Dynamics simulation of upper limb push-and-pull motion on the control interface

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With the development of industrial design and human-computer interaction, ergonomic design for the control interface has been more and more important. However, there is still no ergonomic evaluation platform for control interface in China. For its low cost, longevity and quantification, simulation test has been a good way for ergonomic evaluation. In this paper, dynamics simulation of upper limb’s push-and-pull motions on the control interface was conducted. The simulation includes kinematics simulation and dynamics simulation. Kinematics simulation calculates the joint angles of upper limb joints given a known trajectory of terminal segment. Dynamics simulation calculates the joint torques on the basis of kinematic parameters using Kane Method. Further, simulation results were calculated for the specific push-and-pull motion by the upper limb, opening the refrigerator door. And the results between different conditions (with different widths of refrigerator door and different initial positions) were compared and analyzed. According to numerical results, some suggestions were given for the design of refrigerator and the posture taken while opening the refrigerator door.

Keywords: Control interface, Multi-rigid-body, Dynamics simulation, Kane Method

1. Introduction

With the development of industrial design and human-computer interaction, ergonomic design for the control interface has been more and more important. Although some ergonomics researches have been conducted and some consequents from them have applied to the product design, there is still not ergonomic evaluation platform for control interface in China. For the ergonomic evaluation on the control interface, there are two evaluating ways: user’s subjective evaluation and simulation evaluation. User’s subjective evaluation use the user’s subjective experience, performance and physiological reaction to assess the interface, so it has a strong operability. But it’s difficult to assess the conceptual products or products in production using this evaluating way. The simulation evaluation, however, can be conducted throughout the whole product design and production process. It costs less, has longevity and focuses on quantitative results which the user’s subjective evaluation cannot match.

In the human-machine interaction of control interface, the motions of upper limb are common. People rotate the steering wheel while driving, open the door of a refrigerator or microwave oven while take/put something and click the button while operating a machine. Kinematics and dynamics simulation for these upper limb motions can calculate the quantitative results such as joint angles and torques which is used to evaluate the control interface. In the kinematics/dynamics modeling and simulation, inverse kinematics and inverse dynamics method are always used. Earlier previous studies have included kinematic analyses of everyday activities involved in feeding and personal hygiene (see review by Buckley et al., 1996), but none have included both kinematic and dynamic analysis to provide the data required as an input to a biomechanical model for the calculation of joint torques and muscle forces. In recent years, more specific kinematics/dynamics analyses were conducted on the upper limb motions. For example, Murray I A & Johnson G R (2004) calculated the external forces and torques at the shoulder and elbow while performing every day tasks. And they established a database of ranges of motion and external forces and torques to support the development of biomechanical models of the upper limb. Some other researches focused on the tapping motions of upper limb. Jack T. Dennerlein et al. (2007) used the inverse dynamics method to figure out the contribution of the wrist, elbow and shoulder joints to single-finger tapping.
In this paper, a multi-rigid-body model of upper limb was built and inverse kinematics and Kane method (an inverse dynamics method) were used to calculate the joint angles and torques for the upper limb push-and-pull motion on the refrigerator door. And then some suggestions were given for the design of refrigerator and the posture taken while opening the refrigerator door according to the simulating calculation results.

2. Modeling and simulation

In the modeling and simulation of the upper limb motions, a multi-rigid-body model was firstly built according to the characteristics of upper limb. In the Multi-rigid-body model, each segment of upper limb is simplified to the rigid body and each joint is simplified to the hinge. Then the joint torques on the shoulder, elbow and wrist were considered to build the joint torque model of upper limb on the basis of multi-rigid-body model. Each joint torque corresponds to one DOF (degree-of-freedom) of the joints. In order to avoid the redundant solution, the highest DOF of all the three joints is limited to not more than six. After modeling, inverse kinematics and dynamics method of multi-rigid-body system were used to calculate the joint angles and torques given a known terminal trajectory of upper limb. Finally, the above modeling and simulation method were used to calculate and analyze the push-and-pull motion while opening the refrigerator door.

2.1 Joint torque model of upper limb

According to the characteristics of upper limb, a multi-rigid-body model was firstly built. In the model, the upper arm, forearm, and hand are considered as rigid body, the joints are considered as hinges. For the method of inverse kinematics, once the number of unknown variables is more than 6, it will need to introduce some constraint conditions and criteria which may increase the complexity of model and cause some inaccuracy of the calculation results yet. So the multi-rigid-body had six DOFs at most, which consisted of 3 DOFs of shoulder joint, 1 DOF of elbow joint and 2 DOFs of wrist joint. The dimension parameters were shown and described in Figure 1 and Table 1.

