

Biomechanical Model-Based Control of a Human Leg: An Interactive Educational Module

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1 Introduction

A first challenge for students taking a control systems course is to draw a block diagram to represent a control process. One of the main difficulties of this task is identifying the actuating signals and the response (output) signals. Control applications discussed in a typical undergraduate control system course or those that can be found in control systems textbooks deal with man-made systems and processes, such as cruise control for an automobile, DC motors, vehicle suspension systems, inverted pendulum, etc [1-3]. The intention of the authors was to introduce students to a biological control application consisting of the modeling and control of a human leg. The objective of the study undertaken by the authors was to develop students' understanding of the neuromuscular skeletal system from a control systems perspective using a simplified computer model of the human leg [4].

Specifically, the study aims at:

- (i) Introducing students to forward and inverse kinematics via the aid of graphical user interface and real-time animations;
- (ii) Implementing a computer simulation model of the human leg using a MATLAB/SIMULINK interface;
- (iii) Developing interactive tools for the students to study the human leg model and how to control it.

The study emphasizes computer simulations and visualization. The instructional materials developed in this study have great potential of being *inexpensively disseminated through commercial publishers*. Since one of the main objectives of this study is to expose pre-college students to bioengineering, the developed educational materials have different

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degrees of difficulties. The developed module has a broad applicability and enhances the teaching of control theory which is an important discipline in biomechanics.

2 Methodology Adopted for Building the Educational Module

Students taking a control systems course in many educational programs (for instance, Electrical Engineering) do not have a background in robot manipulators. Hence, they are not expected to have a background knowledge of kinematics which is a prelude to the study of human leg modeling and control. Hence, the first section of the education module is to teach students the concept of kinematics using interactive tools and graphical animations. Students who have used this section of the educational module have found it to be a 'fun' tool and have been able to assimilate the concept of kinematics exceptionally well even though they have not been exposed to the study of kinematics prior to their experience with the interactive module.

After having understood the topic of forward and inverse kinematics and with enough background knowledge in control system modeling and design, students can move on to explore the biomechanical application in two successive stages. The first stage exposed students to the dynamic modeling and control of the human leg without consideration of the muscle dynamics.

The two last stages of the educational module were developed based on the fostering of a sequence of challenges. These challenges serve as a learning mean to prepare the students before they can use the modeling and control simulation tools of the module.

The sequence of challenges are:

Challenge 1: Consider a soccer player kicking a ball with his right leg. The system consists of the player's leg which pivots from the hip joint. What are the inputs and outputs of this system?

Challenge 2: What does generate the torque that makes the leg rotate about the hip joint?

Challenge 3: Can you come up with a simple mathematical model that describes the leg angular movement about the hip joint? Assume that the player is warming up by swinging his leg about his hip joint (consider small angles of rotation). What would be the transfer function that relates the hip joint angle to the torque applied to the joint?

Challenge 4: What muscles of the leg are involved when a player kicks the ball? What does activate these muscle?

Challenge 5: Draw a block diagram that shows the different elements of this biological control system? Can you think of a biological feedback loop?

3 Module Sections

At any level of the interactive module, students can click on a 'help' tab to learn more about the objective of the module and review the mathematical aspect of the problem at hand.

3.1 Forward and Inverse Kinematics

In this section, students have the ability of studying the topic of forward and inverse kinematics [5] through a graphical user interface and real-time animation. There are four different selections that the students can explore: (i) Forward Kinematics, (ii) Inverse Kinematics, (iii) Click and Drag, and (iv) Click on Target. In the Forward Kinematics selection, students can experiment with the concept of forward kinematics. Students can input the angle values of the leg and receive the results showing the x-y coordinates of the foot (Figure 1). The module positions the leg in the x-y coordinate frame accordingly.

In the Inverse Kinematics selection, students can experiment with the concept of inverse kinematics. In this selection, students enter the polar coordinates of the foot position and the program calculates the corresponding joint angles and positions the leg on the graph accordingly (Figure 2).

Students are also provided with two additional interactive features to foster their knowledge and understanding of the concept of forward and inverse kinematics. These features are included in the last two selections, namely Click and Drag selection and Click on Target selection (Figures 3-4). In the graphical manipulation Click and Drag, students can click and hold on the foot and drag it anywhere within the reachable space (Figure 3). The module calculates the position of the leg and displays results (joint angles, Cartesian and polar coordinates) to the user in real-time. In the graphical manipulation Click on Target, students can click on the graph where they want the leg to be positioned (Figure 4). The module calculates and displays the leg position values and brings it to the target position as specified by the user.

