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DYNAMIC MODELING AND SYSTEM IDENTIFICATION OF AN INVERTED PENDULUM APPLIED TO TALOCRURAL JOINT BIOMECHANICS

MODELAGEM DINÂMICA E IDENTIFICAÇÃO DE SISTEMAS DE UM PÊNDULO INVERTIDO APLICADO À BIOMECÂNICA DA ARTICULAÇÃO TALOCRURAL

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ABSTRACT

A Neuropatia Periférica (NP) está associada a disfunções do sistema nervoso periférico, podendo comprometer o controle postural e aumentar o risco de quedas, especialmente em indivíduos idosos. Nesse contexto, a modelagem biomecânica do equilíbrio humano torna-se relevante para o desenvolvimento de estratégias de análise e reabilitação. Este trabalho propõe uma metodologia para estimação de modelos representativos do comportamento da articulação talocrural, utilizando a analogia com o pêndulo invertido. A abordagem integra modelagem matemática, simulação computacional e validação experimental por meio de uma planta eletromecânica de baixo custo instrumentada com sensor inercial. A partir dos dados obtidos, foram estimados dois modelos matemáticos por meio de técnicas de identificação de sistemas. Os resultados indicaram que o modelo obtido a partir da estratégia de aquisição considerando todo o intervalo operacional

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apresentou melhor desempenho, com erro quadrático médio de 0,0389 e erro médio absoluto de 0,0129, demonstrando elevada aderência ao comportamento do sistema real. Os resultados evidenciam a viabilidade da metodologia proposta para aplicações em estudos de controle postural e no desenvolvimento de tecnologias assistivas voltadas à reabilitação motora.
Keywords: modelagem biomecânica; pêndulo invertido; controle postural; identificação de sistemas; sensores inerciais.

ABSTRACT
Peripheral Neuropathy (PN) is associated with dysfunctions of the peripheral nervous system, potentially compromising postural control and increasing fall risks, especially in elderly individuals. In this context, the biomechanical modeling of human balance becomes relevant for developing analysis and rehabilitation strategies. This study proposes a methodology for estimating representative models of the talocrural joint behavior using the inverted pendulum analogy. The approach integrates mathematical modeling, computer simulation, and experimental validation through a low-cost electromechanical plant instrumented with an inertial sensor. It estimates two mathematical models using system identification techniques based on the acquired data. Results indicate that the model obtained from the acquisition strategy considering the entire operational range presents better performance, yielding a Mean Squared Error (MSE) of 0.0389 and a Mean Absolute Error (MAE) of 0.0129. This result demonstrates high agreement with the real system behavior. The findings evidence the feasibility of the proposed methodology for applications in postural control studies and the development of assistive technologies for motor rehabilitation.
Keywords: biomechanical modeling; inertial sensors; inverted pendulum; postural control; system identification

1 INTRODUCTION

Peripheral Neuropathy (PN) consists of a set of disorders that affect the nerves of the peripheral nervous system, compromising sensory and motor functions. It is estimated that approximately 5% of the global population is affected by some form of neuropathy, with a higher incidence in elderly individuals (Russel, 2017). Among the main consequences of PN, the deterioration of postural control stands out, especially associated with the talocrural joint, which significantly increases the risk of falls and functional limitations (Fortaleza, 2011). In this context, understanding and modeling the mechanisms involved in human balance become fundamental for the development of rehabilitation strategies and assistive technologies (Duarte, 2010).

Maintaining balance in an upright posture results from the interaction among sensory, motor, and central control systems. From a biomechanical perspective, this behavior can be represented by simplified models that describe the dynamics of the human body (Mochizuki, 2003). Among these models, the inverted pendulum has been widely used in the literature due to its ability to represent, in a reduced manner, the behavior of the musculoskeletal system in the sagittal plane, considering

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the ankle joint as the rotation point (Amadio et al., 1999; Carmo, Carmo, 2022). This approach allows the application of classic modeling and control techniques to analyze the postural system.

Despite theoretical advances, the experimental validation of these models still represents a challenge, especially when seeking low-cost and easily implementable solutions (Broniera Junior, 2021). In this sense, the integration of mathematical modeling, computer simulation, and experimental testbeds emerges as a promising alternative, yet little explored in low-cost experimental applications focused on the biomechanics of postural control. The use of inertial sensors, such as the MPU6050, combined with embedded platforms, enables real-time data acquisition, contributing to the identification of models that more closely adhere to the system's physical behavior.

Given this scenario, this study aims to develop and validate model estimation methodologies to represent the biomechanical behavior of the talocrural joint using the inverted pendulum analogy. To this end, mathematical models based on literature, computer simulations, and an experimental electromechanical plant built for real data acquisition are employed. Based on the responses obtained, system identification techniques are applied to estimate transfer functions and compare their adherence to the reference model.

As its main contribution, this study proposes an integrated approach for modeling and experimentally validating a biomechanical system, utilizing low-cost instrumentation and system identification techniques. The results obtained demonstrate the feasibility of the proposed methodology, evidencing its applicability in postural control studies and in the development of future solutions aimed at motor rehabilitation.

This article is structured as follows: Section 2 presents the theoretical foundations related to biomechanical modeling and the inverted pendulum; Section 3 describes the adopted methodology; Section 4 presents and discusses the experimental results; and, finally, Section 5 presents the study's conclusions.

2 BIOMECHANICAL SYSTEM MODELING

2.1 Biomechanical Model of Postural Control

Individuals with peripheral neuropathy present compromised postural control due to alterations in the sensorimotor system, primarily affecting the stability of the talocrural joint (Dooley, 2015). This impairment directly impacts the ability to maintain balance, increasing the risk of falls and functional limitations. In this context, postural control analysis becomes fundamental for understanding the mechanisms involved in the stability of the human body in an upright posture (Russel, 2017).

