What strategy CNS used to perform a movement balanced? Biomechatronical simulation of human lifting

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Abstract

How the central nervous system manage the body posture during various tasks despite redundancy problem? It's a well known question mooted in biomechanics and bioengineering field. Some techniques based on muscle and torques synergies presented to express CNS addressing the kinetic redundancy in musculoskeletal system. A 5DOF biomechatronical model of human body subjected to human motion simulation to performe lifting task. Simulation process based on a novel optimization approach named predictive dynamics implements inverse dynamics to model the dynamics of motion in simulation process. An objective function based on ankle torque summation during lifting time subjected to be minimized and considered that CNS does it either. In the other optimization-based techniques subjected to simulation purposes, balancing motion was guaranteed by a nonlinear inequality constraint which restricts the total moment arm of the links to an upper and lower boundaries. In this method there is no need to use this constraint and finally result also shows that total moment arm limited to two these boundaries.

KEYWORDS: CNS, balanced movement, inverse dynamics predictive dynamics, human motion simulation.

1. Introduction:

Multibody dynamics of human body subjected to an extensive area of researches contain robotics, biomechatronics, biomedical engineering, medicine and so on, because it can provide an approach to find some variables that are not possible to measure like: torques and internal forces of joints, stress exerted to joint's soft tissues. These mechanical parameters are so important to understand joint disease initiation and progression, like osteoarthritis [1,2]. In addition to pathological aspects simulation purposes are one of the major causes of human body modeling.

In order to know how the body postures varies during different movements to construct motion animation of human body, a model of whole human body dynamics applied to movement simulation process. Simulation and analysis of human movements commonly used for athletics in order to improve performance of the motion and so prevent injuries in cause of incorrect movements [3]. Some abnormalities accrued in parts of musculoskeletal system resulted in inaccurately function to muscle activation and control [4,5,6]. Therefore it is so important to know
that how the central nervous system (CNS) controls the body posture varies during different tasks.

Large number of degree of freedom is needed to biomechatronical modeling applied to human motion simulation more exactly and accurately. This need create a problem in analysis aspect and provide an efficiently from design viewpoint to have flexible system able to done complicated movements. On the other hand multiplicity of joint space variables (DOFs) causes model maneuverable and create redundancy problem. We face with the redundancy problem when the number of DOFs is more than needed to perform a task. This problem presented to robotic research too, in kinematics, dynamics and control aspects [7-10]. Human body models uses large number of DOF usually, to applying these models to motion simulation optimization-based approaches are good methods to overcome with the redundancy problem. Some of these techniques are applied to robotic manipulator models with redundant DOFs [9,11,12,13]. Optimization-based solutions are completely suitable to solve problem with large number of variables, because this method uses a few amount of data as inputs to result a large number of variables as output set. The input contains two set of constraints impose to motion simulation process: 1. Constraints obtained from motion dynamics and 2. Variety limitation of variables to be optimized. The second type used as inequality constraints and the first one contain some algebraic and differential equations.

CNS manage the task with the balanced movements, walking, running, sitting and lifting are good examples of tasks related to daily living activities which performed completely balanced with no thinking or decision making consciously. CNS uses an unknown algorithm to manage tasks unconsciously. Optimization-based simulation methods have performance analogous with CNS function caused balanced movements. These approaches used objective function description subjected to minimization process which is duality of CNS algorithm manner. On the other hand to simulate a movement as like as shape that biological system does, it assumed that optimization approach minimized the objective function considered that CNS try to minimize it too. Description of stability can be found in medicine and engineering as different meanings but these meanings follows joint goal. In engineering the stability has a mathematical definition commonly described by Lyapanov laws, according to this description a stable system has a minus energy performance called Lyapanov candidate function but stability index in medicine define as pain threshold. A stable system in engineering is which has convergence outputs resulted desire results and instability made outputs divergence. In medicine crossing the pain threshold result uncontrolled motions which CNS can't control musculoskeletal system to reach to the desire value. In optimization approach motion stability guaranteeing caused by constraints which restrict total moment arm (TMA) of links in each configuration.
between horizontal position of heel and toe [14,15]. In fact this constraint prevent of figurate postures will caused to falling to forward and backward. In this research we use an optimization-based algorithm named predictive dynamics [16]. With objective function consist of ankle torque summation during lifting time. In this novel approach inverse dynamics, joints torque limitation and joint ranges of motion are used as constraints to shape the motion as lifting movement. In this algorithm by and large two kinds of constraints are used. 1. The constraints which shape the simulated motion as lifting movement consist of two type constraints. 1-1. Kinematical constraints which formed motion like ones which determine initial and final position of box, body collision avoidance and constraints which guarantee moving up motion of box. These kinds named "kinematical governing constraints". 1-2. Inverse dynamics of system is a differential equation implemented as equality constraint to govern the dynamics of motion to simulation process, named "dynamic governing constrain". 2. the 2nd type named "bounder constraint" which limit the range of variation of variables to be optimized. This classification illustrated in figure1.