These graphical and animation capabilities serve as additional hands-on experience for the students to learn about a new topic in kinematics. Also, students can be asked to manually calculate the forward kinematics or the inverse kinematics and then verify their results using the interactive module. The accessible help utilities are very practical to review the geometrical concepts of the forward and inverse kinematics. This type of learning is different than the traditional lecture and homework format. Based on preliminary assessment and evaluation of the module, students have been found to be very engaged with the module and have shown exceptional interest in learning about the kinematics topics. Finding and exploring ways of how students learn is one of the main goals of this module.

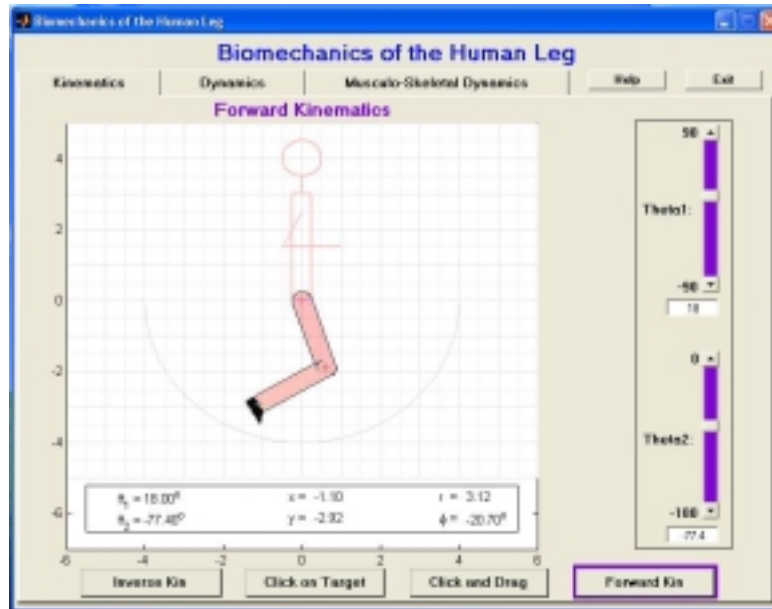


Figure 1- Forward Kinematics : by changing the values of the joint angles using the graphical sliders or by entering the angle values directly in the numerical boxes, the program computes the (x,y) position of the foot and position it accordingly. The values are displayed to the student in real-time.

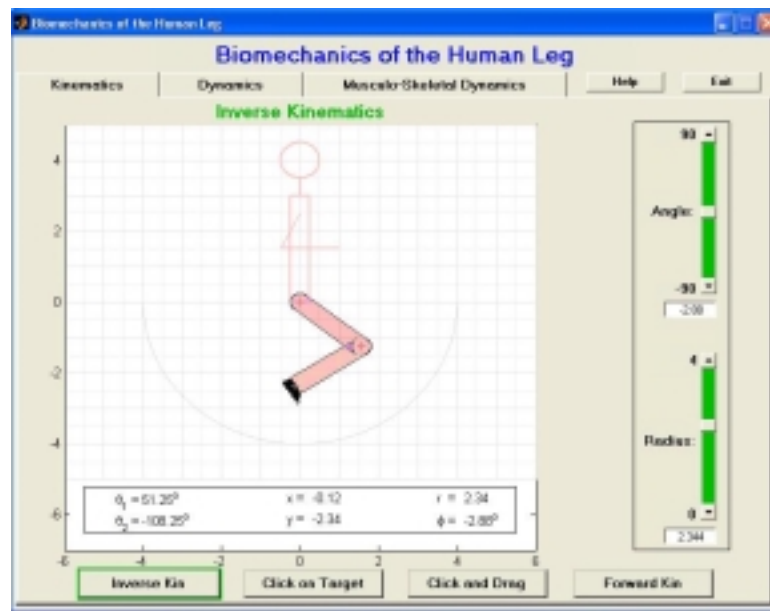


Figure 2- Inverse Kinematics: by changing the value of the polar coordinates of the leg using the graphical sliders or by entering the values directly in the numerical boxes, the program computes the angle values of the foot and position it accordingly on the graph. The values are displayed to the student in real-time.

