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DEALING WITH CONSTRAINTS: OPTIMAL TRAJECTORIES OF THE CONSTRAINED HUMAN ARM MOVEMENTS

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Abstract – Opening a door, turning a steering wheel, rotating a coffee mill are typical examples of human movements that require physical interaction with external environment. In these tasks, the human arm is kinematically constrained by the external environment. Although there are infinite possibilities for human subject to select his/her arm trajectories as well as interacting forces, experimental data of human constrained motion show that there exists some regulation inherent in all the measurement data. It is suggested in this paper that in the constrained movements human optimizes the criterion that minimizes the change of the hand contact forces as well as the muscle forces. This criterion differs from the minimum torque change criterion, predicting unconstrained reaching movements. Our experiments show close matching between the prediction and the subjects' data. Therefore, human may use different optimization strategies when performing constrained movements.

Keywords Crank rotation task, Constrained movement, Optimal trajectory.

1. INTRODUCTION

It is well known that, when human arm performs point to point (PTP) reaching movement in free space, the hand path in the point-to-point movement tends to be straight, slightly curved, and the velocity profile of the hand trajectory is of bell-shaped form [1][2]. These invariant features give hints about the internal representation of movements in the central nervous system (CNS) [3].

One of the main approaches adopted in computational neuroscience is to account for these invariant features via optimization theory. Optimization approaches to the hand trajectory planning are generally divided into two main groups-those formulated using kinematic models and those formulated using dynamic models of the human arm [4][5].

In the optimization approaches to the trajectory of human arm is found by minimizing, over the movement time T_f, an integral performance index J subject to boundary conditions imposed on the start and end points. The performance index can be formulated in the space of joint angles (joint space) or in the task space associated normally with the end-point of the human arm.

Considering these invariant features, Flash & Hogan [6] proposed the minimum jerk criterion

$$J = \frac{1}{2}\int_0^{T_f} \dddot{\boldsymbol{x}}^T \dddot{\boldsymbol{x}}\, dt \tag{1}$$

to show that the human implicitly plans the point-to-point movements in the task space based on the kinematic model. Here $\boldsymbol{x}$ is the position vector of the end-point of human arm. The optimal trajectory with zero boundary velocities and accelerations can be obtained as

$$\boldsymbol{x}(t) = \boldsymbol{x}(0) + (\boldsymbol{x}(T_f) - \boldsymbol{x}(0))(10s^3 - 15s^4 + 6s^5), \tag{2}$$

where $s = t / T_f$ without considering the arm dynamics.

Uno et al. on the other hand proposed to take into account the arm dynamics as a constraint condition when performing optimal planning. Based on this idea, the minimum joint torque-change criterion

$$J = \frac{1}{2}\int_0^{T_f} \dot{\boldsymbol{\tau}}^T \dot{\boldsymbol{\tau}}\, dt, \tag{3}$$

where $\boldsymbol{\tau}$ is the combined vector of the joint torques, is presented in [7]. This criterion implies that human implicitly plans the point-to-point reaching movements in the human body space based on the dynamic model. Later on this approach was expanded to cover a muscle model. A minimum muscle force change criterion has been proposed in [8]. It was shown that CNS may generate unique hand trajectory by minimizing a global performance index,

$$J = \int_0^{T_f} \dot{\boldsymbol{f}}^T \dot{\boldsymbol{f}}\, dt, \tag{4}$$

where $\boldsymbol{f}$ is the combined vector of the muscle forces.

It should be noted that the above criteria were proposed for unconstrained human movements. It was not investigated whether these criteria would be applicable to the constrained human movements. The constrained movements have specific features related to the force redundancy and the necessity to assign the contact forces together with the planning of the joint motion. To clarify these questions, we performed experiments using crank rotation task. By analysis of experimental data and numerical calculations, it is found that:

(1) The minimum muscle force change criterion alone cannot reproduce the movement features as well as interaction forces between the human hand and the crank.

