DTU Autonomous Systems
Department of Elektro

A Simulation Study: Developing an EMG-Based Quasi-Static Controller for Stroke Rehabilitation

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Approval

This thesis has been prepared over six months at the Section for Indoor Climate, Department of Civil Engineering, at the Technical University of Denmark, DTU, in partial fulfilment for the degree Master of Science in Engineering, MSc Eng.

It is assumed that the reader has a basic knowledge in the areas of statistics.

Nuria Fe Garcia del Valle - s202421

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Abstract

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Nuria Fe Garcia del Valle, MSc Civil Engineering, DTU
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Contents

0.1 Dynamic Simulation of the Arm: A Comprehensive Model for Musculoskeletal Dynamics

The study of human mobility has benefited greatly from the development of musculoskeletal modeling, which is now a crucial tool for comprehending the dynamics of the human body. Multibody models have historically proved helpful in resolving inverse dynamic issues, particularly in the analysis of human gait and arm movement (please add paper citation for more information). The main disadvantage of these inverse dynamic techniques is the need to gather data from participants who are actively doing the required movement.

Moving away from conventional techniques, muscle-driven forward dynamics have allowed the simulation of innovative and fictional movements that would resemble impaired movements, such as those of stroke survivors. These simulations have practical applications in fields like rehabilitation and motor control research. In [1] the DAS allowed to test controllers and command interfaces with a human user in the loop. For this project, forward dynamics simulation will be used to test the hypothesis for EMG-inspired PD control of Functional Electrical Stimulation (FES) in stroke rehabilitation.

A summary of the musculoskeletal dynamics, including topics like multibody dynamics, muscle contraction dynamics, and muscle activation dynamics, will be covered in this section. Then, an explanation of the forward-dynamic implicit formulation will be given. This formulation is proven to improve the computational time required for modeling the dynamics with only an RMS error of 0.11 degrees in joint angles when running at real-time speed for a gait simulation with a prosthetic foot and ankle [1].

Overall, the Dynamic Arm Simulator (DAS) offers a robust framework for the simulation of human arm movements. It is implemented as a MATLAB Mex function that contains the system dynamics and other functions, making it accessible via a MATLAB function interface and flexible and adaptable for various applications.

An extended overview of the DAS model follows in the sections below.

0.1.1 Structural Overview

Links and Degrees of Freedom

- **7 Links**: Includes thorax, clavicle, scapula, humerus, ulna, radius, and hand. Figure 1 shows a colour-coded of the different links.

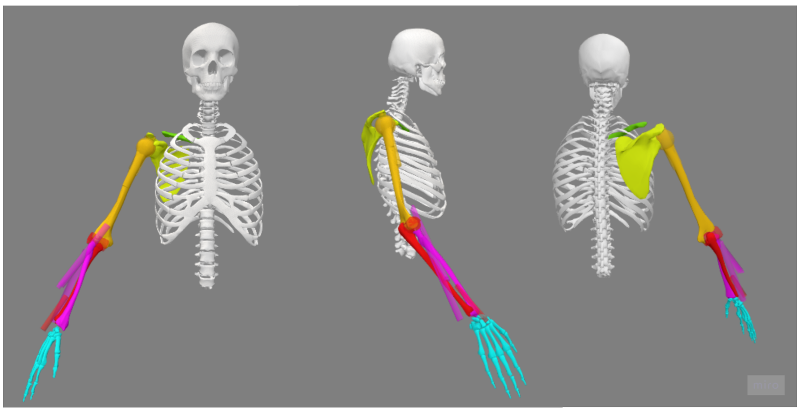

Figure 1: Dynamic Arm Simulator 7 Links. Green: Clavicle, Yellow: Scapula, Orange: humerus, Red: Ulna, Purple: Radius, Blue: hand

- **11 Degrees of Freedom**: These are comprised of 2 orthogonal hinges at specific joints including the sterno-clavicular, acromio-clavicular, and Gh joints, elbow flexion-extension, and forearm pronation-supination. The range of motion of the different DoF is shown in Table 1.
  Inspired on [2] throughout this project the arm configuration is described in 5 DoF: plane of elevation, angle of elevation, internal rotation, elbow flexion and forearm pronation following the recommendation on [3]. These angles were restricted in order to ensure correct wrapping of muscles in the model, the final values are show in Figure 2.

