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Pole placement tuning of proportional integral derivative feedback controller for knee extension model

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ABSTRACT

Functional electrical stimulation (FES) has shown potential in rehabilitative exercises for patients recovering from spinal cord injuries. In recent developments, conventional open-loop FES control techniques have evolved into closed-loop systems that employ feedback controllers for automation. However, closed-loop FES systems often face challenges due to muscle non-linear effects, such as fatigue, time delays, stiffness, and spasticity. Therefore, an accurate non-linear knee model is required during the design stage, and precise tuning of the feedback controller parameters is vital. A proportional–integral–derivative (PID) controller is commonly used as a feedback controller due to its simplicity and ease of implementation. However, most PID tuning methods are complex and time consuming. This paper investigates the viability of employing the pole placement technique for tuning a PID controller that regulates the non-linear knee extension model. The pole placement method aims to improve the control and adaptability of the PID controller in closed-loop FES systems, specifically by facilitating knee extension exercises. MATLAB Simulink was used to assess the effectiveness of this tuning approach. Results showed that the PID controller performed satisfactorily without non-linearities, but performance varied with the inclusion of specific non-linearities. The pole placement tuning method facilitated preliminary assessments of PID controller performance, preceding highly advanced optimization.

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1. INTRODUCTION

Theoretically, feedback control algorithms can potentially enhance the performance of open-loop control algorithms in rehabilitation exercises using functional electrical stimulation (FES) applications. However, the performance of feedback controllers in closed-loop FES devices can deteriorate substantially when confronted with non-linear effects, such as stiffness, fatigue, spasticity, and time delay, as documented in previous research [1]–[4]. The effectiveness of the feedback controllers declines when the knee and muscles experience fatigue and spasticity [2]–[5]. The feedback controllers were only tuned during the simulation design stage, where muscle non-linearity effects and other non-linear disturbances were either ignored or represented by a single predicted value to characterise the non-linear response of the muscle model [3]. However, the non-linear effects of genuine human muscles change with time, and different people exhibit various non-linear muscle responses. Therefore, any new changes or disturbances that occur when a closed-loop FES system is operational, such as different human subjects, non-linear time-varying muscle responses and other disturbances (fatigue, stiffness, and spasticity), will elicit variations in the FES system.

Fatigue and other non-linear effects hinder the real-time tuning of feedback controllers directly on the leg and knee of a patient during therapy [6], [7]. The conventional system identification process requires lengthy clinical setting time and is unsuitable due to dynamic muscle changes [8]. Therefore, one common approach is to perform the tuning process in the simulation stage, which allows for a controlled and safe environment for optimisation. An accurate simulation model incorporating the non-linear effects of muscles is also necessary to guarantee the performance of the controller [8]. Several feedback controllers, such as proportional–integral–derivative (PID) [9], fuzzy logic [10], neural network [11] and adaptive controllers [3], have been proposed. However, the proposed feedback control system demonstrates a decline in control performance in the presence of non-linearities. Therefore, the feedback controllers must be tuned appropriately to address the non-linearity problems, but the systems are complicated and costly.

The advantages of PID controllers over other feedback controllers lie in their robustness, simple design algorithms and stability. Additionally, PID controllers have been widely used in high-order systems since the early 20th century [12], [13]. If appropriately tuned, then the PID feedback controller can perform satisfactorily, even controlling systems with non-linearities. The key to the success of the PID controller lies in the tuning of gain parameter settings, which include proportional (Kp), integral (Ki) and derivative (Kd) gains. Notably, the PID feedback controller will perform poorly and fail if the gain parameters are incorrectly tuned. Several methods, including manual tuning, the Ziegler–Nichols (ZN) tuning method [14], [15], pole placement [16], genetic algorithm (GA) [9], gradient descent (GD) [17] and particle swarm optimisation (PSO), are available for the tuning of the PID feedback controller [3]. The open-loop ZN tuning method only applies to the first-order system, whilst the closed-loop ZN tuning method applies to the linear system [18], [19]. The challenge with the ZN tuning method lies in the preparation necessary to extract key parameters, such as steady-state gain, time delay and time constant, from an open-loop or first-order transient response curve [19]. When determining these parameters, a tangent line must be drawn on the transient-response line before the time delay and time constant can be identified. However, this process is prone to human error because it could be incorrectly interpreted, misrepresented or miscalculated. The closed-loop tuning method is relatively long because the process requires a slow increase in Kp gain until the system oscillates [19]. The controller performance of ZN tuning is generally acceptable but is not the best and is commonly defeated by other tuning methods in several under controlled systems [20]. Therefore, the ZN tuning method is unsuitable for the non-linear system response, in which the system response is unstable and tends to oscillate. Thus, the required parameters, such as steady-state gain, time delay and time constants, cannot be obtained from the non-linear system response.