(2) The minimum hand force change criterion can reproduce the hand trajectory well but not the interaction forces.

(3) The combination of both minimum muscle force change and minimum hand force change criterion agree with the experimental data. This suggests that human may use different strategies to perform different tasks.

The remaining part of the paper is organized as follows. First, we describe our experiment of crank rotation task in section 2, and then give detailed mathematical formulation in section 3. The optimization problem is presented in section 4 and comparative studies between numerical results and experimental measurements are shown in section 5. The conclusions are given in section 6.

2. CRANK ROTATION EXPERIMENT

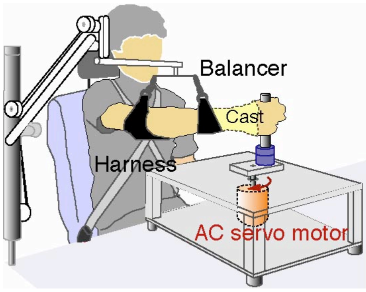


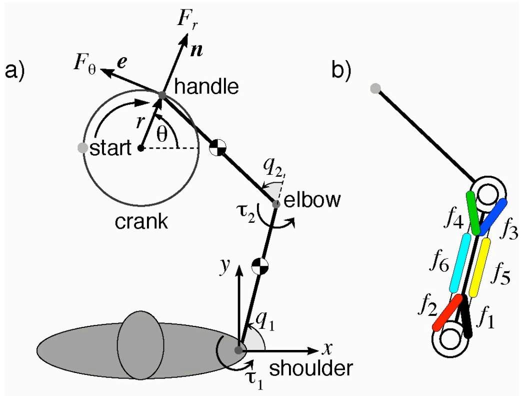
Fig. 1. Experimental setup of crank rotation task.

Fig.1 shows the experimental setup for analysis of human crank rotation task. Eight right-handed naive male subjects, aged between 22 and 25 years old, were trained to make movements in horizontal plane while holding the crank handle. Subjects were asked to make one clockwise circular movement (2π [rad]) by their own paces, as comfortable as possible. The initial crank angle configuration $\theta_0=\pi$ [rad].

The subject's wrist joint was fixed by a cast in order to exclude the kinematic redundancy of the hand. Subject sat in a chair with a harness in order to constrain the shoulder joint and realize planar motion of the elbow. AC servo motor was connected to the crank's shaft to realize the viscous friction. The radius of the crank r=0.05m, the inertia moment of crank I=0.02 kg m^2, and the motor viscosity B=0.3 (Nms/rad).

The subjects were presented with 200-300 trials for each task. During each trial, the angular velocity $\dot{\theta}$ was recorded using rotational encoder on the motor. The interaction force $\boldsymbol{F}$ applied to the handle was measured by a force transducer mounted on the crank handle. To examine the muscle force pattern during the movement, surface electromyogram (EMG) signals are recorded from the muscles that corresponded to six muscles model (see Fig.2 (b) in next section). For the shoulder monarticular muscles, activities in the posterior deltoid (f_1: EMG_1) and the pectoralis major (f_2: EMG_2) were measured. For elbow monarticular muscles, activities in the lateral head of triceps brachii (f_3: EMG_3), and the brachialis (f_4: EMG_4) were measured. For biarticular muscles, activities in the long head of triceps (f_5: EMG_5), and biceps brachii (f_6: EMG_6) were measured. The motion and force data were recorded by sampling frequency of 250 Hz and the EMG signals were recorded at 1000 Hz. Each EMG signal was filtered using a robust low-pass filter with cut-off frequency of 15 Hz, normalized with respect to the maximum voluntary contraction (MVC) and rectified.

