext}} \sin(\theta)}{l_0} L - 2r^2 (K \theta + D \dot{\theta}),
\]

where the joint inertia \( I \), joint radius \( r \), shank length \( L \) are set to 0.5, 0.01 and 0.065. More detail of the SMR model of VAAM can be seen in our previous work [4]. The normalized muscle lengths and forces are given be:

\[
f_p^{1,2} = \frac{l_0 \mp (\theta r)}{l_0}, f^{\text{max}}_p = \frac{\mp (K \theta r + D \dot{\theta})}{f^{\text{max}}_p},
\]

where the initial muscle-like mechanism length \( l_0 \) and maximum force \( f^{\text{max}}_p \) are set to 0.085 and 0.04.
3 Result

The joint driven by a pair of the passive elements $PE_{(1,2)}$ (see Figure 1) is excited by the reflex force $f_{\text{ext}}$ (see Figure 2). The reflex force is the input of the SMR model while the model outputs are the resultant lengths and forces of VAAM (see Eq. (2)).

![Figure 2](https://www.youtube.com/watch?v=B0v5D9yiRH4)

Figure 2: The external load $f_{\text{ext}}$.

We can see that the various stiffness parameters $K$ of VAAM result in different forces and lengths of $PE_{(1,2)}$. The force and length do not form a close work loop of $PE_{(1,2)}$ if $K$ is small (e.g., $K = 1$, see Figure 3 (a)). Interestingly, the forces and lengths of $PE_{(1,2)}$ could return to the initial values that form the closed work loops, if the stiffness parameter $K$ is set to 3 and 10, respectively (see Figure 3 (b) and (c)). The two work loops are comparable to the one shown in cockroach locomotion where muscles serve as brakes that absorb energy [6]. Such brakes could produce compliant and stable joint control, while a smaller or greater stiffness parameter does not close or smoothen the force and length loop (see the dotted areas in Figure 3 (a) and (d)). Therefore, the work loop technique provides a novel and simple way to determine proper stiffness parameters $K$. The technique has facilitated designing a simple online compliance learning mechanism on the high-DOF hexapod robot AMOS, therefore leading to its variable compliant walking over gravels\(^\dagger\), [7].

4 Discussion

We showed that applying the work loop technique on the simple muscle-reflex model of VAAM could result in an insect-like muscle function, i.e., a brake (see Figure 3 (b) and (c)). Our application provides a way forward to easily determine proper joint impedance that could emulate muscle functions in different biological locomotion. Taking the neural activation $N_j$ of VAAM (see Figure 1) into account is an interesting extension of the current work in future.

\(\dagger\)https://www.youtube.com/watch?v=B0v5D9yiRH4

![Figure 3](https://www.youtube.com/watch?v=B0v5D9yiRH4)

Figure 3: The work loops of $PE_{(1,2)}$ of the VAAMs varies with different stiffness parameters $K$. (a) $K = 1$. (b) $K = 3$. (c) $K = 10$. (d) $K = 20$. The figure (b) and (c) show the clockwise and closed force-length loops that are referred as the brakes, while the smaller or greater stiffness parameter does not result in a closed or smooth work loop presented in the figure (a) and (d). These muscle-like functions of $PE_{(1,2)}$ are comparable to those of insect muscles during their locomotion [6]. Here the damper parameter $D$ is set to 1.

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References


