A spatial dynamic model for the simulation of human upper limb

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Abstract In many assembly systems, ergonomics can have a great impact on productivity. To evaluate ergonomics, human energy expenditure can be used as an index. In this paper, an energy expenditure spatial arm model is presented and then compared to a reference planar model. For that purpose, it has been developed both a dynamic and metabolic model of a spatial human arm. It will be shown that the spatial model extends the planar one.

1 Introduction

When designing assembly tasks, it is important to improve ergonomics to increase throughput. In the literature, different indexes have been proposed to evaluate operator comfort. A recent development has proposed an index for quantifying the latter, based on energy (metabolic) expenditure [3]. To evaluate the latter, it is necessary to develop a mathematical model that gives the Energy Expenditure (EE) for a given task. Focusing on the upper limb, it is necessary to develop a model that predicts the metabolic cost for a given trajectory of the hand.

Some simplified models have been developed in the literature. Analytical models such as [1, 14, 15] built a 2 degree of freedom (DoF) model in which EE was minimized to predict human trajectories. In [9] a model based on fitting experimental data was developed. However, all reported models do not allow us to consider complex (spatial) tasks. In this work, an EE model of a spatial human upper limb is developed starting from the planar model proposed by [1]. It is chosen to use a 4 DoF model because is a trade-off between energy evaluation and simplicity. In fact, a more complex model asks to provide trajectory of every single DoF that may be difficult to know *a priori*. A complete arm with fingers has 7 DoF for the arm and 27 for the hand.

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The paper is organized as follows: Section 2 presents the kinematic, dynamic, and metabolic model; Section 3 compares the spatial and planar models of the upper limb: finally, conclusions are drawn in Section 4.

2 Mathematical models

2.1 Kinematic model

To simplify the model, the hand is considered as a lumped mass at the tip of the forearm. For that instance, the kinematic model of the upper limb has 4 DoF against the usual 5, such as presented in [12]. In particular, the pronosupination of the forearm is neglected, since the only contribution of torque in that axis is due to the first moment of inertia of the forearm. Since the center of mass is near the axis, the torque (and so the metabolic power) will be low compared to the other joints. The spatial model of the human arm is developed as a 4 DoF system. In fact, the human arm, without considering the hand, can be represented mainly via a spherical joint at the shoulder and via a rotational joint at the elbow. As a result, considered movements are:

1. Abduction/adduction of shoulder in the horizontal plane
2. Flexion/Extension of shoulder in the sagittal plane
3. Rotation along the arm
4. Flexion/Extension of the forearm

Table 1: DH table of a human arm.

T_{ij}	α_{i-1} [deg]	a_{i-1}	θ_i	d_i
T_{10}	0	0	θ_1	0
T_{21}	-90	0	θ_2	0
T_{32}	90	0	θ_3	d_3
T_{43}	90	0	θ_4	0
T_{54}	-90	0	0	d_5

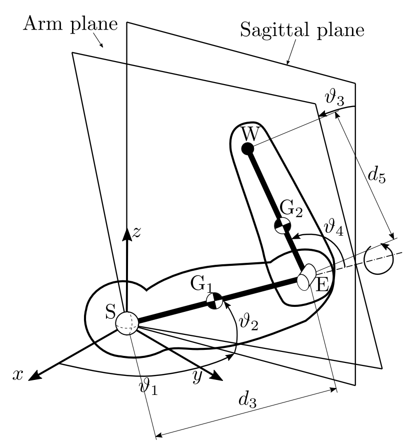

Fig. 1: Kinematic reference scheme, where W is the wrist, E the elbow, and S the shoulder.

From a kinematics point of view, the system is composed of 4 revolute joints, where the first three joints are concurrent in a single point to simulate the shoulder. The first two links are fictitious and are used only to obtain a spherical joint. As a result, it is possible to apply the Denavit-Hartenberg approach to define an equivalent manipulator made of revolute joints. In Table 1 are reported the Denavit-Hartenberg parameters. This notation is useful for simplifying the calculation of the parameters that define the relative transformation matrices. The corresponding scheme of the equivalent manipulator is reported in Figure 1.