Ankle torque amplitude considered as stability index and the optimization algorithm tries to minimize integral of ankle torque squares during lifting time. A five DOF biomechatronical model of whole human body represented in part 2 obtained from kinematical modeling based on D-H method. Based on Lagrangian method dynamics of motion be formulated and results equation of motion named inverse dynamics. In part 3 simulation process is described and parts 4 and 5 present simulation results and conclusion remarks respectively.

2. Modeling
A planar model with 5DOF in sagittal plane utilized to represent kinematics and dynamic of human body. All the limbs as shank, thigh, spine, arm and forearm subjected to modeling and considered as rigid bars with mass points at center of mass of each link which named: \( l_1, l_2, l_3, l_4, l_5 \) respectively. For human major joints as ankle, knee, hip, shoulder and elbow had considered joint angles to figure human body posture and represented by the names: \( q_1, q_2, q_3, q_4, q_5 \) respectively. The box assumed jointed to human body at the wrist joint with a constant orientation. Forward kinematics of this open kinematic chain represents planar position of end-effector (wrist) according to joints angles, and be calculated based on D-H method as will be define [17].

2.1 Forward Kinematics

At first allocate coordinates at each links then calculate the relational rotation of each adjacent coordinate system and finally obtain forward kinematics by post multiply the translational matrixes. Biomechatronical models of human body with coordination systems attached to limbs illustrated by figure. 2:

![Figure 2. 5DOF model of human body with coordination systems attached to each link.](image)

The \((x_0, y_0)\) is global coordinate allocate to ankle joint. The D-H parameters related to coordinates systems fixed to links represented in Table1. These parameters calculated from model represented in figure1.
The figure 3 shows that how the D-H parameters named and choose for two adjacent links.

![Diagram showing D-H parameters](image)

Figure 3. Numbering adjacent joints and bodies to obtain D-H parameters [handbook of robotics].

D-H parameters helps to calculate translational matrixes related to adjacent coordinates calculated as (1).

\[
i_{i-1}^{-1}T = \begin{bmatrix}
C\theta_i & -S\theta_i & 0 & a_i \\
S\theta_iC\alpha_i & C\theta_iC\alpha_i & -S\alpha_i & -S\alpha_id_i \\
S\theta_iS\alpha_i & C\theta_iS\alpha_i & C\alpha_i & C\alpha_id_i \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(1)

In (1) \(C\theta_i, S\theta_i\) represent \(\cos \theta_i, \sin \theta_i\), and \(C\alpha_i, S\alpha_i\) are symbol of \(\cos \alpha_i, \sin \alpha_i\). Finally by using transformation matrixes \(i_{i-1}^{-1}T\) we can calculate forward kinematics \(0_6T\).
as a matrix which interprets the motion of wrist in global coordination system connected to ground as (2).

\[ q^T_{6} = q^T_{1} \cdot q^T_{2} \cdot q^T_{3} \cdot q^T_{4} \cdot q^T_{5} \cdot q^T_{6} \] (2)

2.2 Inverse dynamics

Human body dynamics commonly model as open kinematics chain like robot manipulators as mentioned before [19,20], so the method used to modeling the dynamics of motion of this kinematical chain is like ones used for robotic manipulators. In this approach it's needed to calculate system's kinetic and potential energies, and finally by minimizing the integral of system's energy function the equations which govern the dynamics of motion will be obtained. The kinetic energy of the model presented before define as bellow:

\[ K = \frac{1}{2} \dot{q}^T D(q) \dot{q} \] (3)

\[ D(q) = \sum_{i=1}^{5} (m_i J_{vc_i}^T J_{vc_i} + J_{\omega_i}^T R_i^0 l_i R_i^0) \] (4)

In equation \( \dot{q} \) is a 5 × 1 vector of angular velocities of joints, and \( \dot{q}^T \) is transpose matrix of \( \dot{q} \), and \( D(q) \) is a 5 × 5 matrix related to mass and inertial properties of the model. \( J_{vc_i} \), \( J_{\omega_i} \) are 3 × 5 Jacobin matrix which translate linear and angular velocities of COM of i’th link to universal coordinate system respectively. \( R_i^0 \) is rotational transformation matrix which interpret the orientation of i’th links from its coordinate to ground coordinate. \( m_i \) is mass of i’th link. By considering g as gravitational force vector, and \( r_{ci} \) as height of i’th link’s COM from ankle position, System’s potential energy describes as bellow:

\[ V = \sum_{i=1}^{5} (m_i g^T r_{ci}) \] (5)