The GD, GA and PSO optimisation methods require performance measurements such as fitness function. The fitness function represents the performance of the system. A steady-state error is generally used to indicate the performance of the system. The fitness function is easily obtained for a steady-state system. However, tuning a system that requires a transient response involving rise time, time delay, overshoot, steady state error and oscillation is difficult. These parameters must be extracted using digital signal processing, such as a system identification controller, for performance evaluation [3]. Overall, the GD, GA and PSO optimisation methods are complex and time consuming to prepare for the optimised gain settings.

By contrast, pole placement is simple when the system characteristic equation is known [16]. For the unknown characteristic equation, the input and output of the open-loop system must be obtained to determine the transfer function of the system. Pole placement is a fundamental control system technique applicable to transfer function-based systems controlled by feedback controllers such as PID [21], [22] and full-state feedback [23]. In rehabilitation engineering for lower limb exercise, the pole placement technique was used to tune the PID feedback controller for direct FES (or exoskeleton) [24], [25]. This method strategically positions the poles of the feedback controller to influence and shape the performance and behaviour of the system. The selection of pole locations is critical because it directly affects the response of the system to various inputs and disturbances [26]. Figure 1 illustrates the location of poles for the system and the controller. The x- and y-axes represent the real and imaginary values of the poles, respectively. The pole of the controller near the origin produces a highly stable system response. However, this enhanced stability often comes at the expense of a slow, transient response. In this context, pole placement is a powerful tool to fine-tune the behaviour of dynamic systems to meet specific requirements. System stability and the desirable response speed can be achieved by choosing suitable pole locations according to the desired performance criteria [16].

The performance of the PID feedback controller using the pole placement tuning method was investigated in this study. A non-linear knee model, which comprises fatigue, stiffness, spasticity and time delay, was also developed to accurately represent the actual non-linear effects of the muscle. The pole placement method was used to fine-tune the gain settings of the PID feedback controller to control the non-linear knee extension system for the closed-loop FES application. The tuned PID feedback controller was tested with and without a non-linear knee model in a MATLAB/Simulink environment. Finally, the performance of the PID feedback controller was investigated and analysed during testing with and without a non-linear knee model.

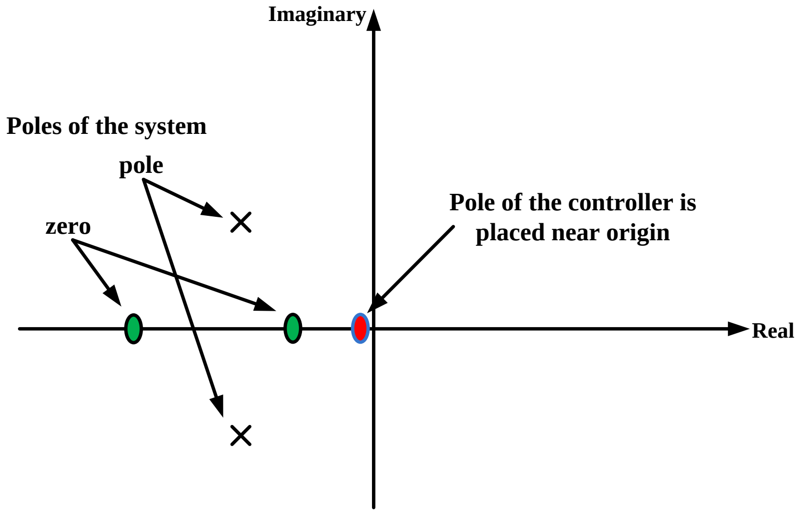


Figure 1. System and controller poles are placed near the origin

2. METHOD

This section discusses the design methodology of the knee extension model transfer function, the integration of non-linearities into the knee model, the detailed mathematical derivation of PID controller gain tuning settings using the pole placement method and the development of the PID controller and knee model using the MATLAB/Simulink environment. The design process started with modelling the non-linear knee extension for a closed-loop FES knee extension application and then the gain tuning of the PID controller using the pole placement method. The PID controller and knee model were developed and tested in MATLAB/Simulink environments once all the gain parameters were obtained.