From a biomechanical perspective, maintaining balance results from the interaction between internal forces, associated with muscle action, and external forces, such as the ground reaction. To simplify the analysis of this complex system, several studies propose reduced models capable of representing the global behavior of the human body. Among these approaches, the representation of the body as an articulated system with a dominant degree of freedom stands out, in which the ankle joint acts as the main rotation point in the sagittal plane (Fortaleza, 2011). In this modeling, the human body can be approximated as a rigid segment that oscillates around the talocrural joint while the feet remain fixed to the support base (Kendall et al., 2007).

This simplification allows describing the dynamic behavior of the system through equivalent mathematical models, enabling the application of analysis and control techniques (Duarte, 2010). Figure 1 illustrates this simplified representation, highlighting the relationship between the body, the rotation points at the ankle, and the support base.

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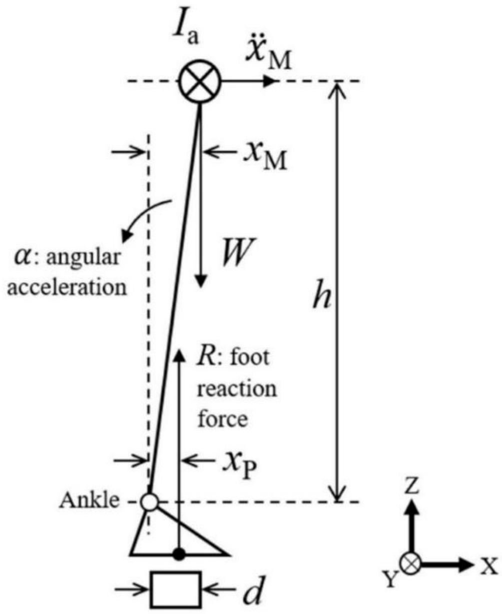
Figure 1 - Simplified representation of human postural control, modeled as an inverted pendulum with rotation at the ankle joint



Source: Russel (2017)

Based on the presented representation, the behavior of the human body in an upright posture can be described by dynamic variables associated with the displacement of the center of mass and the action of forces acting on the support base. Simplifying the system as an inverted pendulum allows for a direct relationship between the angular movement of the structure and the reaction forces at the ankle, highlighting the role of this joint as the primary control element in the sagittal plane. This approach enables the formulation of mathematical models that describe the system's dynamics, serving as a foundation for developing analysis, simulation, and parameter identification techniques (Palastange, 2000).

2.2 Inverted Pendulum Approximation

The modeling of human postural control can be simplified through the inverted pendulum analogy, widely used in the literature to represent the dynamics of the body in an upright posture. This approach considers movement in the sagittal plane, where the talocrural joint acts as the rotation point, while the rest of the body is represented by a rigid segment with mass concentrated at its center of gravity (Maya, 2014).

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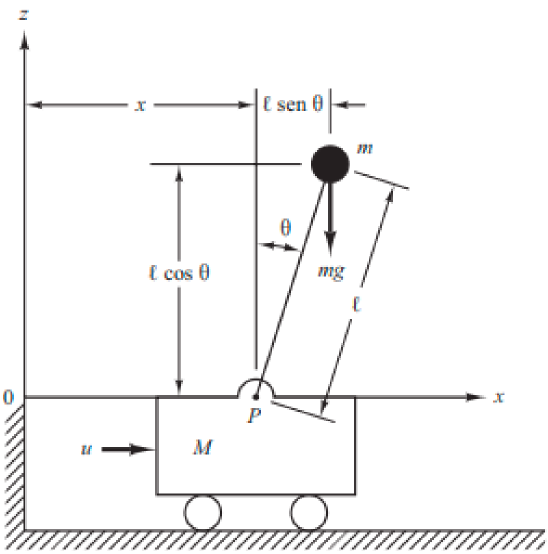
The inverted pendulum characterizes an intrinsically unstable system, requiring the application of control forces to maintain balance (Ogata, 2010). Considering a two-dimensional model, dynamic equations relating the angular movement of the pendulum to the force applied at the base describe the system, as Figure 2 illustrates.

Figure 2 - Inverted pendulum model used to represent postural control



Source: Adapted from Ogata (2010).

Based on the system analysis, the model assumes that the mass concentrates at the top of the rod, allowing the simplification of the moment of inertia around the center of gravity. Therefore, differential equations describing the relationship between angular displacement and applied force represent the system's dynamic behavior. Applying classical modeling techniques yields the transfer function that describes the system dynamics, relating the force input to the pendulum's angular displacement (Ogata, 2010):

$$\frac{\Theta(s)}{U(s)} = \frac{1}{Mls^2 - (M+m) \times g} \quad (1)$$

This model constitutes the basis for analyzing the simplified biomechanical system and finds wide application in control and system identification studies (Ogata, 2010). Building upon this representation allows advancing to the modeling of more complex systems, which includes incorporating actuators and physical elements that approximate theoretical behavior to experimental conditions (Coelho, 2005).

2.3 Mathematical Modeling of the System

The proposed system modeling relies on the representation of an inverted pendulum driven by a direct current (DC) motor, as addressed in the literature. Although the human musculoskeletal system presents high complexity, simplified models that preserve the main characteristics of postural control, especially in the sagittal plane, can adequately approximate its dynamics (Coelho, 2005; Cavalheiro, 2010).

Considering the analyzed structure, the balance of forces and moments acting on the pendulum describes the system, considering the mass concentrated at the center of gravity, the rod length, and the torque applied to the joint. These considerations yield differential equations that describe the dynamic behavior of the system's angular movement (Pereira; Araújo, 2019).