The planar model of the arm can be retrieved from the spatial model by removing the two joints in the shoulder that does not lie on the sagittal plane.

2.2 Dynamic model

The inverse dynamics model of the arm is calculated from the Lagrange formulation.

$$\frac{d}{dt}\left(\frac{\delta\mathcal{L}(t)}{\delta\underline{\dot{q}}(t)}\right)-\frac{\delta\mathcal{L}(t)}{\delta\underline{q}(t)}=\underline{\tau}(t) \quad , \quad \mathcal{L}(t)=\mathcal{T}(t)-\mathcal{U}(t) \tag{1}$$

where $\underline{q}$ is the vector of the joint variables, $\underline{\dot{q}}$ is the vector of the joint speeds, $\underline{\tau}$ is the vector of the joint torques, $\mathcal{T}$ is the total kinetic energy, $\mathcal{U}$ is the total potential energy, and $\mathcal{L}$ is the Lagrangian. Equation 1 terms depend on time t. However, for the sake of simplicity, from now on time dependency is omitted from equations. Substituting the expression of the kinetic and potential energy into Equation 1, the general form for the dynamics of a manipulator is:

$$\boldsymbol{M}(\underline{q})\underline{\ddot{q}}+\boldsymbol{C}(\underline{q},\underline{\dot{q}})\underline{\dot{q}}+\underline{g}(\underline{q})=\underline{\tau} \tag{2}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$, and $\underline{g}$ are respectively inertia, Coriolis matrix and gravity vector, $\underline{\ddot{q}}$ is the vector of joint accelerations.

It should be noted that the matrix $\boldsymbol{M}$ depends both on the inertial properties of the arm and the forearm and on the lumped mass that represents the hand and any object it holds. Since the lumped mass is fixed on the forearm, the $\boldsymbol{M}$ needs to be updated every time an object is picked or placed. To do so, the forearm inertial properties are considered to be fixed, while the contribution of the lumped mass is calculated by means of the Huygens-Steiner theorem.

The joint trajectories, described by the vectors $\underline{q}$, $\underline{\dot{q}}$, and $\underline{\ddot{q}}$, depend on the task to be performed. In fact, in our work the trajectories are considered known, so the joint torques $\underline{\tau}$ can be calculated.

2.3 Metabolic model

Once the joint torques are obtained, it is possible to calculate the metabolic expenditure. For this purpose, the Alexander model is followed [1]. The procedure consists first of the calculation of the isometric moment τ_{iso}, starting from the joint torque τ, that is the moment the muscle would exert if contracting isometrically.

$$\tau_{\text{iso}} = \tau \frac{\dot{\theta}_{\text{max}} + G\dot{\theta}}{\dot{\theta}_{\text{max}} - \dot{\theta}} \qquad \text{if doing positive work} \tag{3}$$

$$\tau_{\text{iso}} = \tau \frac{\dot{\theta}_{\text{max}} - 7.6G\dot{\theta}}{\dot{\theta}_{\text{max}} - 13.6G\dot{\theta} - 0.8\dot{\theta}} \qquad \text{if doing negative work} \tag{4}$$

The sign of the work depends on the fact that the joint velocity and the joint torque have the same (positive) or different (negative) sign. The factor G is a constant that depends on muscle velocity $\dot{\theta}$. The former is assumed equal to 4 for moderate fast muscles. The velocity $\dot{\theta}_{\text{max}}$ is the maximum reachable joint speed. It is considered equal to 22 rad/s for flexion and 28 rad/s for extension, as proposed in [13].