2.1. Knee extension model

The second-order knee extension model was developed based on the mechanics of the human body using the control model of Veltink *et al.* [27], which was utilised in a controlled study on ankle joint movement. The study used an equation to establish the relationship between torque and angle movement. This relationship allowed for the characterisation of the knee angle trajectory response in correspondence to the electrical charges applied to the muscle. The mathematical framework used to describe these dynamics involves linear differential equations and transfer functions, as presented in (1) and (2), respectively. These equations are the foundation for understanding and quantifying the intricate interplay between electrical stimulation, muscle response and joint movement in controlled experiments and modelling within biomechanics or related disciplines.

$$M = I\ddot{\theta} + B\dot{\theta} + \frac{\theta - \theta nom}{C} \tag{1}$$

$$\frac{\theta(s)}{M(s)} = \frac{1}{(Is^2 + Bs + \frac{\theta - \theta_{nom}}{C})} \tag{2}$$

Where:

- M : Joint torque
- θ : Joint angle
- $\dot{\theta}$: Joint angle velocity
- $\ddot{\theta}$: Joint angle acceleration
- θ_{nom} : Angle at which the steady-state torque is equal to zero
- I : Inertia
- B : Damping

C : Compliance with the load = $\frac{1}{m \times g \times l}$
m : Shank weight (7 kg)
l : Length to the centre of the shank
g : Gravity (9.81 m/s^2)

As shown in (3) is derived from (1) and is used to establish a physical-based model.

$$\ddot{\theta} = \iint \frac{M - B\dot{\theta} - \frac{\theta - \theta_{nom}}{C}}{I} \quad (3)$$

A system-to-be-controlled transfer function model (knee extension model) must be established for tuning the PID controller. The knee extension model, which requires specific system parameters and dynamics, was developed using the method employed by Veltink *et al.* [27]. The given parameters were used in (2) to create such a model:

– Mass (m) = 7 kg.
– Damping coefficient (B) = Given.
– Shank length (L) = 0.32 metres.
– ζ (Damping ratio) = 1 (for critical damping).

The established transfer function model from (2) for the knee extension model is updated, as shown in (4).

$$\frac{418.5}{(s^2 + 36.99s + 61.31)} \quad (4)$$

2.1.1. Knee model non-linearities

The knee extension model was introduced with non-linear effects of fatigue, spasticity, stiffness and time delay to further test the capability of the pole placement method. These effects considerably influence muscle torque and the knee trajectory response. Figure 2 shows the block module of the system with non-linearities. The subsequent sections provide detailed explanations of specific muscle non-linearities, including fatigue, time delay, stiffness and spasticity.

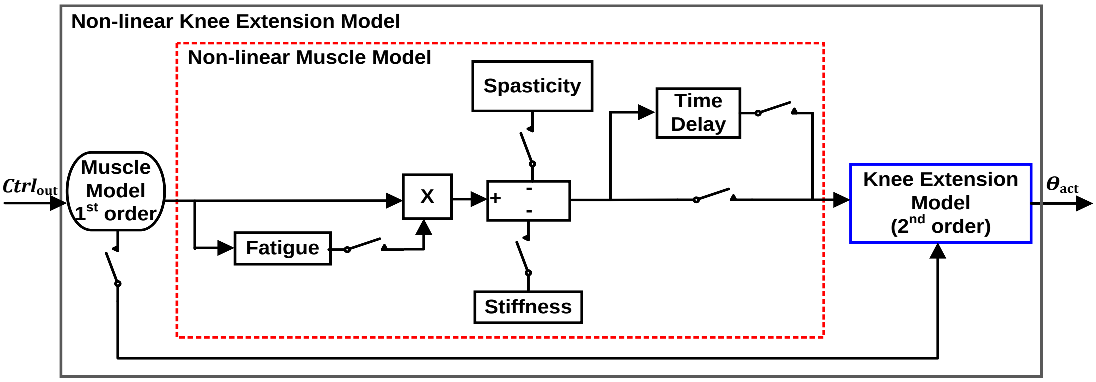


Figure 2. Internal architecture of the knee extension model with non-linearities [3]

a) Muscle fatigue effect

Muscle torque decreases over time with the introduction of muscle fatigue. The value of the fatigue waveform ($T_{fat}(t)$) ranges between 0 and 1 in the time domain, with 1 corresponding to no fatigue and 0 corresponding to no measurable response to stimulation [28]. The muscle torque rapidly decreases when the fatigue is high. As shown in (5) and (6) represent the fatigue effect for mild and severe fatigues in the time domain, respectively.