3. MATHEMATICAL MODEL OF HUMAN CRANK ROTATION TASK



(a) Crank and human arms model (b) Muscle model

Fig. 2. Model of crank rotation task

The coordinate of the crank rotation task is shown in Fig.2. Here, the human arm is modeled as a planar 2 D.O.F link with length l_1, l_2, masses m_1, m_2, and centres of mass I_1, I_2, respectively. The geometric constraints imposed on the system are:

$$l_1 \cos q_1 + l_2 \cos(q_1 + q_2) = r \cos\theta - x_0, \tag{5}$$

$$l_1 \sin q_1 + l_2 \sin(q_1 + q_2) = r \sin\theta + y_0, \tag{6}$$

where x_0 is the length of the shoulder, y_0 is the distance from the body center to the crank axle, q_1 and q_2 are the joint angles of the arm.

The crank system has the inertia moment I, and the AC motor attached directly at the axis of the crank generates the torque of constant viscosity B. The basic dynamic equations of the system including the crank and the human arm are

$$I\ddot{\theta} + B\dot{\theta} = r\boldsymbol{e}^T \boldsymbol{F}, \tag{7}$$

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q},\dot{\boldsymbol{q}}) = \boldsymbol{\tau} - \boldsymbol{J}(\boldsymbol{q})\boldsymbol{F}, \tag{8}$$

where $\boldsymbol{q}$ is the vectors of joint angle, $\boldsymbol{J}$ is the Jacobian matrix of the end-point of the arm, $\boldsymbol{M}$ is the inertia matrix of the arm, $\boldsymbol{h}$ is the generalized vector of centrifugal and Coriolis forces.

In addition,

$$\boldsymbol{J}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \dot{\boldsymbol{J}}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} = r(\boldsymbol{e}\ddot{\theta} - \boldsymbol{n}\dot{\theta}^2) \tag{9}$$

where vector $\boldsymbol{n}$ and $\boldsymbol{e}$ are the unit vectors of the contact frame.

As seen from the crank rotation direction, the system under constraint has only one degree of freedom. Taking θ

as the independent coordinate and eliminating the hand contact force $\boldsymbol{F}$ from the dynamic equations (7,8) using the acceleration constraints (9), the system dynamics can then be simplified to the following form

$$R(\theta)\ddot{\theta} + H(\theta,\dot{\theta}) = r\boldsymbol{e}^T \boldsymbol{J}^{-T}\boldsymbol{\tau}, \quad (10)$$

where the configuration-dependent inertia moment

$$R(\theta) = I + r^2\boldsymbol{e}^T \boldsymbol{J}^{-T}\boldsymbol{M}\boldsymbol{J}^{-1}\boldsymbol{e}, \quad (11)$$

and the configuration-dependent damping term

$$H(\theta,\dot{\theta}) = B\dot{\theta} + r\boldsymbol{e}^T \boldsymbol{J}^{-T}\{\boldsymbol{h} - \boldsymbol{M}\boldsymbol{J}^{-1}(r\dot{\theta}^2\boldsymbol{n} + \dot{\boldsymbol{J}}\dot{\boldsymbol{q}})\}. \quad (12)$$

As described by (10), the simplified system dynamics do not explicitly depend on the contact forces. Given the crank motion and the joint torques, the dynamic reaction forces are obtained as

$$\boldsymbol{F} = \{\boldsymbol{J}\boldsymbol{M}^{-1}\boldsymbol{J}^T + r^2 I^{-1}\boldsymbol{e}\boldsymbol{e}^T\}^{-1} \cdot \{\boldsymbol{J}\boldsymbol{M}^{-1}(\boldsymbol{\tau} - \boldsymbol{h}) + \dot{\boldsymbol{J}}\dot{\boldsymbol{q}} + r(\boldsymbol{n}\dot{\theta} + I^{-1}B\boldsymbol{e})\dot{\theta}\} \quad (13)$$

This reaction forces can be determined uniquely if the system is dynamically non-singular, i.e. $\det \boldsymbol{M} \neq 0$ and $I \neq 0$ (see, for example, [9]). If the inertia of the arm is much less than that of the crank, $\boldsymbol{F} = \boldsymbol{J}^{\mathrm{T}}\boldsymbol{\tau}$ as in the static case. For the other extreme case, when the inertia of the crank is much less than that of the arm, repartitioning of the (7-9) is necessary to express the end-point forces.