Table 1: *Angular limits for each degree of freedom (in degrees)*: The arm mechanism consists of the following skeletal entities SC: Sternoclavicular joint, AC: Acromioclavicular joint, Gh: Glenohumeral joint, EL: Elbow, PS: Forearm Pronation and Supination.

Degree of Freedom	**Min Angle (degrees)**	**Max Angle (degrees)**
SC y	-65.00	-19.00
SC z	5.00	30.00
SC x	0.00	83.00
AC y	33.00	69.00
AC z	-22.00	20.00
AC x	-17.00	18.00
Gh y	-170.00	175.00
Gh z	-30.00	84.00
Gh yy	-177.00	179.00
EL x	5.00	141.00
PS y	5.00	160.00

TABLE I
ANGULAR LIMITS FOR EACH DEGREE OF FREEDOM (IN DEGREES)

Degree of freedom	Min angle	Max angle
Plane of elevation	-90	90
Angle of elevation	5	90
Internal rotation	-55	70
Elbow flexion	5	140
Forearm pronation	5	160

Figure 2: Angular limits for each degree of freedom (in degrees) for the arm configuration following [3]. Table from [2]

- **22 Muscles and 138 Muscle Elements:** The real-time model consists of 22 muscles and muscle components in total. In order to accurately represent the mechanical line of action of each member, muscles are modeled using the fewest amount of parts possible. The table in Figure 4 displays the amount of elements utilized for each muscle as well as the degrees of freedom that each muscle crosses

TABLE II
MUSCLES INCLUDED IN REAL-TIME MODEL, SHOWING JOINTS CROSSED BY EACH MUSCLE (GLENO-HUMERAL: GH, HUMERO-ULNAR: HU, OR RADIO-ULNAR: RU) AND NUMBER OF ELEMENTS USED TO MODEL MUSCLE

Muscle	Joints	No. of elements
Deltoid, scapular part	GH	11
Deltoid, clavicular part	GH	4
Coracobrachialis	GH	3
Infraspinatus	GH	6
Teres minor	GH	3
Teres major	GH	4
Supraspinatus	GH	4
Subscapularis	GH	11
Biceps, long head	GH, HU and RU	1
Biceps, short head	GH, HU and RU	2
Triceps, long head	GH and HU	4
Latissimus dorsi	GH	6
Pectoralis major, thoracic part	GH	6
Pectoralis major, clavicular part	GH	2
Triceps, medial head	HU	5
Brachialis	HU	7
Brachioradialis	HU and RU	3
Pronator teres	HU and RU	2
Supinator	HU and RU	5
Pronator quadratus	RU	3
Triceps, lateral head	HU	5
Anconeus	HU	5

Figure 3: Muscle elements and degrees of freedom crossed by the muscles. Table from [2]

0.1.2 Musculoskeletal Dynamics

The dynamics governing the musculoskeletal system must be thoroughly understood in order to research it. This analysis is divided into three interconnected components: multibody dynamics, muscle activation dynamics, and muscle contraction dynamics. Multibody dynamics allows us to represent the system as a collection of interconnected rigid or flexible bodies, focusing on the kinematic constraints that guide motion. Muscle contraction dynamics describes the complex interactions of the muscle fibers and surrounding elements using the three-element Hill-type model, while muscle activation dynamics explores how neural signals translate into muscle actions.

The thorough analysis of the musculoskeletal dynamics is described in [1]. In this section a summary of each most relevant section is presents with specific focus on the project's application.

State variables

It is necessary to define the state variables before examining the various dynamics of the multibody system.

The multibody model has 298 state variables. It is represented with the letter ***x***:

- 11 angles, q
- 11 angular velocities, $\dot{q}$
- 138 muscle contractile element (CE) lengths, L_{CE}
- 138 muscle active states, a

Multibody dynamics
Multibody dynamics is used to study the motion and forces acting on the musculoskeletal system as it is identified as a system composed of interconnected rigid or flexible bodies.

Generalized coordinates are used to simplify the description of the system. As a result, the configuration of the system can be represented using the minimum number of coordinates to described the position and orientation.

Generalized coordinates, are often denoted by *q*. They are set of independent parameters that define the configuration of the system. In the DAS *q* represents the 11 joint angles.

The equations of motion for a multibody system can be expressed in the following matrix form ([4]):

$$M(q) * \ddot{q} + B(q, \dot{q}) = \tau \tag{1}$$

Where,

- $\ddot{q}$ is the vector of generalized accelerations
- $M(q)$ is the mass matrix that describes the inertia of the system. It relates the acceleration of *q* to the generalized forces.
- $B(q, \dot{q})$ is the matrix that described Coriolis and centrifugal forces that arise from the motion of the bodies in the system. Moreover, it contains gravity and other passive forces.
- τ is the generalized forces vector. In the case of DAS it represents the forces generated by muscles according to the muscle contraction and activation dynamics.