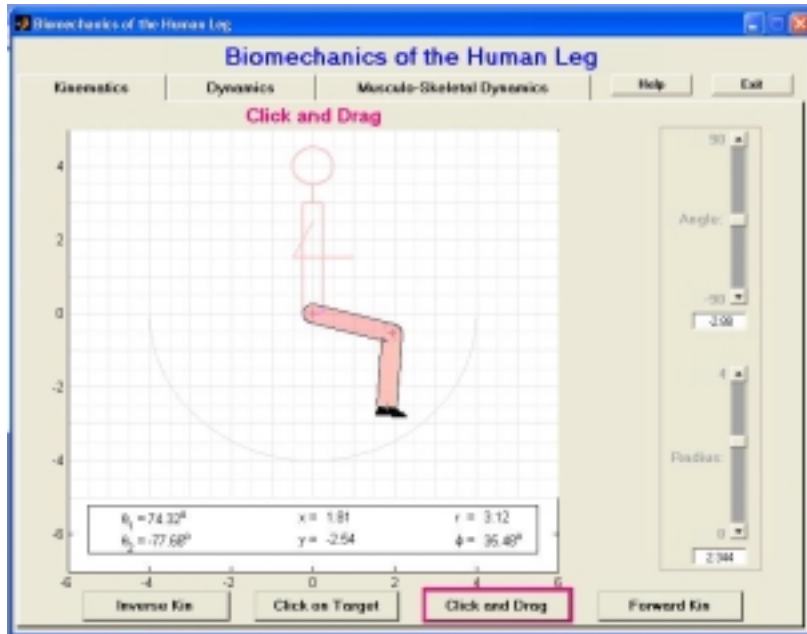


Figure 3- Graphical Manipulation 1: Students can click and hold on the foot and drag it anywhere within the reachable space.

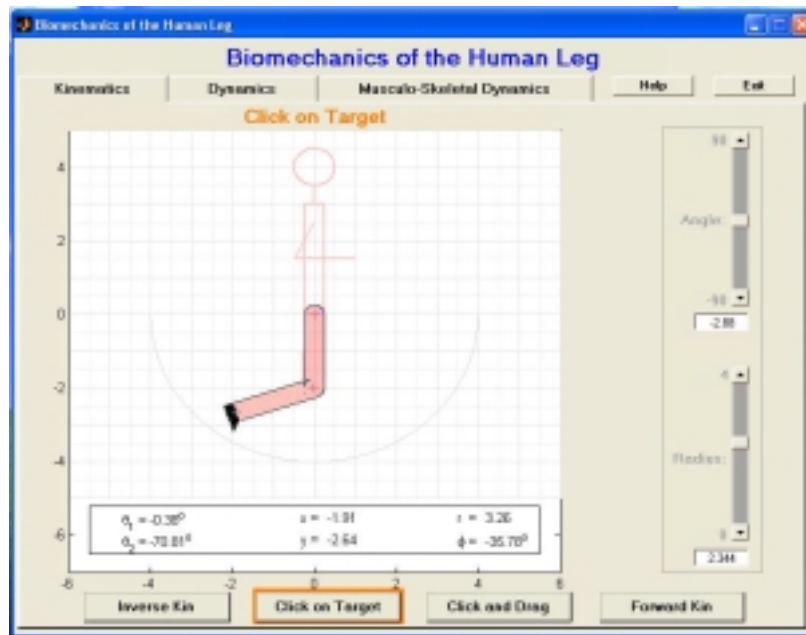


Figure 4- Graphical Manipulation 2: Students can click on the graph where they want the leg to be positioned. The program calculates and displays the leg position values and brings it to the target position.

3.2 Dynamics and Control

Students can specify the desired motion of the leg and simulate the feedback control system using a SIMULINK diagram (Figure 5). This section does not involve the muscle dynamics and is kept simple to allow the students to progressively learn the skeletal modeling and control of the human leg.