Assuming small oscillations around the equilibrium position, such that $\theta \approx 0$, linearizing the model simplifies its mathematical representation (Resnick, 2003). Applying the Laplace transform to the system equations yields a transfer function that relates the pendulum's angular displacement to the excitation applied at the base (Pereira; Araújo, 2019). Thus, a transfer function of the following type expresses the system dynamics:

$$\frac{\theta(s)}{X_p(s)} = \frac{-Mls^2}{as^2 + bs - mgl} \quad (2)$$

where the system's physical properties, such as mass, rod length, and damping coefficient, define the model parameters. This study uses this model as a reference to validate the experimental results, enabling a comparison between theoretical behavior and the implemented physical system.

2.4 Experimental System and Instrumentation

The implementation of an electromechanical plant designed to reproduce the described biomechanical system's dynamics in a simplified manner experimentally validates the proposed model. The structure consists of an articulated mechanism that simulates the inverted pendulum's behavior, where the lower joint represents the rotation point corresponding to the talocrural joint.

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A direct current (DC) motor drives the system, applying torque to the joint and allowing the pendulum rod to move. An embedded platform based on the myRIO module controls the system and acquires data, acting as the central processing unit and enabling the execution of real-time routines and communication with peripheral devices.

An MPU6050 inertial sensor, composed of a three-axis accelerometer and gyroscope, measures the system's angular positioning. A complementary filter processes the sensor signals, allowing data fusion and yielding a more precise estimate of the system's tilt angle over time.

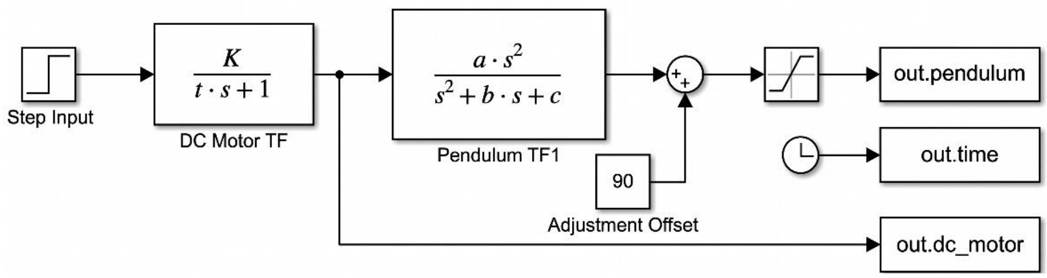
The I²C protocol establishes communication between the devices, while an H-bridge drives the motor, controlling its direction and rotational speed.

To obtain the experimental data, the study performs tests applying step input signals, which allows the analysis of the system's dynamic response. Subsequent system identification processes use the collected data to estimate mathematical models, enabling the comparison between the experimental behavior and the proposed theoretical model.

3 METHODOLOGY

The methodology proposed in this work consists of the integration of theoretical modeling, computational simulation, and experimental validation, with the objective of estimating models that represent the dynamic behavior of the biomechanical system. Initially, the study utilized a reference mathematical model based on literature, representing the system as an inverted pendulum driven by a direct current (DC) motor. Based on this model, the methodology performed a computer simulation in the Simulink® environment, obtaining the system's response to step input signals. Figure 3 shows the model implemented in the Simulink® environment, consisting of a series association between the DC motor model and the inverted pendulum model, yielding the system's dynamic response to a step input signal.

Figure 3 - Simulation model of the system implemented in the Simulink® environment



Source: The author.

To parameterize the pendulum model, the study adopts values based on physical approximations of small-scale systems, compatible with the scale of the developed experimental plant. The parameters used include pendulum mass of 0.5 kg, rod length of 0.1 m, viscous damping coefficient of 0.25 N/(m/s), and gravity acceleration of 9.83 m/s², according to Equation (3):

$$\frac{\theta(s)}{X_p(s)} = \frac{-\frac{3}{2l}s^2}{s^2 + \frac{3\,B_r}{2ml^2}s - \frac{3g}{2l}} \tag{3}$$

The study defines these values to represent a viable physical system consistent with the mechanical structure implemented on the bench. For modeling the direct current (DC) machine, the methodology adopts a first-order approximation, as proposed by Montenegro (2021), considering the low influence of the utilized motor's electrical time constant. Thus, a transfer function of the following type represents the actuator's dynamics:

$$\frac{W(s)}{V(s)} = \frac{K}{s \times \tau + 1} \tag{4}$$

where [insert gain variable] represents the system gain and [insert time constant variable] the time constant. For the adopted model, the study utilized the values $K = 540$ and $\tau = 0.0018$s, defining them based on the employed motor's characteristics and adjusting them to adequately reproduce the dynamic response observed in the real system. The association between the actuator model and the pendulum model allows representing the system's global behavior. The methodology uses the obtained response as a reference for comparison with the experimental data.

In the experimental stage, the research developed an electromechanical plant capable of reproducing the proposed system's dynamic behavior. The structure consists of an articulated

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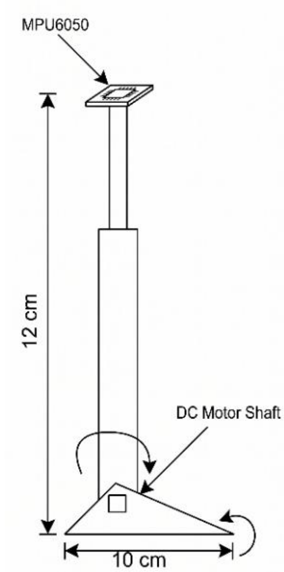
mechanism driven by a direct current (DC) machine, with an inertial sensor measuring the angular positioning. Figure 4 presents the architecture of the implemented experimental system.