Once the isometric moment is obtained, the metabolic power consumption is calculated as follows.

$$P = \tau_{\text{iso}}\dot{\theta}_{\text{max}}\Phi\left(\dot{\theta}/\dot{\theta}_{\text{max}}\right) \tag{5}$$

Where Φ is a function of the ratio between the actual and the maximum joint velocity:

$$\Phi\left(\dot{\theta}/\dot{\theta}_{\text{max}}\right) = 0.23 - 0.16\exp\left(-8\dot{\theta}/\dot{\theta}_{\text{max}}\right) \qquad \text{if doing pos. work} \tag{6}$$

$$\Phi\left(\dot{\theta}/\dot{\theta}_{\text{max}}\right) = 0.01 - 0.11\dot{\theta}/\dot{\theta}_{\text{max}} + 0.06\exp\left(23\dot{\theta}/\dot{\theta}_{\text{max}}\right) \qquad \text{if doing neg. work} \tag{7}$$

Finally, the overall metabolic energy expenditure can be calculated as:

$$EE = \int_0^T P(t)dt \tag{8}$$

where T is the total movement time. Equations 5 and 8 are general and therefore can be applied to both the planar and the spatial model of the upper limb. In fact, Equation 3 calculates the moment of the muscles that equals the corresponding joint, so there is no indication of which direction such moment is applied, hence the method is general.

3 Comparison of spatial model with a planar model

The model presented in Section 2 is now compared to a reference planar model, the Alexander model [1].

To do so, in the following the models are compared in two situations: (a) a movement of the wrist in the sagittal plane and (b) a movement of the wrist in the horizontal plane. For plane names, see Figure 3. The trajectory is planned as point-to-point movements by means of a five-degree polynomial law, in accordance with the neuroscience results [10].

All simulations are carried out using standard normal weight male data (that is, 1.78 m height and 72 kg for European [2]). For the inertial data different model where proposed in the literature [6, 11, 5, 8, 7]. According to a recent comparison, such models can be considered equivalent [4]. In this work, it is used the Dempster model [6] for its easier implementation. The inertial properties of the human arm are resumed in Table 2, where the reported dimensions are shown in Figure 2. For simplicity, inertia off-diagonal terms are neglected. In the forearm parameters, the mass of the hand is included.

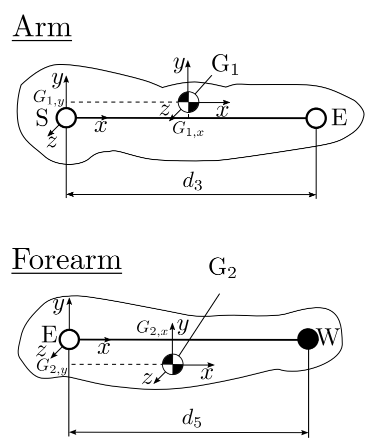

Fig. 2: Scheme for arm and forearm parameter

3.1 Movement in the sagittal plane

The trajectory of the wrist is defined in the sagittal plane by the starting and ending positions listed in Table 3. The movement time *T* is fixed at 1 s.

The two models both delivered an EE of 13.3 J, demonstrating the validity of the 2 DoF simplification for this case. The metabolic power is reported in Figure 4. This result is expected: in fact, on the sagittal plane the only joints that are providing an active movement are the ones of the 2 DoF model; in the 4 DoF model, the joints of the shoulder that lie on the sagittal plane are inactive as there are no movements off-plane.

Table 2: Dynamic parameter used for the human arm model. G_x and G_y are respectively the positions of the center of mass of the link along the x and y coordinate. It is considered $G_z = 0$.

Parameter	Arm	Forearm
d_3/ d_5 [mm]	311	266
Mass [kg]	2.03	1.2
I_{xx} [kg·m^2]	4.8 $\cdot 10^{-4}$	2.0 $\cdot 10^{-4}$
I_{yy} [kg·m^2]	1.9 $\cdot 10^{-2}$	7.8 $\cdot 10^{-3}$
I_{zz} [kg·m^2]	1.9 $\cdot 10^{-2}$	7.8 $\cdot 10^{-3}$
G_x [mm]	131	114
G_y [mm]	0	0

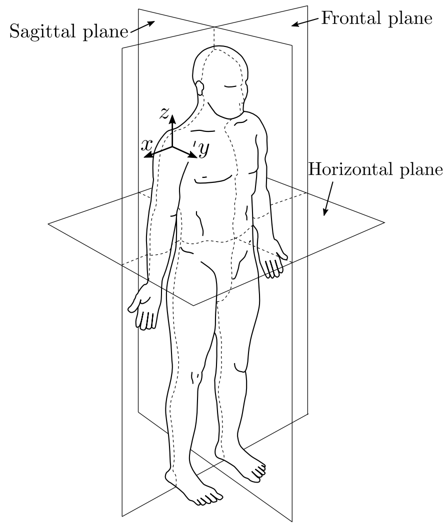

Fig. 3: Names of reference anatomical planes.