Forward dynamics is used to predict the motion of a multibody system based on its initial conditions and known forces. As a result Equation 1 is solved to the generalized accelerations $\ddot{q}$.

$$\ddot{q} = M(q)^{-1}(\tau - B(q, \dot{q})) \tag{2}$$

The inverse of the mass matrix, M, is a critical component, as the simulation will not be possible if its singular. This singularity is quite common in musculoskeletal systems due to small mass and moment of inertia of body segments.

Moreover, elements of B can present high stiffness and damping, leading to high eigenvalues of the Jacobian matrix that correspond to fast-changing components of the system. These high stiffness and high damping lead to oscillatory behaviours within the system. The presence of stiffness, originates from the ligaments and tendons having highly nonlinear mechanical properties (zero stiffness when unloaded, high stiffness when maximally loaded).

To counteract the stiff system, standard numerical methods, such as Euler method, require small time steps.

Muscle contraction dynamics
The muscle contraction dynamics is based on the three-element Hill-type model. It represents the muscle fibers (CE: contractile element), the tendon and force transmitting tissue (SEE: series elastic element), and the passive elastic tissue surrounding the muscle fibers (PEE: passive elastic element).

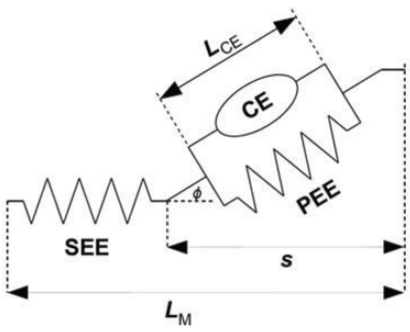

Figure 4: Three-element muscle model. CE: contractile element, SEE: series elastic element, PEE: parallel elastic element, Pennation angle ϕ: Angle between the muscle fiber in the CE and the line of action of the muscle, s state variable for the muscle contraction dynamics [1]

The contractile force is calculated by the multiplicative interaction of the maximal isometric force, the activation, the fiber length and the fiber length velocity, respectively represented in the formula below:

$$F_{CE} = F_{max} * a * f_{FL}(L_{CE}) * f_{FV}(\dot{L_{CE}}) \tag{3}$$

The series and parallel elastic elements are represented by passive force-length relationships.

$$F_{SEE} = f_{SEE}(L_M - L_{CE} * cos(\phi)) \tag{4}$$

$$F_{PEE} = f_{PEE}(L_{CE}) \tag{5}$$

The force balance equation following Figure 4 is equal to:

$$(F_{CE} + F_{PEE}) * cos(\phi) - F_{SEE} = 0 \tag{6}$$

The differential equation for the state variable L_{CE} is defined by Equation 6.

Muscle activation dynamics
The nervous system sends a neural excitation $u(t)$ as a control signal into the muscle that changes the activation via a first-order nonlinear activation-deactivation process. This is because the activation a, also called *active state* cannot be directly controlled by the nervous system. The muscle activation of a muscle, a, is formulated as:

$$\dot{a} = (u - a)(c_1 u + c_2) \tag{7}$$

,

where $c_1 + c_2$ is the rate constant for activation and c_2 is the rate constant for deactivation, typically in the range of 20-50 s^{-1} [1].

Combining Equation 1, Equation 6 and Equation 7 an implicit state equation for musculoskeletal dynamics can be formulated.

0.1.3 Forward Dynamics for implicit state equation

0.1.4 Functionalities

1 Implementation

Table 1.1: Comparison of Two Simulation Studies

Developing a Quasi-Static Controller for Paralyzed Human Arm	Developing an EMG-Based Quasi-Static Controller for Stroke Reaching Rehabilitation
Focused for spinal cord injury	Focused on stroke survivors
Controlling 9 muscles	Controlling 2 muscles
Surgical FES at 13Hz	External FES stimulation
Exoskeleton Arm Support	No Exoskeleton Arm (enough mobility provided by the patient)
Wrist Position Control	EMG and Wrist Position Control
Multiple movements in the workspace	Same target, different initial positions. Repetition of movement for rehabilitation purposes.

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A Title

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