$$T_{fat}(t) = \big(1 - (cout * ftqc)\big) for\ all\ \ t < 8.5\ s \quad (5)$$

$$T_{fat}(t) = (1 - (cout * ftqc1))\ for\ all\ \ t\ > 8.5\ s \quad (6)$$
$$T_{fat}(t) = 0, for\ all\ \ t\ > 20\ s$$

b) Muscle spasm and spasticity

The non-linearities of spasm and spasticity included in the simulation model to represent the spasticity effect derive the spastic hamstrings torque as (7) [28]:

$$T_{spastics}(t) = T_{spasm}(t)\bar{l}sin\,\psi(t) \tag{7}$$

where $T_{spasm}(t)$ denotes the tension in the hamstrings due to the spasm. Assume that the distance (denoted as $\bar{l}$) between the centre of knee rotation and the point at which the biceps femoris muscle inserts into the fibula is 5 cm. The angle between the longitudinal axis of the hamstrings and the axis of the shank can be expressed as in (8).

$$\psi(t) = \pi - \phi(t) - (\pi/2 - \theta(t)) \tag{8}$$

The tension in the hamstrings due to spasticity is defined in (9) [28]:

$$T_{spasm}(t) = \begin{cases} 0, & \forall\, \dot{\theta}(t) < 0 \\ 0, & \forall\, \dot{\theta}(t) \geq 0 \quad and\ t < T_d \\ \lambda\dot{\theta}(t) & otherwise \end{cases} \tag{9}$$

where T_d represents the time delay between the initiation of stretching and the onset of contraction due to the stretching, which is set at 40 ms. The parameter ƛ is chosen to ensure the occurrence of the highest spastic torque at the maximum knee angular velocity.

c) Muscle stiffness

Muscle stiffness is a critical factor that impacts the behaviour of the knee extension system. As shown in (10) controls for the muscle stiffness [28].

$$T_{stiffness}(t) = \lambda e^{-E(\theta(t)+\frac{\pi}{2})} + (\theta(t) + \frac{\pi}{2} - w) \tag{10}$$

Including muscle stiffness in the simulation knee model is essential for gaining insights into the nuanced behaviour of the knee extension system. This non-linearity accurately represents real-world scenarios and the transient influence of stiffness on muscle torque during movement initiation.

d) Time delay

A two-fold approach is employed to simulate the time-delay effect. A built-in MATLAB/Simulink transportation delay icon was used for simple scenarios. This direct method enables the integration of time delays into the model when the fatigue level is relatively uncomplicated. The effects of muscle non-linearities on muscle torque are presented in the result and discussion sections.

2.2. PID controller gain tuning settings

The mathematical equations of the PID controller represented in the Laplace transform are shown in (11) to (14).

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt}\right) \tag{11}$$

$$u(s) = K_p\left(e(s) + \frac{1}{T_i}E(s) + T_d sE(s)\right) \tag{12}$$

$$u(s) = E(s)\left(K_p\left(1 + \frac{1}{T_i} + T_d s\right)\right) \tag{13}$$

$$\frac{U(s)}{E(s)} = K_p(s)\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{14}$$

The open-loop transfer function of PID controller gains can be extracted using (15) to (17).

$$K_p\left(1 + \frac{1}{T_i s} + T_d s\right) = (K_p + \frac{K_i}{s} + K_d s), \tag{15}$$

$$\frac{1}{T_i s} = \frac{K_i}{s} \tag{16}$$

$$T_d s = K_d s \quad (17)$$

For the pole placement tuning technique, the controller must initially be connected to the system in an open-loop connection to establish an open-loop equation. The controller must then be connected to the system in a closed-loop connection to establish the closed-loop equation. In this work, the PID controller is firstly connected to the knee model in an open-loop connection, as shown in Figure 3. The mathematical equations for the open-loop form are shown in (18) and (19).

$$G(s)H(s) = C(s)P(s)H(s) = \left(K_p + \frac{K_i}{s} + K_d s\right) x \left(\frac{418.5}{s^2 + 36.99s + 61.31}\right) x\ 1, \quad (18)$$

$$(s)H(s) = \frac{418.5(Kds^2 + Kps + Ki)}{s(s^2 + 36.99s + 61.31)}. \quad (19)$$

For the closed-loop pole placement tuning, the PID controller is connected to the knee extension model in a closed-loop connection, as shown in Figure 4. The mathematical equation for the closed-loop connection is shown in (20).