To take into account muscle properties, a simple model shown in Fig.2 (b) is employed. The transformation of the muscle force vector $\boldsymbol{f} = (f_1,\ldots,f_6)^T$ into the joint torque $\boldsymbol{\tau} = (\tau_1, \tau_2)^T$ is defined

$$\boldsymbol{\tau} = \boldsymbol{G}^T \boldsymbol{f}, \quad (14)$$

where

$$\boldsymbol{G}^T = \begin{bmatrix} d_1 & d_2 & 0 & 0 & d_{51} & d_{61} \\ 0 & 0 & d_3 & d_4 & d_{52} & d_{62} \end{bmatrix}, \quad (15)$$

and d_1, d_2, d_3, d_4, d_{51}, d_{52}, d_{61}, d_{62} are the corresponding moment arms of the muscles. It is assumed here that the moment arms are constant.

In this crank rotation task, the human-crank system is over-actuated because there are six independent control inputs (muscle forces f_1 ,…, f_6) for only one motion of equation (10). Therefore, the experimental data also imply that the CNS somehow resolves the force redundancy problem in choosing an invariant velocity profile.

4. OPTIMUM MOTION CRITERIONS

In this section, we explain the trajectory formation of the human crank rotation task from the optimization point of view. We first describe the standard optimal control problem and exploit the conventional criteria (1, 4), which have been successfully used in predicting unconstrained reaching movements of the human hand in free space.

At this point, it is to be noted that if optimal trajectory of crank task were defined using only the kinematic formulation, as it is in the minimum jerk criteria (1), the angular velocity profiles would be exactly of the bell shape. However, the experimental data show the features of a local minimum in the angular velocity profiles (see Fig.3 (a) in the next section), and this rules out the minimum jerk model, and indirectly, it implies that the formation of the optimal trajectory is done in the dynamic formulation.

Taking into consideration the muscle properties, we employ a simple muscle model as shown in Fig.2 (b). The driving system of the human arm is a unilaterally actuated mechanism, since the muscles can only stretch for producing the joint torques. Therefore, one has to impose the inequality constraints

$$f_i \geq 0, \; i = 1,\ldots,6. \quad (16)$$

To be able to use standard optimization techniques, define the control vector as

$$\boldsymbol{u} = \dot{\boldsymbol{f}}, \quad (17)$$

and select the state variables

$$\boldsymbol{y} = \begin{bmatrix} \theta \\ \dot{\theta} \\ \boldsymbol{f} \end{bmatrix}. \quad (18)$$

The state equation can now be expressed as

$$\dot{\boldsymbol{y}} = \begin{bmatrix} \dot{\theta} \\ \dfrac{r\boldsymbol{e}^T \boldsymbol{J}^{-T}\boldsymbol{G}^T\boldsymbol{f} - H(\theta,\dot{\theta})}{R(\theta)} \\ \boldsymbol{0}_{6\times 1} \end{bmatrix} + \begin{bmatrix} \boldsymbol{0}_{2\times 1} \\ \boldsymbol{u} \end{bmatrix}. \quad (19)$$

The boundary conditions are posed as

$$\begin{cases} \theta(0) = \theta_0, \theta(T_f) = \theta_0 - 2\pi, \\ \dot{\theta}(0) = \dot{\theta}(T_f) = 0, \\ \boldsymbol{f}(0) = \boldsymbol{f}(T_f) = \boldsymbol{0}. \end{cases} \quad (20)$$

where θ_0 is the starting angle. Now, for the given cost functional

$$J = \frac{1}{2}\int_0^{T_f} L(\boldsymbol{y},\boldsymbol{u})dt, \quad (21)$$

we are ready to use standard optimization techniques.