![Figure 1. Simplified graphic of the upper limb multi-rigid-body model.](image)

Table 1. Physical parameters of every segment of upper limb.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Length (m)</th>
<th>BabyCenter (m)</th>
<th>Mass (kg)</th>
<th>Rotary inertia (kg.m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B₁</td>
<td>l₁ = 0.333*</td>
<td>c₁ = 0.145</td>
<td>m₁ = 2.356</td>
<td>J₁ = 0.077</td>
</tr>
<tr>
<td>B₂</td>
<td>l₂ = 0.254*</td>
<td>c₂ = 0.109</td>
<td>m₂ = 1.188</td>
<td>J₂ = 0.021</td>
</tr>
<tr>
<td>B₃</td>
<td>l₃ = 0.105</td>
<td>c₃ = 0.053</td>
<td>m₃ = 0.396</td>
<td>J₃ = 0.002</td>
</tr>
</tbody>
</table>

The joint torque model was built based on the multi-rigid-body model. And the joint torques of each joint was the mechanical parameters needed to solve. One joint torque corresponds to one DOF of one joint, so there are totally 6 joint torque parameters which contain 3 torques of the shoulder joint, 1 torque of elbow joint and 2 torques of wrist joint. The detailed symbol expressions are shown in Table 2. Use the Cardan angle to describe the joint angle corresponding to each DOF of the joint torque model. The inertial coordinate system is built on the shoulder and siamese coordinate systems, and are fixed on each segment of the upper limb; see Figure 2. Combined with the Table 2, the joint torque vectors of shoulder joint, elbow joint and wrist joint are respectively expressed in Eq 2.1.

\[
\begin{bmatrix}
\tau_1 \\
\tau_2 \\
\tau_3
\end{bmatrix} = \begin{bmatrix}
\tau_{11} & \tau_{12} & \tau_{13} \\
0 & 0 & \tau_{23} \\
0 & \tau_{32} & \tau_{33}
\end{bmatrix}
\] (2.1)

Table 2. Expression of torque vector components on each joint.

<table>
<thead>
<tr>
<th>Joint</th>
<th>internal/external rotation torque</th>
<th>abduction/adduction torque</th>
<th>anteflexion/backward extension torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>(\tau_{11})</td>
<td>(\tau_{12})</td>
<td>(\tau_{13})</td>
</tr>
<tr>
<td>Elbow</td>
<td>—</td>
<td>—</td>
<td>(\tau_{23})</td>
</tr>
<tr>
<td>Wrist</td>
<td>—</td>
<td>(\tau_{32})</td>
<td>(\tau_{33})</td>
</tr>
</tbody>
</table>

Figure 2. Inertial coordinate system and siamese coordinate systems of the upper limb model. (Each system is a right-handed three-dimensional coordinate system where the z-axis is not shown.)

According to the coordinate rotation of Cardan angle, the orientation cosine matrixes of shoulder, elbow and wrist under their respective DOFs are expressed as follows (Eq 2.2 – Eq 2.4).

\[
A_j = A(\alpha_j)A(\beta_j)A(\gamma_j)
\]

\[
A_1 = \begin{bmatrix}
\cos \beta_1 \cos \gamma_1 \\
\cos \alpha_1 \sin \gamma_1 + \sin \alpha_1 \sin \beta_1 \cos \gamma_1 \\
\sin \alpha_1 \sin \gamma_1 - \cos \alpha_1 \sin \beta_1 \cos \gamma_1
\end{bmatrix}
\]

\[
A_2 = \begin{bmatrix}
\cos \gamma_2 \\
\sin \gamma_2
\end{bmatrix}
\]

\[
A_z = \begin{bmatrix}
\cos \gamma_2 & -\sin \gamma_2 & 0 \\
\sin \gamma_2 & \cos \gamma_2 & 0 \\
0 & 0 & 1
\end{bmatrix}
\] (2.2) (2.3)
\[ A_3 = A(\beta_3)A(\gamma_3) = \begin{bmatrix} \cos \beta_3 \cos \gamma_3 & -\cos \beta_3 \sin \gamma_3 & \sin \beta_3 \\ \sin \gamma_3 & \cos \gamma_3 & 0 \\ \sin \beta_3 \cos \gamma_3 & \sin \beta_3 \sin \gamma_3 & \cos \beta_3 \end{bmatrix} \]  

(2.4)

Where, \( \alpha \) is the angle of internal/external rotation; \( \delta \) is the angle of abduction/adduction; \( \nu \) is the angle of anteflexion/backward extension. And subscript 1, 2, and 3 correspond to shoulder, elbow and wrist joint respectively.

2.2 Inverse kinematics and dynamics

On the joint torque model of upper limb, the inverse kinematics and dynamics method were used to calculate the kinematics and mechanics parameters such as the joint angles, joint torques and so on. The results of inverse kinematics were the input of the inverse dynamics calculation.

2.2.1 Inverse kinematics

In the Inverse kinematics of multi-rigid-body system, it’s simpler to choose the angle parameter to describe the movement mainly consisted of rotation. So the angles of each joint, \( \theta \), were chosen as the generalized coordinate and their derivatives, \( \dot{\theta} \), were chosen as the generalized velocities. There was a certain relationship (Eq 2.5) between the (angular) velocity vector of the terminal segment and generalized velocities vector according to the inverse kinematics. Once the Jacobian matrix was solved, Eq 2.5 then could be expanded to the differential equations of the generalized coordinate (\( \dot{\theta} \)).

\[ \begin{bmatrix} v_{30x} \\ v_{30y} \\ v_{30z} \\ \omega_{30x} \\ \omega_{30y} \\ \omega_{30z} \end{bmatrix}^T = J^T \begin{bmatrix} \ddot{\alpha}_1 \\ \dot{\beta}_1 \\ \dot{\gamma}_1 \\ \dot{\beta}_2 \\ \dot{\gamma}_2 \end{bmatrix} \]  

(2.5)

Where, \( v \) are three components of the centroid velocity of terminal segment (hand) in the inertial coordinate system, \( \omega \) are three components of the centroid angle velocity.