To acquire data, the methodology performed tests applying step input signals, allowing the observation of the system's time response. The study considers different initial operating conditions, including rest and saturation positions, aiming to capture the dynamic behavior across different regimes.

Figure 4 - Schematic diagram and physical dimensions of the developed electromechanical plant



Source: The author.

Figure 5 shows the system architecture, in which the FPGA-based myRIO embedded controller acts as the central processing unit. Due to its high sampling rate of around 10 kHz, the system enables higher-frequency data acquisition compared to conventional microcontrollers. Through the I²C communication protocol, the controller reads data from the MPU6050 inertial sensor and sends control signals to the L293D H-bridge, which drives and modulates the power applied to the motors.

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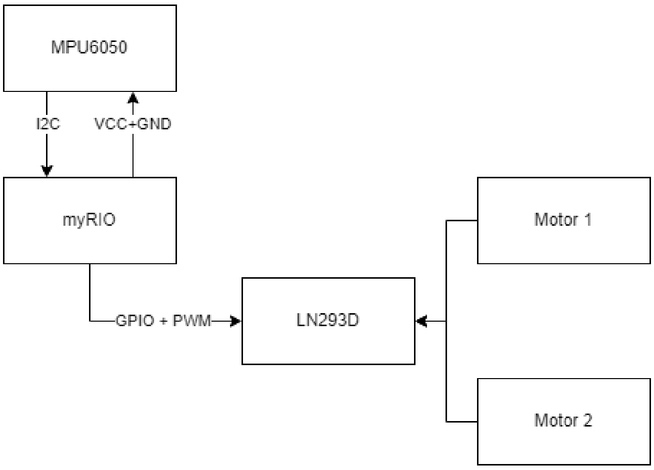
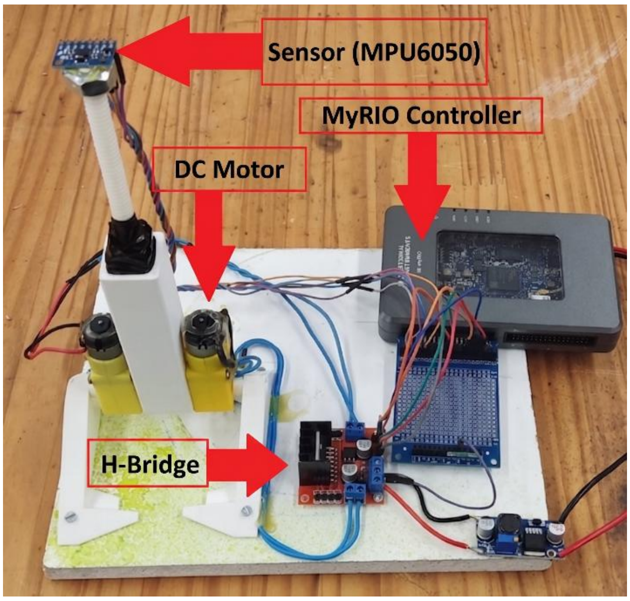
Figure 5 - Architecture of the experimental system and signal flow



Source: The author.

Programmed in the LabVIEW® environment, the controller acquires data from the MPU6050 sensor and generates command signals, including pulse-width modulation (PWM). The system applies these signals to the L293D H-bridge to control the motors' rotational direction and speed. Figure 6 shows the experimental plant assembly used in the tests.

Figure 6 - Assembly of the experimental plant used in the tests



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Source: The author.

The tests were conducted by applying step input signals to the system, driving the direct current (DC) machines and the subsequent movement of the pendulum rod. During the trials, the controller acquired the angular positioning over time, enabling the analysis of the system's dynamic response. The experimentally obtained signals underwent pre-processing stages, including filtering and smoothing, to reduce noise effects in the measurements. To estimate the models, the methodology utilized MATLAB® computational tools through system identification techniques based on step response.

Based on the processed data, the study estimated transfer functions representative of the system, allowing for a comparison between the experimental behavior and the theoretical reference model. The resulting models were subsequently implemented in a simulation environment for validation and performance analysis. This approach evaluates the adherence between the theoretical model and the experimental behavior, providing the basis for validating the proposed methodology.

The next section addresses the results obtained through tests in the simulated environment and the physical plant, as well as the estimation of the equations using the presented tools.

4 RESULTS AND DISCUSSION

Computer simulation yielded the theoretical model's dynamic response, as presented in Figure 7. This model served as a reference for evaluating the models estimated from the experimental data.

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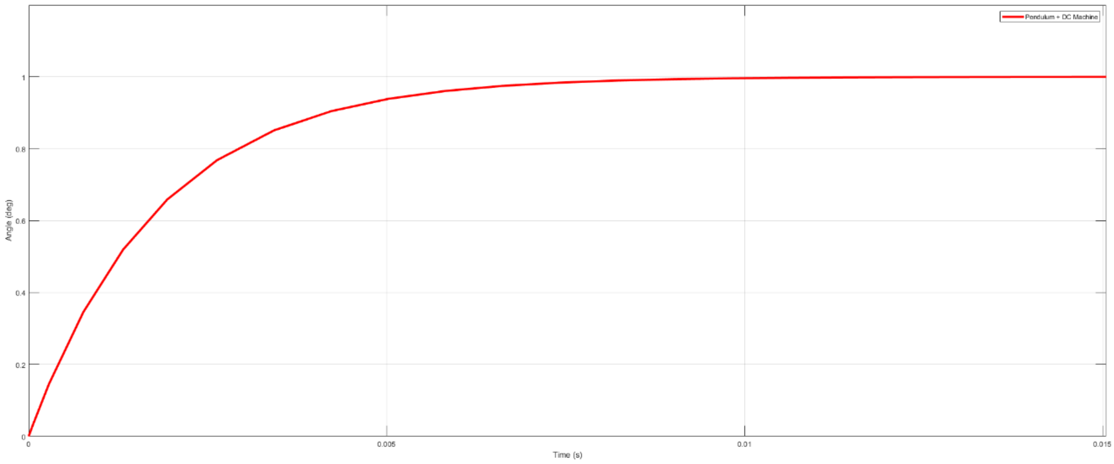
Figure 7 - Step response of the theoretical model obtained through simulation



Source: The author.