$$\frac{G(s)H(s)}{1 + G(s)H(s)} = \frac{418.5(Kds^2 + Kps + Ki)}{s(s^2 + 36.99s + 61.31) + 418.5(Kds^2 + Kps + Ki)}. \quad (20)$$

The rearrangement of (14) leads to the following (21):

$$\frac{G(s)H(s)}{1 + G(s)H(s)} = \frac{Kds^2 + Kps + Ki}{(s^3 + (418.5Kd + 36.99)s^2 + (61.31 + 418.5Kp)s + 418.5Ki)}. \quad (21)$$

The knee extension equation cannot be directly factorised. Therefore, (22) addresses this factorisation complexity.

$$\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}. \quad (22)$$

Based on the knee model, (4) denominator $(s^2 + 36.99s + 61.31)$, the parameters in (16) are set as follows: $a = 1, b = 36.99, c = 61.31$ and shown in (23).

$$\frac{-36.99 \pm \sqrt{36.99^2 - 4x(61.31)}}{2} \quad (23)$$
$$-18.495 \pm \frac{\sqrt{1123.1}}{2}$$
$$-18.495 \pm 18.38.$$

As shown in (23) indicates the results of a pole at -18.5 and -18.3 for real and imaginary values, respectively. In (24), the PID controller poles are placed in three similar locations (-13) to form a new characteristic equation. The relocation of system poles to -13 is a deliberate strategy to slow down the response of the system (knee extension model). Careful consideration and analysis are required to balance the realisation of the desired response time and maintain system stability, ensuring that the gain remains positive to enable effective control.

$$(s + 13)(s + 13)(s + 13) \;=>\; (s^3 + 39s^2 + 507s + 2197). \quad (24)$$

Notably, bypassing the system poles by bringing the controller poles closer to the origin effectively introduces high stability and reduces the overall system sensitivity to changes and disturbances. However, exercising caution when determining the new pole locations is essential. Suppose the selected pole locations are too far from the original system poles (especially for system poles closer to the origin). This phenomenon can lead to an unfavourable outcome where the gain in the system becomes negative. This situation is undesirable and leads to an unstable and ineffective response from the controller. The denominator of the closed-loop system from (21) is equated with the equation for the new pole placement characteristics, as shown in (18). The result of these equivalent equations is presented in (25).

$$(s^3 + (418.5Kd + 36.99)s^2 + (61.31 + 418.5Kp)s + 418.5Ki) = (s^3 + 39s^2 + 507s + 2197) \quad (25)$$

The closed-loop system denominator from (21) containing Laplace domain s^2 is equated with the pole placement in (24) also containing Laplace domain s^2 to determine the PID derivative gain (Kd). The solution of these equivalent is shown in (26).

$$\begin{aligned}&(418.5Kd + 36.99) = 39 \\ &418.5Kd = 2.11 \\ &Kd = 0.005\end{aligned} \quad (26)$$

The closed-loop system denominator from (21) containing Laplace domain s is equated with the pole placement as in (18) also containing Laplace domain s to determine the PID proportional gain (Kp). The solution of these equivalent is shown in (27).

$$\begin{aligned}&(418.5Kp + 61.31) = 507 \\ &418.5Kp = 445.69 \\ &Kp = 1.06\end{aligned} \quad (27)$$

The closed-loop denominator of (21) without Laplace domain s is equated with the pole placement as in (24) also without Laplace domain s to determine the PID integrator gain (Ki), resulting in (28). The obtained values of PID controller gains for Kd, Kp, and Ki are shown in (29).

$$\begin{aligned}&418.5Ki = 2197 \\ &Ki = 5.249\end{aligned} \quad (28)$$

$$Kp = 1.06, Kd = 0.005, Ki = 5.249 \quad (29)$$

Indeed, the PID controller parameters obtained through the pole placement technique form a solid foundation for control. Thus, acknowledging that these values might necessitate some fine-tuning and adjustment in practice is essential. The real-world dynamics of a system can introduce variations and uncertainties that may not be fully accounted for during the initial design and tuning process. Therefore, conducting practical testing and potentially adjusting the gains of the controller are often advisable to ensure optimal performance under actual operating conditions. This iterative process of adjustment and optimisation allows for the precise tailoring of the PID controller to the specific characteristics and variations encountered in the system it controls. Ultimately, this process ensures the effective operation of the controller, delivering the desired control performance and maintaining stability across various operational scenarios. Consider placing the poles at three similar locations, that is, -12, which results in the pole placement characteristics of the controller, as shown in (30).