The system's energy function which called Lagrangian calculated as bellow:

\[ L = K - V = \frac{1}{2} \dot{q}^T D(q) \dot{q} - \sum_{i=1}^{5} (m_i g^T r_{ci}) \] (6)

Total system energy named E defines as integral of system's lagrangian during lifting time interval[0 T], as bellow:
Lagrangian formulation represented in (8) is an analytical method to minimizing the integral \( E \) to results equation of motion. In (8) \( \Gamma \) is generalized joints torque vector inserted to this formulation as an external generalized force vector. Finally general form of motion equations will be obtains as(9).

\[
D(q)\ddot{q} + C(q, \dot{q})\dot{q} + V(q) = \Gamma
\]  

(9)

In (9) \( C(q, \dot{q}) \) is a term related to centrifugal and coriolis forces and \( V(q) \) is gravitational forces vector, these terms calculates as bellow:

\[
C(q, \dot{q}) = \dot{D}(q) - \frac{1}{2} \dot{q}^T \left( \frac{\partial D(q)}{\partial q} \right)
\]  

(10)

\[
V(q) = \left( \frac{\partial V}{\partial q} \right)^T
\]  

(11)

Generalized joint torque represented in (9) divided in two parts: 1. torques resulted in muscle forces and 2. torques due to the box load exerted on wrist. These kinds obtain as (12):

\[
\Gamma = \tau_{\text{muscle}} - \tau_{\text{box}} \quad ; \quad \tau_{\text{box}} = J^T( m_{\text{box}} g^T)
\]  

(12)

In (12) \( J^T \) is transpose of Jacobean matrix which project box load to joints \( m_{\text{box}} \) is box mass and \( g^T \) is transpose of gravity force vector.

3. Simulation process

In this paper lifting movement simulation considered as optimization problem which CNS do either. In this problem an objective function subjected to be optimized with some constraints which limit the motions boundary to a feasible range to construct motion naturally. In other words it's being assumed that CNS try to minimize a particular function value to perform each task, and musculoskeletal system impose some constraints to the motion too. Predictive dynamics is a novel approach used to motion simulation [16, 23]; it implements inverse dynamics as a major constraint to modeling the dynamics of the motion in the simulation process. The joints torques and angles are the optimization process variables, so by using this method we can obtain
joint angles and torques as output according to task constraints used as inputs. Simulation elements are described in below sections.

3.1 Objective function

Considering the lifting task as a simple inverted pendulum motion, can represents an insight to motion stability analysis. In other hand If lifting motion modeled as a inverted pendulum (fig.4) [21] we can claim that magnitude of pendulum joints torque has relation to amount of deviation from stability position ($\theta = 0^\circ$) directly. Therefore we can use of a particular function which constructed in term of ankle torque as motion stability index. This function is integral of ankle torque squares in each time sequence (13).

$$Y_{wrist}(t) = y(q(t))$$  \hspace{1cm} (14)

In each time sequence $Y_{wrist}(t)$should be higher than previous sequence:

3.2 Constraints

The constraints used in this research are: joints torques and angles limitations, initial and final position of box, elevating constraint, inverse dynamics, and body collision avoidance constraint used for prevent of collision box with body. Vertical position of wrist (14) is a function of joint angles $q(t)$ calculated from forward kinematics (1):

$$Y_{wrist}(t) = y(q(t))$$  \hspace{1cm} (14)
\[ y_{wrist}(i) > y_{wrist}(i - 1) \]  

(15)

So the elevating constraint defined by:

\[ y(q(t - 1)) - y(q(t)) < 0 \]  

(16)

In fact elevating constraint guaranteed moving up motion of box during time sequences. The equality constraints which impose initial and final position of box to optimization process are defined by (17).

Which \( x_{wrist}(t) \) and \( y_{wrist}(t) \) are respectively horizontal and vertical position of wrist considered fixed to box. According to fourfold constraints set (16) should be placed at initial position \( x_{initial}, y_{initial} \) and final position \( x_{final}, y_{final} \) of box at \( t = 0 \) and \( t = T \) respectively. Inverse dynamics constraint express as bellow:

\[ \tau - \tau_{invd} = 0 ; \tau_{invd} = f(q, t) \]  

(18)

In equation (18) \( \tau \) is joints torque vector should be predicted, and \( \tau_{invd} \) is joints torque vector obtained from inverse dynamics. Body collision avoidance implemented in this simulation is a systematic method to check the penetration value of the box into the body in each iteration of optimization process to determine horizontal position of the box to collision avoidance adaptively. This process described as bellow briefly:

The collision avoidance considered in optimization process as a constraint to prevent penetration of box with the body. It’s inequality constraint and defined as a term of sufficient horizontal distance \( dx \) which wrist should move to prevent collision box with the body.