This response serves as a reference to validate the models estimated from the experimental data. Following the presented methodology, the study conducts bench experimental tests, collecting the system's response to a step input. The methodology employs two testing strategies:

- Applying the step input with the pendulum in the rest position (0°);
- Applying the step input with the pendulum in the negative saturation position (-90°).

The study conducted experimental trials on a experimental setup by applying step input signals, considering different initial system conditions. Figure 8 shows the resulting responses.

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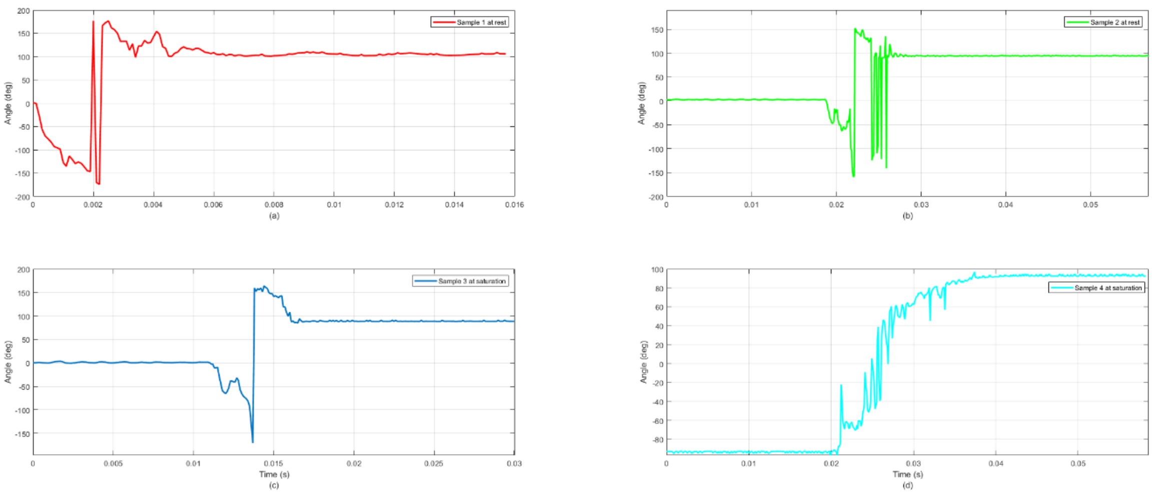
Figure 8 - Experimental step responses obtained under different initial operating conditions: (a) raw response at rest; (b) raw response in saturation; (c) filtered response at rest; (d) filtered response in saturation



Source: The author.

The experimental curves demonstrate the system's dynamic behavior under different operational conditions, including rest and saturation regimes. The results reveal the presence of noise associated with mechanical vibrations, as well as the plant's physical limitations, which directly influence the system's response.

The system exhibits a fast dynamic response, with a settling time on the order of milliseconds, a characteristic compatible with small-scale systems with a low moment of inertia. These effects highlight the influence of the physical system's non-idealities, such as friction and mechanical backlash, which are absent in the theoretical model.

The study subjected the experimental signals to pre-processing stages, including filtering and smoothing via MATLAB's Curve Fitting Toolbox, aiming to reduce the influence of noise originating from the mechanical structure. Figure 9 illustrates the obtained result, displaying the smoothed sample curve and effectively removing the noise caused by the plant's mechanical vibration.

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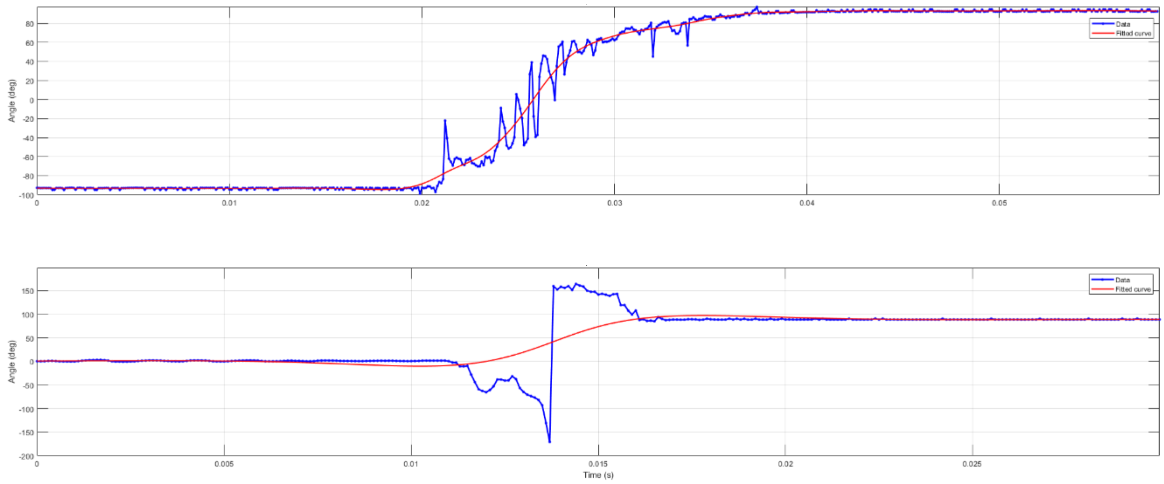
Figure 9 - Experimental signals after the filtering and smoothing process



Source: The author.