$$(s + 12)(s + 12)(s + 12) => (s^3 + 12s^2 + 288s + 24s^2 + 144s + 1728). \quad (30)$$

The closed-loop system denominator from (21) is equated with the equation for the new pole placement characteristics in (30), resulting in (31).

$$\begin{aligned}&(s^3 + (418.5Kd + 36.99)s^2 + (61.31 + 418.5Kp)s + 418.5Ki) = \\ &(s^3 + 36s^2 + 532s + 1728).\end{aligned} \quad (31)$$

The closed-loop system denominator from (21) containing Laplace domain s^2 is equated with the pole placement in (31) also containing Laplace domain s^2 to determine the PID derivative gain (Kd). The solution of these equivalent is shown in (32).

$$\begin{aligned}&(418.5Kd + 36.99) = 36 \\ &418.5Kd = -0.99\end{aligned} \quad (32)$$

Suppose the final result of the PID derivative gain (Kd) is a negative value. Therefore, identification of the PID proportional (Kp) and integral (Ki) gain values can be stopped because negative results should not be obtained for all PID gains. This negative result indicates that the poles cannot be lower than -13.

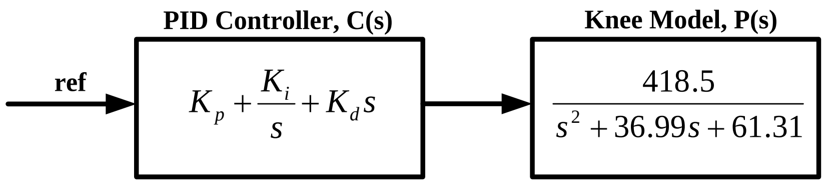


Figure 3. Open-loop connection of the PID controller and knee model

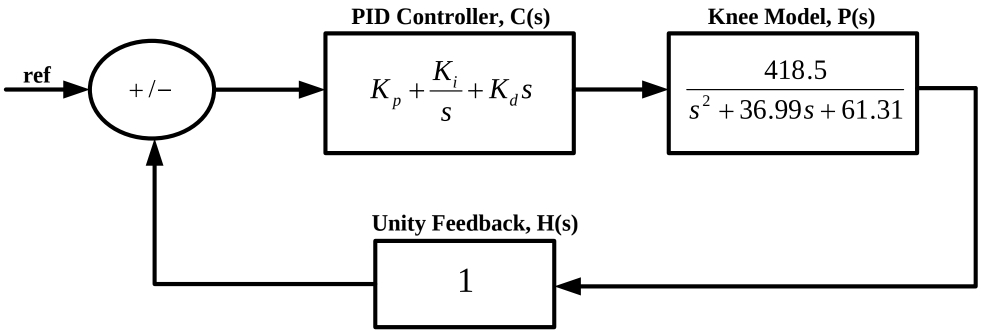


Figure 4. Closed-loop connection of the PID controller and knee model

2.3. Development of PID controller and knee model in MATLAB/Simulink

Figure 5 depicts the top level of the closed-loop FES system, which comprises the designed PID feedback controller and the knee extension model developed using MATLAB/Simulink. The internal block of the PID feedback controller is shown in Figure 6. Figure 7 depicts the internal block design of the knee extension model to be controlled by the PID feedback controller. Figure 8 illustrates the internal block design of the knee extension model to be controlled by the PID feedback controller with non-linear effects (fatigue, stiffness, spasticity and time delay) incorporated into the knee model.