4.1. Minimum muscle force change criterion

Minimum muscle force change criterion (4) implies that the human arm movement is planned directly in the human body space using the dynamic model by minimizing a criterion,

$$L(\boldsymbol{y},\boldsymbol{u}) = \boldsymbol{u}^T\boldsymbol{u}. \quad (22)$$

4.2. Minimum hand force change criterion

Minimum muscle force change criteria find the smoothest actuation force trajectory. But in the constrained movement, there is a force interaction with the external environment via the human hand, and it is reasonable to take into account of the interaction force.

To this end, one might try to use the criterion

$$L = \dot{\boldsymbol{F}}^{\square T}\dot{\boldsymbol{F}}^{\square}, \quad (23)$$

$$F^{*} = K^{T} J^{-T} G^{T} f\,, \tag{24}$$

where F^* is the joint torque transformed to the task space coordinates, K is the orientation matrix of the contact frame with respect to the base. As the crank dynamics in experimental conditions is more dominant, the transformed joint torque is approximately equal to hand contact force. Then we call this criterion (23) minimum hand force change criterion [10]. The hand force change can be defined as

$$\dot{F}^{*} = K^{T} J^{-T} G^{T} \dot{f} + (\dot{K}^{T} J^{-T} + K^{T} \dot{J}^{-T}) G^{T} f\,. \tag{25}$$

This criterion implies that, during the constrained motions the human subjects plan the point-to-point reaching movements using dynamic formulation (as in the minimum muscle force change model) in the task space (as in the minimum hand jerk model). It follows from (25) that the minimum hand force-change criterion depends on the frame of task space. Therefore, the criterion also then implies that in constrained movements the human CNS assigns a moving contact frame.

4.3. Minimum hand force change + muscle force change criterion

Instead of the above criterions, we propose a combined (minimum hand force change + muscle force change) criterion

$$L = \dot{F}^{*T} \dot{F}^{*} + \dot{f}^{T} W \dot{f}\,. \tag{26}$$

where $F^*=KJ^TG^Tf$, and W is symmetric positive-definite weight matrix. The weight matrix W is set as $W=k$ diag$\{w_1,\ldots,w_6\}$, with $w_i = 1/P_i^2$, where P_i is the physiological cross sectional area (PCSA) of i-th muscle matrix and k is a weight coefficient balancing the contribution of the hand force-change and muscle force-change. This combined criterion finds the smoothest the equivalent hand force as well as the muscle force trajectory. It also implies that, in constrained movement the human CNS select a moving contact frame like a minimum hand force change criterion (23). In our previous research of [11], we used a criterion where muscle force change component was added with some scalar weight coefficient. However, it was not clear how to assign the weight coefficient. Now we do not face this problem for the criterion (26) as the weights are naturally assigned from physiological considerations.

5. COMPARISON BETWEEN NUMERICAL RESULTS AND EXPERIMENT DATA

To solve the optimal control problem numerically, we use the software package RIOT95 [12]. In our computer simulation, we use the following parameters of the dynamic model: l_1=0.31 m, l_2=0.33 m, m_1=1.91 kg, m_2=1.48 kg, l_{g1}=0.157 m, l_{g2}=0.167 m, I_1=0.014 kg m^2, I_2=0.020 kg m^2, d_1=−0.352m, d_2=0.0437m, d_3=−0.0203m, d_4=0.0275m, d_{51}=−0.0254m, d_{52}=−0.0305m, d_{61}=0.0290m, d_{62}=0.0432m. The data are taken from [13], [14]. In addition, we set x_0= 0.18 m, y_0=0.50 m, and the motion time T_f=1.55 sec. To take into account the unilateral constraints (16), we use a penalty function technique implemented in RIOT95 [12]. The penalty term is defined as

$$P = \sum_{i=1}^{6} c_i \max(-f_i, 0)^2\,, \tag{27}$$

where the coefficients c_i are adjusted to be in the range 400-500.