Figure 9 shows the signals following the smoothing process, highlighting a significant reduction in noise and allowing for a better fit of the mathematical models. Using this data, the study applied system identification techniques, yielding two transfer functions that represent the system, as expressed by Equations (5) and (6).

$$\frac{\theta}{V} = \frac{Kp}{1 + (2 \times \zeta \times Tw \times s) + (Tw \times s)^2} \quad (5)$$

Where $Kp = 368.57; Tw = 0.0030967; \zeta = 0.91282$

$$\frac{\theta}{V} = \frac{Kp \times (1 + T_z \times s)}{(1 + Tp_1 \times s) \times (1 + Tp_2 \times s)} \quad (6)$$

Where $Kp = 222; Tp1 = 0.0011103; Tp2 = 0.0011086; Tz = 7.559e^{-5}$.

Obtaining two distinct models allows for evaluating the impact of the data acquisition strategy on the system estimation quality.

The methodology inserted the obtained models into a simulation environment for comparison with the reference model, as Figure 10 shows.

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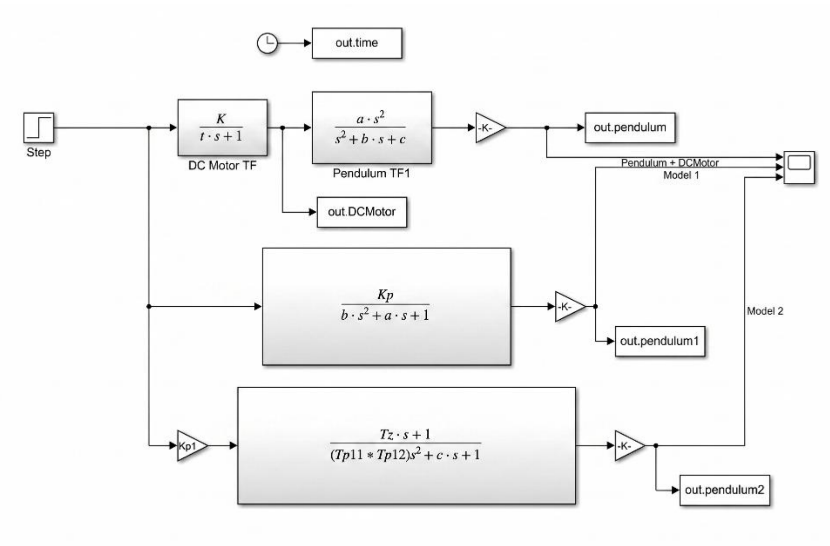
Figure 10 - Comparison between the estimated models and the reference model in simulation



Source: The author.

Figure 10 shows the response of the estimated models in comparison with the theoretical model, allowing for an evaluation of the obtained transfer functions' adherence. Figures 11 and 12 display the individual model responses.