With the differential equations, the numerical solution of generalized coordinate (\( \dot{\theta} \)) can be solved under the reasonable initial and boundary conditions. Further, other relevant kinematics parameters such as joint angular velocity/acceleration and centroid velocity/acceleration of each segment in the inertial coordinate system can be also solved.

2.2.2 Inverse dynamics – Kane method

With the concept of internal coordinate and an intuitive derivation process, kane method is a widely used inverse dynamics method. So in this paper, Kane method was also used in the simulating calculation of joint torque model. The main steps using Kane method was as follows.

(1) Choose the partial (angular) velocity. In this paper, the derivatives of joint angle parameters were chosen as the partial (angular) velocities; (2) Calculate the generalized active force and generalized inertial force. In the joint torque model, the active force was gravity and the active torques was joint torque; (3) Solve the Kane equation. According to the Kane method, the final kane equation of the joint torque model was shown as Eq 2.6. Solve the equations expanded from the Kane equation and then get the numerical solution of joint torques.

\[ m_1 \ddot{x}_1 + \tau_1 = m_2 \ddot{x}_2 + \tau_2 + m_3 \ddot{x}_3 + \tau_3 \]

\[ -m_1 \ddot{v}_1,0 = -m_2 \ddot{v}_2,0 + m_3 \ddot{v}_3,0 \]

\[ -[J_1 \ddot{\omega}_1,0 + \ddot{\omega}_1,0 \times (J_1 \cdot \ddot{\omega}_1,0)] \cdot \ddot{\omega}_1,0 = 0 \]  

(2.6)

3. Simulation results of upper limb push-and-pull motion

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The above modeling and simulation method are used to simulate and analyze the push-and-pull motion while opening and closing the refrigerator door (Figure 3). The dimension parameters of the upper limb were shown in Figure 1 and Table 1. The radius of terminal trajectory was $r$ and the force on the terminal was $F$. Considering the complexity of the model and the joint motions while opening the fidge door, the degrees of freedom was reduced to four DOFs including abduction/adduction angle of shoulder ($\theta$), flexor angle of shoulder ($\alpha$), flexor angle of elbow ($\beta$) and flexor angle of wrist ($\gamma$).

For the simulation motion, kinematics and dynamics results were calculated under different initial positions and different values of $r$. Each simulation was shown in Table 3. The group of condition 1, condition 2 and condition 3 had the different radius of the terminal trajectory but the same initial joint angles, while the group of condition 1, condition 4 and condition 5 had the same radius of the terminal trajectory but the different initial joint angles. The joint angle and torques under each condition was calculated and their results were shown in Figure 4.

![Diagrammatic sketch of opening the refrigerator door.](image)

(a) Condition 1
(b) Condition 2

(c) Condition 3

(d) Condition 4
Figure 4. Joint angle and torque results of each simulation condition.

Table 3. Initial and boundary conditions of simulation groups.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Radius of the terminal trajectory ( r ) (m)</th>
<th>Initial joint angles (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45</td>
<td>=0</td>
</tr>
<tr>
<td>2</td>
<td>0.55</td>
<td>=0</td>
</tr>
<tr>
<td>3</td>
<td>0.35</td>
<td>=0</td>
</tr>
<tr>
<td>4</td>
<td>0.45</td>
<td>=10</td>
</tr>
<tr>
<td>5</td>
<td>0.45</td>
<td>=0</td>
</tr>
</tbody>
</table>

4. Discussion and conclusion

Comparative analysis between the simulation results of condition 1, condition 2 and condition 3 showed that the change range of wrist joint angle enlarged with the increase of the terminal trajectory radius \( r \) (corresponding to the width of the fridge door). Meanwhile, the maximum flexor angle of elbow (\( \theta \)) increased. Especially when \( r \) was up to 0.55m, \( \theta \) was slightly over the flexor limit of elbow, which meant it had become difficult for a person to open the fridge door with the shoulder fixed posture. So in the design of domestic refrigerator, it is suggested that the width of fridge door is not more than 0.60m considering the redundancy.

Comparative analysis between the simulation results of condition 1, condition 4 and condition 5 showed that the initial joint angles, or the upper limb posture, had a significant influence on the joint torques while opening the fridge door. From the point of view of the kinematics, the change range of shoulder flexor angle in condition 1, where the initial shoulder position was horizontal, was significantly less than those in condition 4 and condition 5. Besides, from the point of view of the dynamics, the joint torque of shoulder would significantly increase when the upper arm took an upward or downward posture, especially for the upward posture. So it is suggested to avoid the upward posture of upper limb while opening and closing the fridge door. It should also be considered in the design of the domestic refrigerator.

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