5.1. Minimum muscle force change criterion

In our computer simulation, the boundary conditions for the muscle forces are set zero. The kinematic profiles - the crank angular velocity and the joint velocities - are shown in Fig.3 (last five trajectories of same subject are shown). It is clear that, the results of the minimum muscle force change criterion do not match well the experimental data. As can be seen in Fig.4, there exists larger discrepancy between the simulation and experimental data in the hand force profiles.

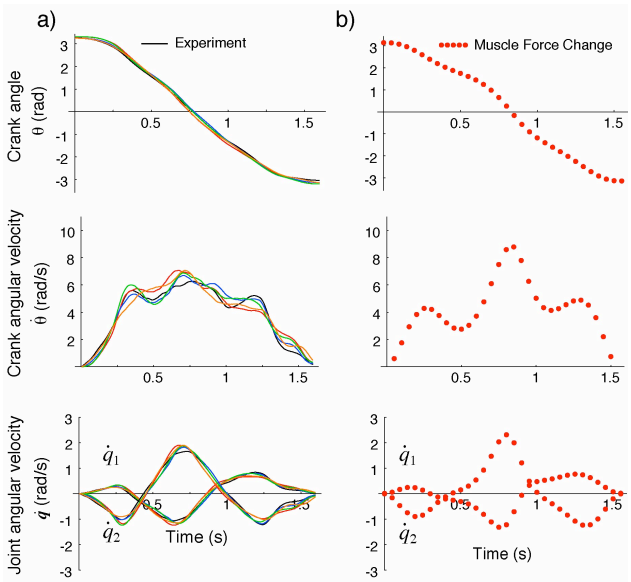


Fig. 3. Kinematic profiles predicted by the minimum muscle force change criterion.

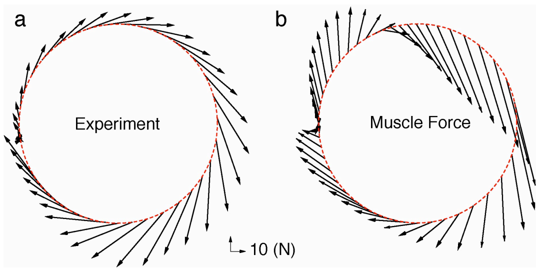


Fig. 4. Force profiles predicted by the minimum muscle force change criterion.

5.2. Minimum hand force change criterion

To test the feasibility of the minimum hand force change criteria, we also performed the same computer simulation. The kinematic profiles - the crank angular velocity and the joint velocities - are shown in Fig.5. The hand force profiles are shown in Fig.6.

This criterion predicts well the kinematic trajectories (see Fig.5) but still fails to predict the correct force profiles (see Fig.6). In particular, when using the criterion (23), the normal component of the hand contact force tends to be zero, which does not match the experimental data.

5.3. Minimum hand force change + muscle force change criterion

Numerical simulation considering the combined criterion of (26) reproduces the experimental data well. In the simulation, we set the following values for the PCSA: P_1=38.71cm^2, P_2=19.36cm^2, P_3=7.75cm^2, P_4=10.30cm^2, P_5=3.87cm^2, P_6=3.23cm^2. These data are taken from [14]. During the course of several simulation runs with different values of the weight coefficient *k*, we found that the value *k*=1 produces very satisfactory the results. The comparison of the simulation results with the experimental data is shown in Fig.7 and Fig.8. From these results it is clear that not only the kinematic trajectories are predicted now accurately enough but also the force profiles capture the tendency of the human motions. Thus, we conclude that the combined (minimum hand force + muscle force change) criterion match the experimental data much better than the minimum muscle force change criterion.