Table 3: Initial and final points of the task. The reference frame is located in the center of the shoulder, as shown in Figure 3.

Coordinate	Initial P.	Final P.
x [mm]	0	0
y [mm]	300	300
z [mm]	-300	0

3.2 Spatial movement

However, most movements of the human arm are not in the sagittal plane. In fact, if assembly tasks are considered, the objects are mostly placed on a horizontal plane. In such a condition, the 2 DoF planar model is of no use, since the movements on the sagittal plane are limited.

Using the spatial model, the metabolic expenditure is predicted for a Point-to-Point spatial trajectory. The extreme points are reported in Table 4. The points are chosen to simulate an assembly task of transporting an object between two points on a horizontal plane.

In Table 5 the results for different payloads transported are reported. In particular, three cases have been simulated: without payload, with a payload of 2 kg, and one of 5 kg.

The metabolic power, for the no payload case is reported in Figure 5.

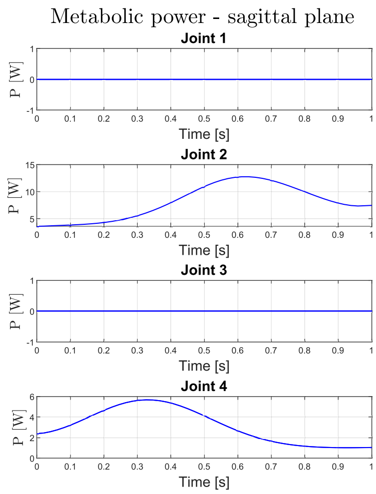

Fig. 4: Metabolic power for movement in the sagittal plane. 2 DoF and 4 DoF model give the same results. The first and the third joint have null power because they are not involved in the movement.

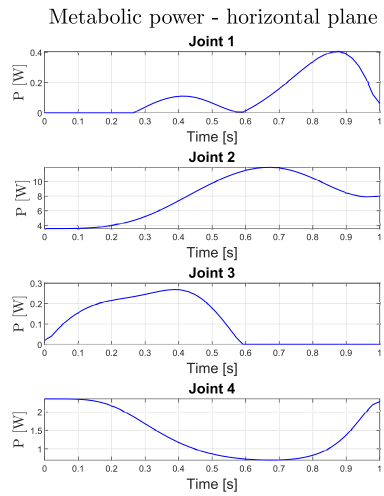

Fig. 5: Metabolic power for movement in the horizontal plane for the 4 DoF model in the case of no payload. It has to be underlined that all joints contribute to the overall expenditure.

Table 4: Initial and final points of the task.

Coordinate	Initial P.	Final P.
x [mm]	0	300
y [mm]	300	300
z [mm]	-300	-300

Table 5: Results of the simulations. Using the same points, three different payloads were studied.

Payload [kg]	Metabolic expenditure [J]
0	9.4
2	21.8
5	40.4

4 Conclusions

In this paper, a spatial model for predicting the metabolic expenditure of a human arm has been presented. It is an extension of a reference planar model. The 4 DoF model is easily implementable since it relies on the well-known dynamic equation. The consistency of the spatial (4 DoF) and planar (2 DoF) models in the Energy Expenditure for movements on the sagittal plane show the validity of the 4 DoF model, which in turn improves the possible movement simulations by allowing sagittal off-plane displacements.

In future works, the 4 DoF model will be validated through metabolic measurements with human subjects.

The 4 DoF model is useful in industrial applications, such as assembly tasks, in which the movements of the upper limbs are not confined to the sagittal plane, therefore they cannot be simulated with a simpler 2 DoF model.

The model can be used to improve ergonomics during the execution of assembly tasks, with the aim of minimizing metabolic expenditure.

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