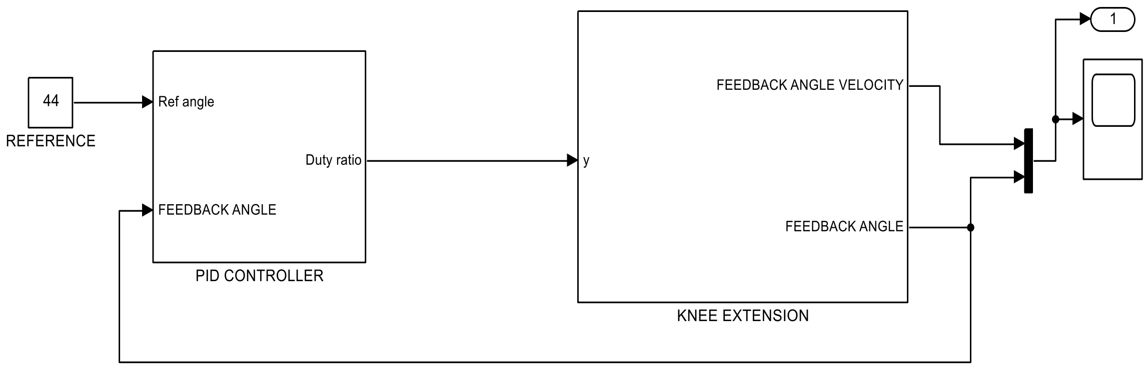


Figure 5. Closed-loop FES system using PID controller and non-linear knee model

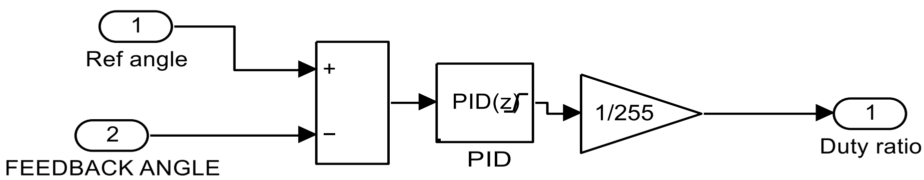


Figure 6. Internal architecture of PID controller

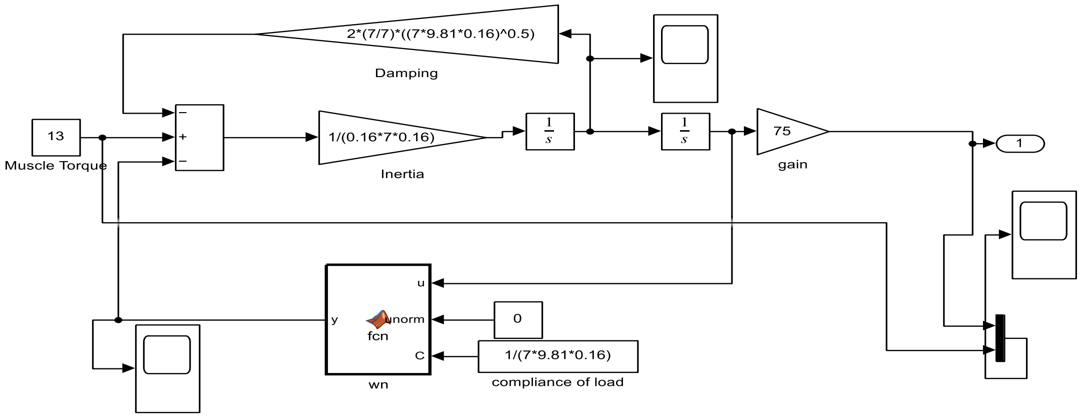


Figure 7. Internal architecture of knee extension model

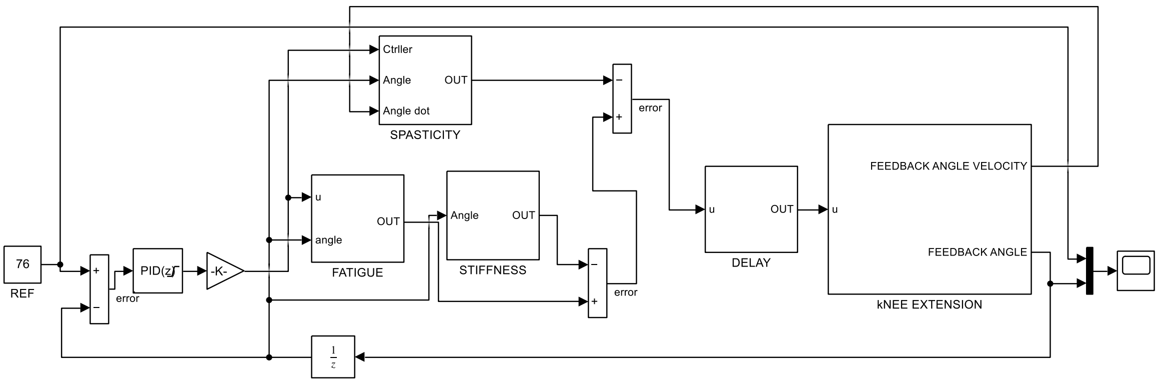


Figure 8. Knee extension model with non-linearities in MATLAB/Simulink

3. RESULTS AND DISCUSSION

This section discusses the performance of the PID controller using pole placement tuning when tested with the knee extension model. This testing primarily aimed to assess the control bandwidth of the PID controller under varying conditions. Initially, the PID controller was tested with a knee extension model without non-linearity and later with non-linearities (fatigue, time delay, stiffness and spasticity). The controller is subjected to testing with four distinct reference angles, which include 20°, 30°, 40°, and 76°, to rigorously evaluate the efficacy of the tuning approach.