To examine the criterion (26) more thoroughly, we compare the muscle force patterns predicted theoretically with the patterns estimated from EMG data (see Fig.9). The results can be compared with the numerical prediction shown in Fig.10. One can see that the combined criterion is reasonably good in predicting the muscle activities in the constrained multi-joint motions.

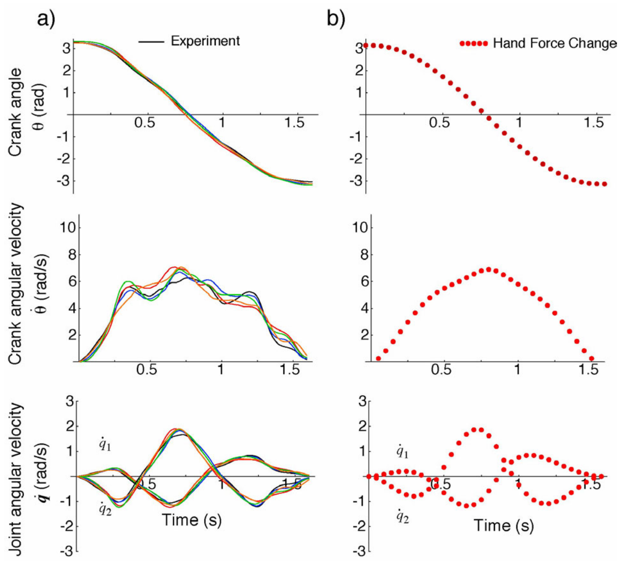


Fig. 5. Kinematic profiles predicted by the minimum hand force change criterion.

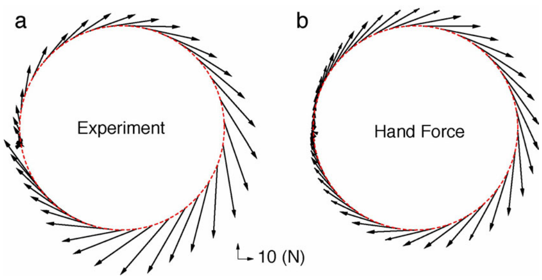


Fig. 6. Force profiles predicted by the minimum hand force change criterion.

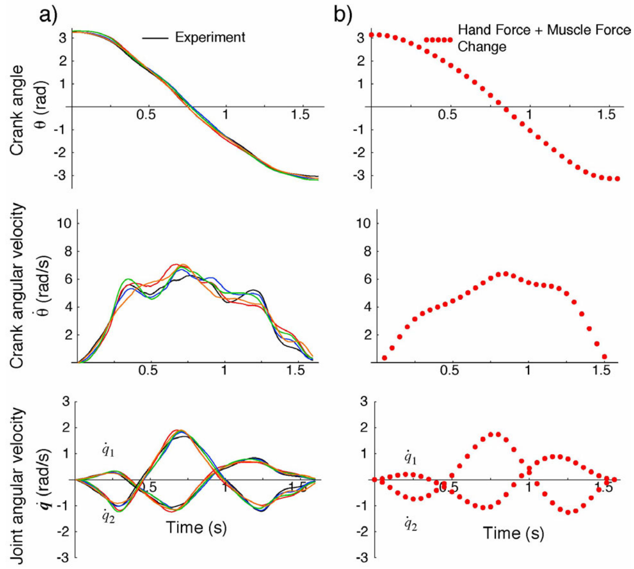


Fig. 7. Kinematic profiles predicted by the combined criterion

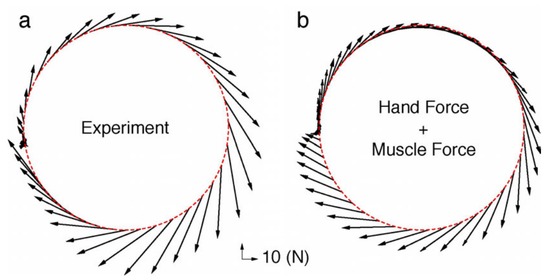


Fig. 8. Force profiles predicted by the combined criterion.