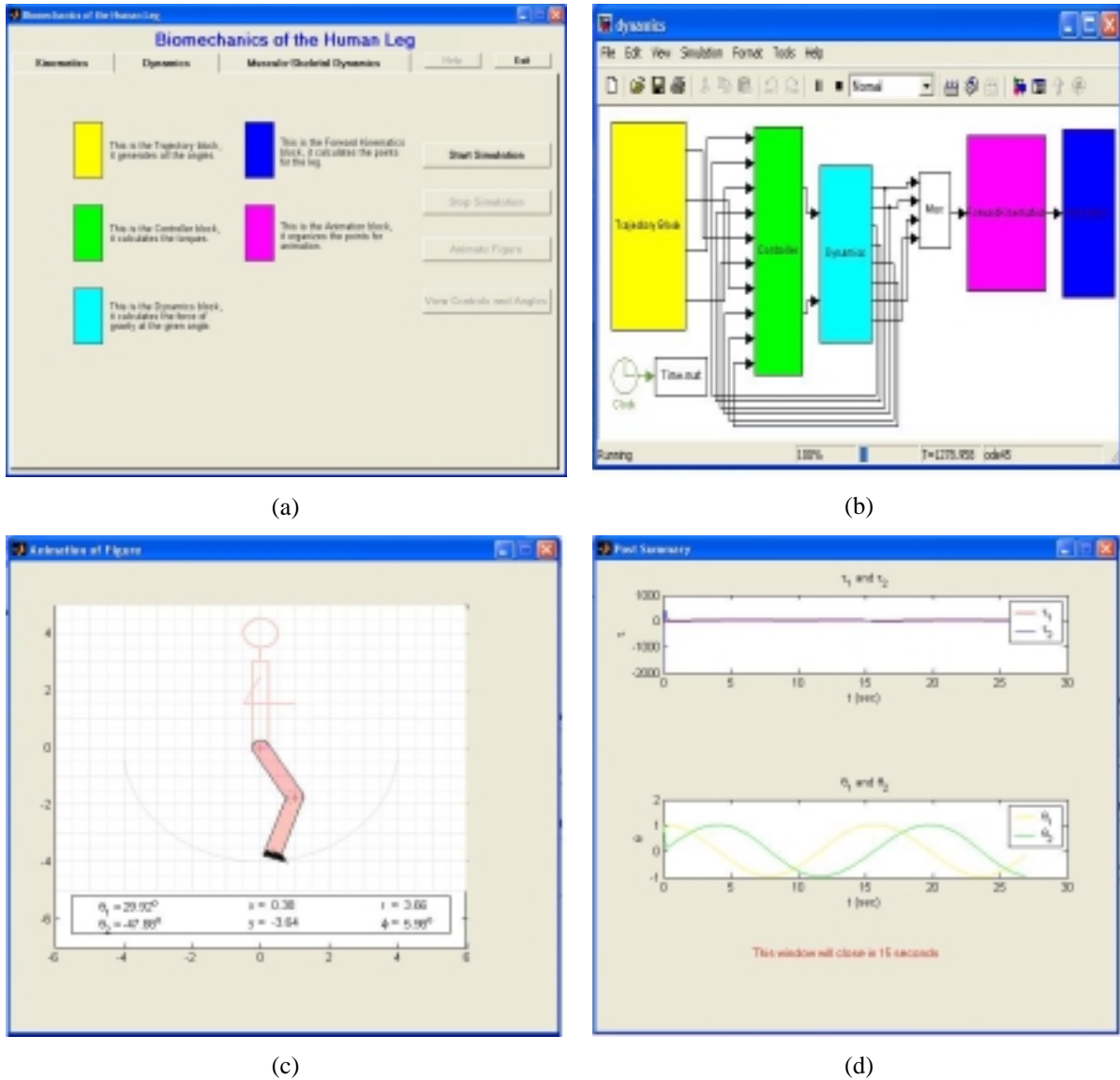


Figure 5- Dynamics and Control - Modeling, Control and Simulation of the Human Leg without accounting for the muscle dynamics; (a) Module window and color codes referring to the different main blocks of the SIMULINK diagram, (b) SIMULINK diagram containing closed-loop control systems for the skeletal model of a leg, (c) Animation window showing the motion of the controlled leg, (d) Post-simulation and animation summary window showing the time history of the leg joint torques and angles.

3.3 Musculo-skeletal Dynamics and Control

In this section (third tab), the muscle dynamics of the human leg are included. Through dialog boxes and help windows, students are able to: (i) modify and select muscle characteristics, (ii) select and/or modify system parameters (masses, lengths, stiffness and viscosity coefficients, joint position and velocity initial conditions, etc.), and (iii) select a control strategy to actuate the leg muscles. The GUI interface of the module software makes it easy for students to understand the effects of system parameters by interactively modifying their values and observing the resulting system response (torque generated, and animated leg movement). More detailed description of this module will be presented elsewhere.

4 Conclusion and Future Work

The main objective of this module is to introduce students to the study of the human musculo-skeletal system from a control point of view. The specific knowledge outcomes of this module include: 1) becoming familiar with the basic structure of the human musculo-skeletal system, 2) understanding the macrostructure of a muscle model and its role as a biological actuator, 3) being able to define the functional motions of human extremities or trajectories as sequence of positions, velocities and accelerations, 4) becoming aware of functional neuromuscular stimulation and its importance for partial restoration of function to paralyzed limbs, and 5) being able to compare open-loop and closed-loop control of functional neuromuscular activated muscles.

The main advantages of the education module are: (1) An interactive GUI for teaching students about the mechanics of a human leg and its representation as a component of a biological control system; (2) An interactive GUI for control system configuration and implementation with numerical simulation, data visualization and object animation capabilities. Work is underway to enhance and further develop the different sections and features of the module. The testing of the module in a formal class setting is planned in the near future. Evaluation and assessment methodology along with the qualitative and quantitative test results will be reported in the near future.

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