Distance which wrist should move to arrive to horizontal boundary position \( X_{boundary} \) represent by \( dx \), and boundary position is a horizontal position of wrist which box edge touch the body. \( X_{wrist_d} \) is desire horizontal position of wrist which should be greater than \( X_{boundary} \). \( X_{wrist_{pr}} \) is horizontal position of wrist obtained from optimization algorithm in current iteration.

According to Figure 5. Penetration value of the box in the body \( d \) would be obtained through equation (20), \( X_{body} \) and \( X_{edge} \) obtain from body line and box line respectively.
Maximum penetration value determine the horizontal distance which wrist should move to arrive to boundary position, $d$ is penetration index so $dx$ is maximum value of $d$.

4. Results

The optimization process designed for 10 evenly distributed time sequences. By considering 5 control points and 10 joint torques values, we have 75 variables subjected to be optimized. Inertial properties considered as data used previously [22]. The experimental data used in [23] implemented to validate the simulation process. Subjected population of experiment had a average height 5’7” and average weight of 143 lbs, the mean age of participants was 34 years. Lifting task parameters presented in table 2.

<table>
<thead>
<tr>
<th>Lifting parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box depth</td>
<td>0.370 (m)</td>
</tr>
<tr>
<td>Box height</td>
<td>0.365 (m)</td>
</tr>
<tr>
<td>Box weight</td>
<td>9 (kg)</td>
</tr>
<tr>
<td>Initial height</td>
<td>0.365 (m)</td>
</tr>
<tr>
<td>Final height</td>
<td>1.37 (m)</td>
</tr>
<tr>
<td>Initial horizontal position</td>
<td>0.490 (m)</td>
</tr>
<tr>
<td>Final horizontal position</td>
<td>0.460 (m)</td>
</tr>
<tr>
<td>Lifting time duration</td>
<td>1.2 (sec)</td>
</tr>
</tbody>
</table>

Total moment arm (TMA) of all the links are calculated as (22) it's calculated from the moments respect to all of the links weight for each configuration related to time sequence.
$m_{\text{all}}$ is total weight of body and $x_i(t)$ is horizontal position of $i^{th}$ links at time $t$, and $N$ is number of links. Optimized joint angles show that how the body posture varies during lifting task, it illustrated in figure 6.

Figure 6. Human body postures during lifting task.

Joints torque profiles shows in figure7.
Ankle torque (N.m)

Knee torque (N.m)

Hip torque (N.m)

Shoulder torque (N.m)
Joint angles profiles are presented in figure 9. by comparison between predicted and experimental results. Solid line is predicted and dashed line shows experimental results.
Figure 8. Joints angles profiles result in optimization process in comparison with experimental results.

TMA calculated in (22) plotted in figure 9 For all the time sequences. Dashed lines show the upper and lower boundary of region with balanced motion. In fact these are the horizontal position of heel and toe in sagittal plane.

Figure 9. TMA values during lifting time with its boundaries and relation with heel and toe.

5. Discussion

Simulation process implemented biomechatronical 5DOF model of human body to simulate lifting motion by using predictive dynamics approach. The constraints applied to these processes limit motion space of movements to a region that human limbs move through it. One major constraint named inverse dynamics exerts the dynamics of the motion to the simulation process and finally objective function minimization shapes the posture variation form. 10 time segments with 100 variables considered to optimization process. Figure 6 shows that posture variation does in a natural shape with box uprising motion, accurate initial and final position of box and no box collision to the body and Figure 8 Compare the simulation process results with experimental results due to the CNS, on the other hand figure 8 shows the optimization approach in contrast with CNS action to manage the body posture. Predictive angles of ankle, knee and hip joints has good compatibility with experimental results, and results for elbow is good to some extend either. But against these joints, the shoulder's results hasn't good correlation with the experimental results. It caused because of shoulder complex structure which needs to modeling more exactly and considering suitable and sufficient constraints.
Figure 9 illustrate the TMA values during lifting time and its boundaries, according to figure 9. Lifting movement performed completely balanced because TMA have a value between upper and lower boundaries. In other words minimizing summation of ankle torque can guarantee motion balancing.

According to figure 6 it is concluded that: in the sequences 1 to 6, the box lifted by action of joints of lower limbs: ankle, knee and hip. In the remained sequences lifting motion continued by action of shoulder and elbow joints. In other hand this simulation approach is able to simulate leg lift (squat) motion accurately. It can be used to construction the skillful movement for athletics based of properties of their bodies which presented in table II and lifting task parameters presented in table I. it can also be implemented to improvement the performance of athletic movements and injury presentation.

In the sequences 6 to 10 the profile of ankle torque and TMA of links has the same trends. It concluded that in standing posture, the ankle torque has a direct relation with TMA of links. So by minimizing the ankle torque in standing postures the TMA also will be minimized. This strategy can be used to guarantee balancing of motion in standing postures.

References