Figure 11 - Step response from model 1

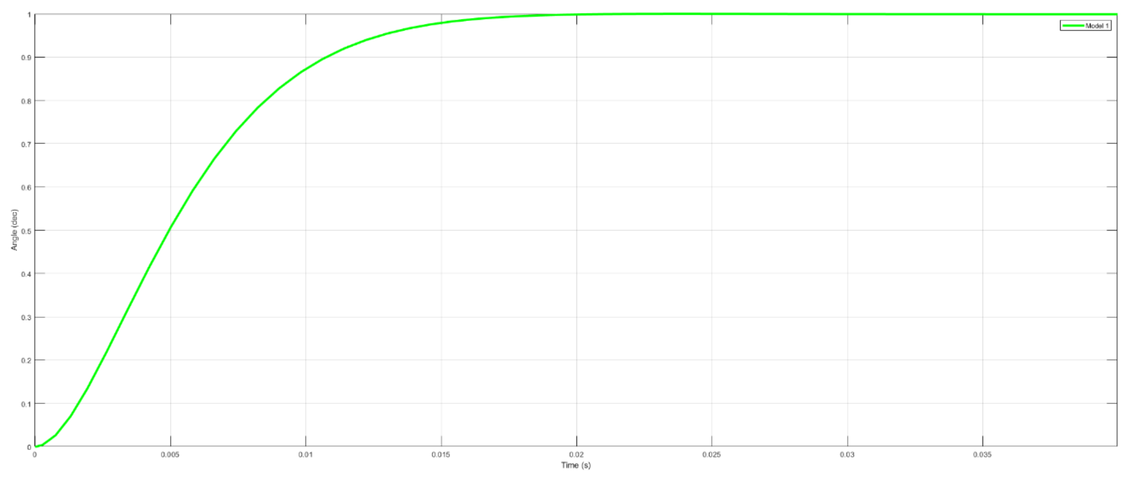


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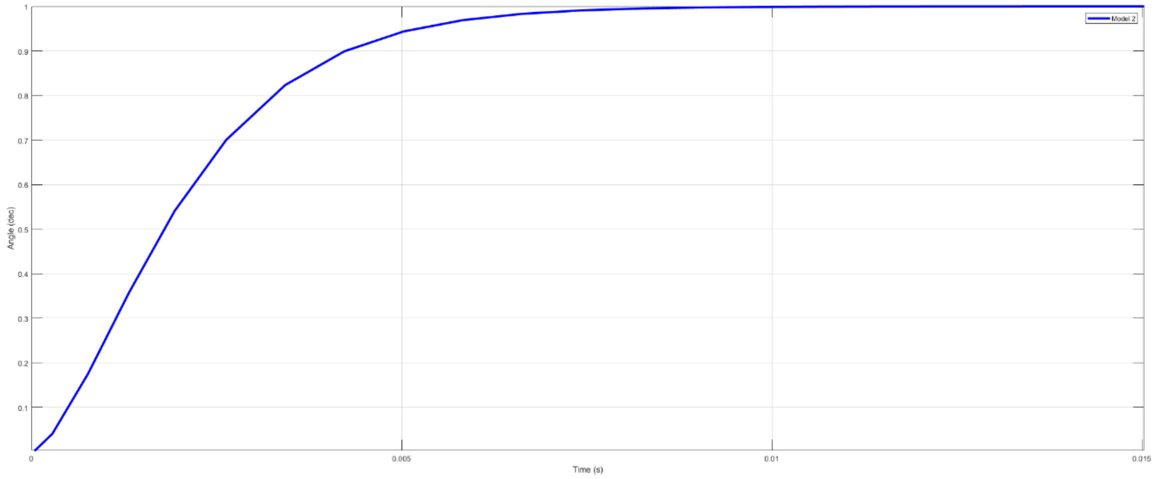
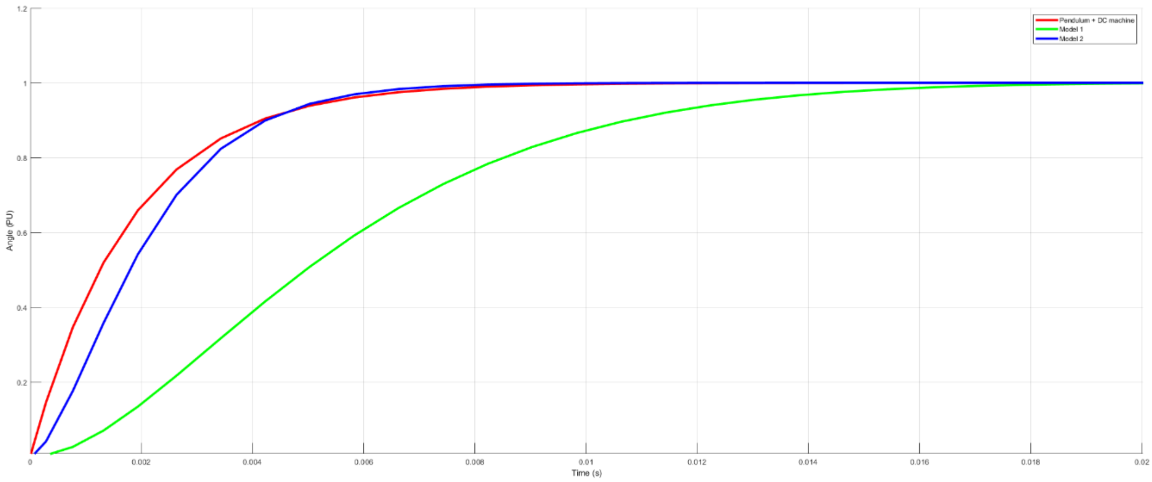
Figure 12 - Step response from model 2



Source: The author.

The results demonstrate that both models can represent the system's behavior; however, they exhibit significant differences in the transient response. Figure 13 shows the overlay of the models' responses and the reference model.

Figure 13 - Overlay of the estimated models' responses and the reference model



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Model 2 demonstrates a better fit to the system's behavior, particularly during the transient response, indicating greater accuracy in representing the plant's dynamics. This outcome is directly associated with the data acquisition strategy, as Model 2 considers the plant's entire operating range, allowing it to more accurately capture the non-linear dynamics present within the system.

The quantitative evaluation employed error metrics, as Table 1 presents.

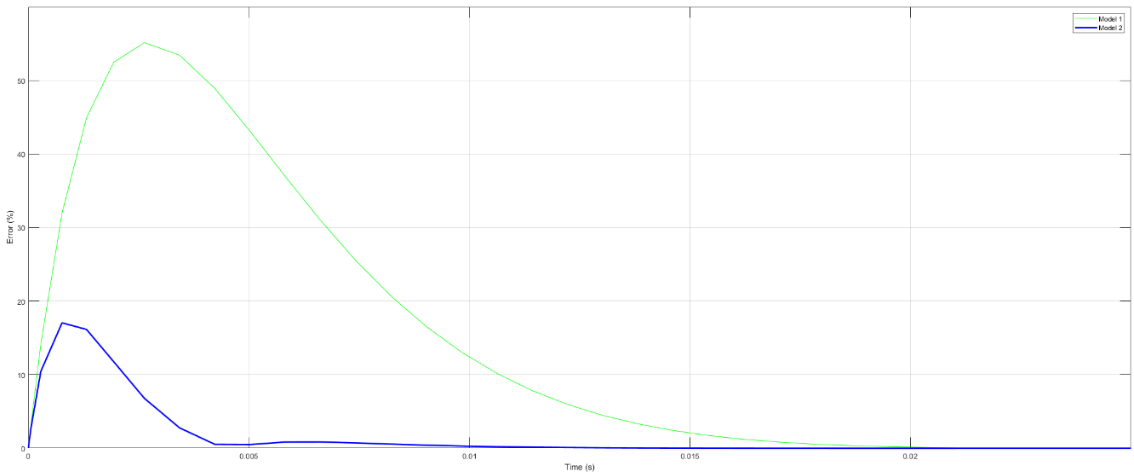
Table 1 – Mean Squared Error (MSE) and Mean Absolute Error (MAE)

	Model 1	Model 2
MSE	0.1884	0.0389
MAE	0.0933	0.0129

Source: The author.

The results indicate a significant reduction in errors for Model 2, particularly concerning the Mean Squared Error (MSE) and the Mean Absolute Error (MAE), demonstrating greater accuracy in approximating the real system. Figure 14 shows the evolution of error over time.

Figure 14 - Temporal evolution of the error between the estimated models and the reference model



Source: The author.

