Identification of multi-muscle reflex structure in walking

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I. BACKGROUND

The contribution of muscle reflexes in the control of human locomotion has been studied via avatar-based muscle-driven simulations [1]. Results showed muscle reflex formulations can explain a variety of walking tasks. However, the structure of multi-muscle inhibitory and excitatory reflex connections was defined *a priori* based on empirical knowledge [2]. This limited the ability of explaining complex situations (*e.g.*, perturbed walking) or capturing person-specific characteristics. Person-specific reflex-based controllers are central for implementing versatile human-machine interfaces for wearable robots (*e.g.*, bionic limbs or exoskeletons) and relax, or even eliminate, the need for electromyography (EMG) sensors [3]. In this study, we assess whether the structure of multi-muscle reflexes for the control of the ankle joint can be entirely identified from multi-modal walking data on a subject-specific basis.

II. METHOD

Lower-body kinematics, foot-ground reaction forces and ankle muscle EMG data were collected from 5 healthy adults walking on an instrumented split-belt treadmill at 4 walking speeds (0.9, 1.8, 2.7, 3.6 *km/h*). The minimal structures (and underlying parameters) of muscle reflex controllers for the ankle joint were identified from this dataset, starting with a fully connected network *i.e.*, with all possible muscle force- and length-dependent feedback loops enabled. An indirect identification approach (Fig. 1) was used, which based on trajectory optimization with the direct collocation method.

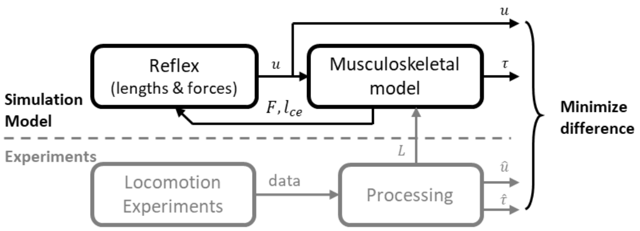

Fig. 1 Schematics of the reflex controller identification. Where, u represents muscle excitations; τ represents joint torques; F represents muscle forces; L represents muscle lengths; l_{ce} represents lengths of muscle contractile element.

The objective was to find the minimal reflex structure that explained both EMGs as well as joint kinetic data. Besides the data tracking terms, another term was added to the objective function: $O_{min-loops} = \sum_{j=1}^{M_f} |\bar{k}_f|^{\frac{1}{2}} + \sum_{j=1}^{M_l} |\bar{k}_l|^{\frac{1}{2}}$, where $\bar{k}_f$ and $\bar{k}_l$ were the normalized reflex gains. Minimizing this additional objective function ensured a minimal set of reflex loops was chosen for explaining the experimental movement excitations.

III. RESULTS & DISCUSSION

Fig. 2 depicts the muscle reflex structure identified for one representative subject. This blindly identified reflex network only rely on a few major feedback loops (the minimal structure), instead of using all possible feedbacks. Minimal reflex structure means simple control, which we think is the principle that humans taking in developing their neural-muscular control. In addition, identified structure shows similar features as widely used reflex models in the literature [1], such as, the positive length reflexes of the tibialis anterior (TA) muscle, the positive force reflexes of soleus (Sol) and m/l gastrocnemius (Gas) muscles at the stance phase. However, additional reflex paths were also found. For instance, the TA has a strong positive feedback from muscle force of itself at the middle stance phase; lateral Gas has a strong negative feedback from the Sol muscle force. This approach may enable the automated identification of neuromuscular networks for the control of a large variety of locomotion tasks, with applications in wearable robotics.

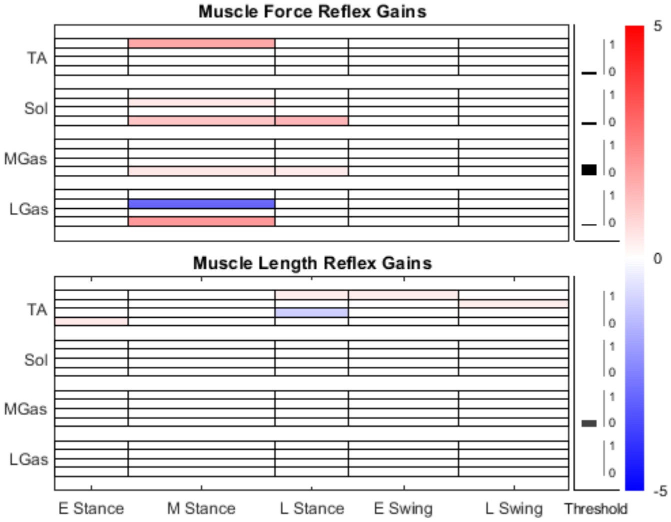

Fig. 2. Identified reflex control model of subject no. 1 at walking speed of 3.6 *km/h*. Grids in the two subplots indicate all possible reflex control loops. The averaged gait cycle was divided into five phases. Each muscle has four reflex paths (four sub-rows) from all four muscles in each phase. A reflex gain was defined (and optimized) in each muscle reflex path and at each phase (each grid). Colors in each block indicate the significance of this reflex loop in explaining muscle excitations. Muscle force reflex feedback signals were normalized by 1.5 times the maximum muscle forces. Muscle fiber length reflex feedback signals were normalized by 3 times the optimal fiber lengths; The threshold column indicates the values when the reflexes started to trigger from specific muscles. Their values were normalized the same way as reflex feedback signals.

IV. ACKNOWLEDGMENT

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