Definition of Muscle Synergies for Automobile Steering

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Abstract

We have defined a set of muscle synergies that can be used in the real-time optimal control of a 3D musculoskeletal arm model rotating a steering wheel. In the context of the 1-DoF driver/steering wheel system, two synergies can be defined to rotate the steering wheel in clockwise and counter-clockwise directions. These synergies can then be used to determine the optimal muscle forces in real-time.

Introduction

We still do not know how the central nervous system controls body movements. Muscle synergy is a famous theory suggesting that muscles are activated in groups (Bizzi et al. 2008). A challenge associated with this method is the definition of the synergies. Various methods have been proposed to find the synergies.

We suggest defining the synergies based on the task, and for a certain output space. For example, if the controller variable is the elbow flexion, one flexor and one extensor synergies are needed. In reaching actions, shoulder and elbow muscles are recruited to satisfy hand force requirements. Both synergies are known to the CNS, but are recruited for different scenarios.

This work is meant to show the possibility of such a definition. In this study, we focus on a 3D model of the human arm attached to a steering wheel (Mehrabi et al. 2013). We have defined two synergies for the 15 muscles of the 3D arm model, with the rotation of the steering wheel being the designated action.

Methods

For a simple joint actuated with multiple muscles, it is easy to show that the optimization problem of minimizing J:

$$J = \sum_i \left(\frac{F_i}{F_{i,max}} \right)^2 \quad , \quad \sum_i r_i F_i = T \qquad (1)$$

will result in the optimal muscle forces:

$$F_i^* = \frac{r_i}{F_{i,max} \sum_j \left(\frac{r_j^2}{F_{j,max}} \right)} T \qquad (2)$$

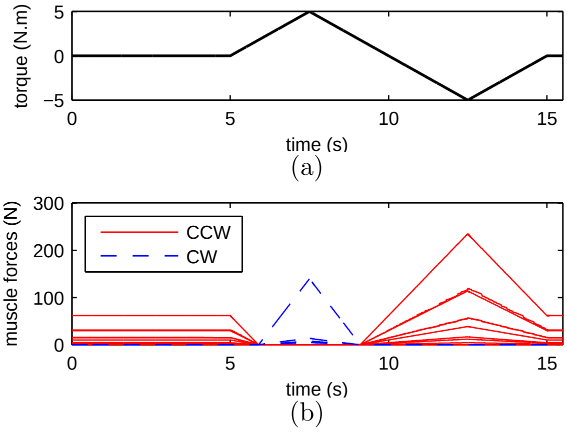

Figure 1: (a): The input torque, and (b): the optimal muscle forces to resist the applied torque

In this case, the moment arms, r_i, which are possibly functions of the joint angle, govern the relation between the recruited muscles. Therefore, knowing the required joint torque, T, we can easily use the expressions (2) to control the joint, without the need to solve the optimization problem at each time step. In such a system, we can therefore define two sets of synergies based on the desired output space, i.e. the joint angle: one for the positive and one for the negative joint torques.

For the more complex system of driver/steering wheel, the above mathematical arguments are much harder to make. However, extensive numerical and experimental observations on the optimization solutions showed that even for the 3D arm model with mono- and bi-articular muscle (which has no clear agonist and antagonist sets) we can still define two synergies that act on the steering wheel rotation (the output space).

To find the synergies, optimization problems were solved where the steering wheel was required to remain at a constant angle. During such actions, an external torque with the shape shown in Fig. 1a was applied to the steering wheel. Then the optimal muscle forces that minimized the cost function (1) were found using the static optimization method. As can be seen in Fig. 1b, two distinct sets of muscles can be found: the ones that oppose the positive torque (CW rotators) and the ones opposing the negative torque (CCW rotators).