Model 1 exhibits larger deviations during the transient response, whereas Model 2 maintains a reduced error throughout the entire response. These results confirm Model 2's superiority in representing the system, validating the proposed methodology for model estimation based on different operating conditions.

5 CONCLUSIONS

This work presented the development and validation of a methodology for model estimation applied to the biomechanical behavior of the talocrural joint, using the inverted pendulum analogy. The proposed approach integrated theoretical modeling, computational simulation, and benchtop experimentation, allowing for a comparison between the reference mathematical model and the models obtained from experimental data.

The results demonstrated that the employed methodology satisfactorily represented the system's dynamics, highlighting Model 2, which exhibited a better fit to the plant's actual behavior. This model achieved a Mean Squared Error (MSE) of 0.0389 and a Mean Absolute Error (MAE) of 0.0129, evidencing high accuracy in approximating the physical system. These results confirm the effectiveness of the data acquisition strategy that considers the plant's entire operating range.

From a scientific perspective, this paper's main contribution lies in proposing a low-cost integrated approach for the modeling and identification of biomechanical systems using inertial sensors and embedded platforms. This approach demonstrates potential applications in postural control studies and the development of assistive technologies aimed at motor rehabilitation.

The study's limitations include the simplification of the biomechanical system through a single-degree-of-freedom (1-DOF) inverted pendulum model, which does not fully account for the human body's complexities, such as multi-segmental effects and more pronounced non-linearities. Furthermore, the experimental plant presents mechanical limitations, such as friction, structural backlash, and saturation, which directly influence the obtained results.

As future work, this study proposes expanding the model to multiple-degree-of-freedom (multi-DOF) systems, allowing for a more faithful representation of human biomechanics. Additionally, it suggests the application of advanced identification and control techniques, including artificial intelligence-based methods, as well as the implementation of real-time control strategies for functional electrical stimulation (FES) applications and balance assistance systems.

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REFERENCES

AMADIO, A. C.; COSTA, P. H. L.; SACCO, I. C. N.; SERRÃO, J. C.; ARAUJO, R. C.; MOCHIZUKI, L.; DUARTE, M. Introdução à análise do movimento humano: descrição e aplicação dos métodos de medição. **Revista Brasileira de Fisioterapia**, v. 3, n. 2, p. 41-54, 1999. [in Portuguese].

BRONIERA JÚNIOR, P. B. Interface cérebro computador aliada à estimulação elétrica funcional e detecção de fadiga neuromuscular por MMG aplicada ao controle muscular isométrico em pessoas com lesão medular completa. 2021. Ph.D. **Thesis (Electrical Engineering)** – Faculdade de Engenharia, Universidade Estadual Paulista, Ilha Solteira, 2021. [in Portuguese].

CARMO, R. L.; CARMO, L. L. Articulação talocrural. Kenhub, 2022. Available at: https://www.kenhub.com/pt/library/anatomia/articulacao-do-tornozelo. Accessed on: Apr. 25, 2026. [in Portuguese].

CAVALHEIRO, G. L. Análise da postura ereta quieta em diferentes faixas etárias utilizando o discriminante linear. 2010. Ph.D. **Thesis (Sciences)** – Universidade Federal de Uberlândia, Uberlândia, 2010. [in Portuguese].

COELHO, D. B. Modelo de ativação neural do controle postural humano durante postura ereta. **Engevista**, São Paulo, v. 7, n. 1, p. 83-90, Apr. 2005. [in Portuguese].

DOOLEY, K. Anatomy angel: gastrocnemius. Dr. Dooley Noted, 2015. Available at: https://drdooleynoted.com/2015/06/23/anatomy-angel-gastrocnemius/. Accessed on: Oct. 21, 2022.

DUARTE, M.; FREITAS, S. M. S. F. Revisão sobre posturografia baseada em plataforma de força para avaliação do equilíbrio. **Revista Brasileira de Fisioterapia**, São Carlos, v. 14, n. 3, p. 183-192, May/Jun. 2010. [in Portuguese].

FORTALEZA, A. C. S. Controle postural e equilíbrio funcional em indivíduos com neuropatia diabética periférica. 2011. **Master's Thesis (Physical Therapy)** – Faculdade de Ciências e Tecnologia, Universidade Estadual Paulista, Presidente Prudente, 2011. [in Portuguese].

KENDALL, F. P.; MCCREARY, E. K.; PROVANCE, G. P.; RODGERS, M. M.; ROMANI, W. A. Músculos: provas e funções. Barueri, SP: Manole, 2007. [in Portuguese].

MOCHIZUKI, L.; AMADIO, A. C. Aspectos biomecânicos da postura ereta: a relação entre o centro de massa e o centro de pressão. **Revista Portuguesa de Ciências do Desporto**, São Paulo, v. 3, n. 3, p. 77-83, 2003. [in Portuguese].

MONTENEGRO, L. P. Controle digital de velocidade de um motor CC de baixa potência utilizando Arduino. 2021. B.S. **Thesis (Electrical Engineering)** – Universidade Federal do Ceará, Fortaleza, 2021. [in Portuguese].

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(DOI): 10.18624/e-tech.v19i1.1478

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Wesley Candido Da Silva
Renato Kazuo Miyamotoa

OGATA, K. Modern Control Engineering. 5th ed. Upper Saddle River: Prentice Hall, 2010.

PEREIRA, R. L.; ARAUJO, R. B. Controle I+PD clássico e adaptativo via síntese direta de um pêndulo invertido com 1 grau de liberdade para utilização prática. [S. l.]: SBA – Sociedade Brasileira de Automática, 2019. [in Portuguese].

RUSSELL, J. A. General approach to peripheral nerve disorders. Continuum (Minneap Minn): lifelong learning in neurology, v. 23, n. 5, p. 1241-1262, Oct. 2017.