6. CONCLUSIONS

In this paper, we studied the specific crank rotation task from both human experiment and numerical simulations. To resolve the force redundancy, a novel criterion that takes into account both the hand force change and the muscle force change has been proposed and verified. The analysis of the experimental data shows that in comfortable point-to-point motions, our criterion matches experimental data much better than the minimum muscle force change criterion. In addition, the combined criterion captures well the muscle activity in the constrained multi-joint motions.

Our research indicates that both the smoothness of the hand force and muscle force are of primary importance in the force interactive tasks where the force perception plays a fundamental role in the trajectory planning. A physiological interpretation of this finding is that the trajectory of the human arm in constrained movements is planned directly in the task space using the dynamic model. The good matching for the criterion (26) implies that in constrained movements the human CNS also assigns a moving contact frame and this contact frame depends of course on the contact task. The interpretation offers a new insight into the nature of the biological motor control of human movements. More accurate muscle models, including the metabolical level, are necessary for the future research. Also, more accurate experimental analysis, including advanced sensor systems for measuring the muscle activity, would be beneficial.

The last comment is about unconstrained motions in a force field. Shadmehr et al. [15][16] studied human arm movement in viscous force vector fields. They found that after motor learning, the arm trajectory has the same features as in free space. Based on this observation, they suggested that human learns the inverse model of the external force field and uses this inverse model to delete the influence from the external force. However, the aspects of the end-point force formation were left unanswered. From our study, it is found that in the kinematic constrained movements human may select different motion strategies. Therefore, it would be interesting to check whether the end-point force formation can be predicted by our criterion when human arm moves in a force field.

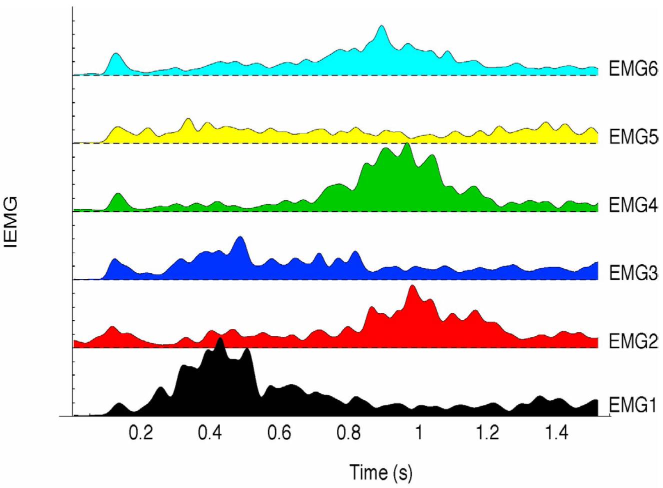


Fig. 9. Experimental EMG data

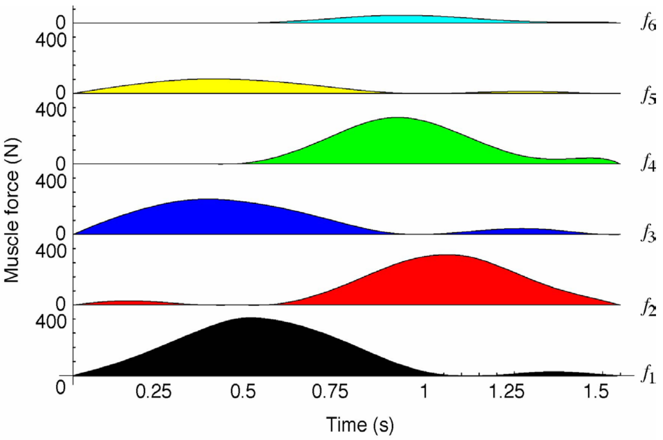


Fig. 10. Muscle forces predicted by the combined criterion.

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