Our 3D model agrees with previous findings (Jonsson and Jonsson, 1975) that during the steering task, the anterior deltoid and long head of

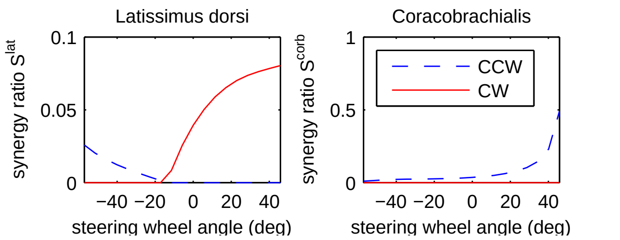

Figure 2: The synergy ratios, S^i, for two muscles

triceps are primary CCW and CW rotators, respectively. Therefore, we have chosen these two muscles as our representatives of the two synergies. Automated classification of the muscles for the two synergies involved calculating the regression between the muscle forces and the representatives. The slope of the linear regression (when $R^2 > 0.95$) indicates the synergy ratio, S.

$$S^i_{ccw} = \frac{F_i}{F_{delt}}\ ,\ S^i_{cw} = \frac{F_i}{F_{triLong}} \tag{3}$$

$$S^i = 0 \text{ if } R^2 < 0.95 \tag{4}$$

During simulations, it was observed that except for three muscles (anterior deltoid, long head of triceps, and coracobrachialis) all other 12 muscles change function at a certain steering wheel angle (from CCW rotator to CW rotator or vice versa). Figure 2 shows two examples of synergy ratio, S^{lat} and S^{corb}, as functions of the steering wheel angles. Note the change in the function of latissimus dorsi.

To show the effectiveness of the synergies for control purposes, we have employed a simple PI controller to control the steering wheel angle. The output of the controller is a *signed force*. The positive and negative values are interpreted as the representative muscle forces for the CCW and CW synergies, respectively. The output of the PI controller is then used to build the 15 muscle forces, by multiplying the representative forces by the synergy ratios as:

$$F = S_{ccw}.F_{delt} + S_{cw}.F_{triLong} \tag{5}$$

where S_{ccw} and S_{cw} are 15-element vectors containing synergy ratios, S^i_{ccw} and S^i_{cw}, respectively.

Results

Figure 3 shows the simulations, in which the steering wheel is required to follow a random motion (Fig. 3a). In Fig.3b, the solution of the optimization for supraspinatus is compared against the solution of the PI controller. While the CPU time is reduced by 3 orders of magnitude, the physiological effort only increases 0.8% when compared against the static optimization solution.

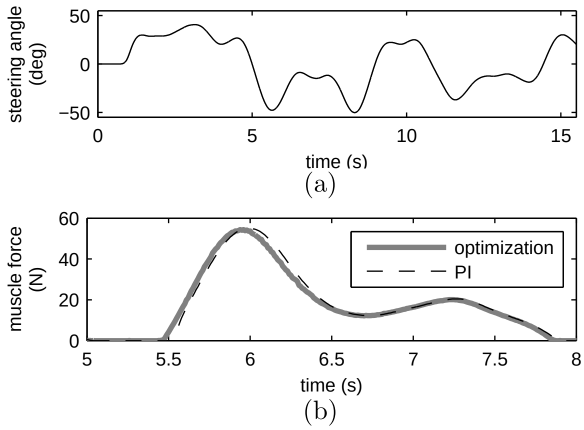

Figure 3: The simulation results. (a): The desired motion of the steering wheel. (b): Supraspinatus forces from the two methods

Discussions

In this abstract we have introduced a set of upper extremity muscle synergies, which are functions of the controlled variable (steering wheel angle). We could then control the one-degree-of-freedom driver/steering wheel system optimally with little computational effort. It should be noted that, despite the fact that the synergies themselves are optimal, the PI controller used here is not an optimal controller. Therefore, the employment of these two muscle synergies may not be optimal. The performance of the motor control scheme can be further enhanced by using optimal control methods such as Linear Quadratic Regulator (LQR) or Model Predictive Controller (MPC).

Such a real-time and optimal control scheme has strong potential in clinical applications, especially in the control of Functional Electrical Stimulation (FES) systems. With the introduction of such synergies, the FES controller can activate the muscles in such a way that reduces fatigue, while keeping the motions close to normal.

References

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