3.1. Knee response without non-linearity

Figure 9 depicts the knee angle response at four reference angles (20°, 30°, 40°, and 76°) without non-linearity for the PID controller. The critical performance parameters of the PID controller, which include rise time, settling time, overshoot and steady-state error at four reference angles (20°, 30°, 40°, and 76°), are tabulated in Table 1. Figure 9(a) shows the knee angle responses of the PID controller in the absence of any non-linearity during the initial application of the pole placement technique. An initial overshoot is observed for all reference angles, accompanied by some degree of oscillation. However, despite these transient behaviours, the system stabilises at the desired setpoint, finally attaining a zero steady-state error. Details of the performance of critical parameters are tabulated in Table 1. Under the column of first PID tuning in Table 1, the tabulated results show that the rise and settling times of the PID controller increase with the reference angles. The overshoot at this initial PID tuning helped identify areas for improvement and refinement of the controller parameters to achieve the desired system behaviour.

The most crucial change was the elimination of overshooting and stabilising the system. Based on the obtained results in Figure 9(a) and Table 1 (column first PID tuning), an analysis focusing on the issue of overshoot was conducted by reducing the PID integral gains [28] by a factor of two ($Ki = 2.6$). Figure 9(b) and Table 1 (column second PID tuning) indicate the outcomes after fine-tuning the PID integral gain ($Ki = 2.6$). As shown in Figure 9(b) and tabulated in Table 1 (column second PID tuning), the knee response has almost zero steady-state error, no oscillations and no overshoot. These outcomes highlight the effectiveness of the tuning method in ensuring balanced precision and stability in controlling the system. Additionally, these changes considerably impacted the performance of the system. This result emphasises the practical benefits of fine-tuning the controller parameters and demonstrates the pivotal role of gain adjustments in optimising the behaviour of the system.

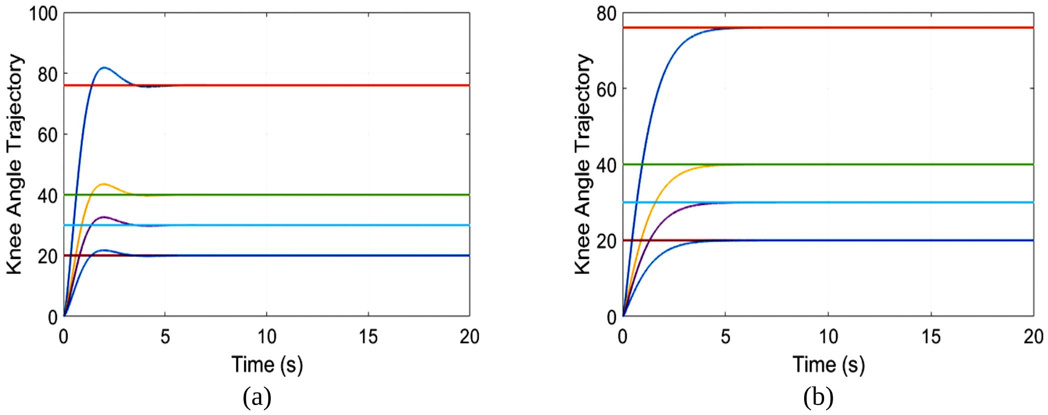


Figure 9. Knee angle response, (a) knee angle response for first PID tuning with gain settings: $Kp = 1.06$, $Kd = 0.005$, $Ki = 5.249$ and (b) knee angle response for second PID tuning with gain settings: $Kp = 1.06$, $Kd = 0.005$, $Ki = 2.6$. The reference angle (ref) and knee response (resp) are represented in different coloured lines as follows: (i) ref 76°: orange and resp: blue; (ii) ref 40°: light green and resp: yellow; (iii) ref 30°: light blue and resp: purple; (iv) ref 20°: red and resp: blue

Table 1. Performance of PID controller for first and second tuning

Gain Settings	First PID Tuning (Kp = 1.06, Kd = 0.005, Ki = 5.249)				Second PID Tuning (Kp = 1.06, Kd = 0.005, Ki = 2.6)			
Ref. Angle	20°	30°	40°	76°	20°	30°	40°	76°
Rise Time (s)	0.95	0.95	0.95	0.96	2.22	2.22	2.22	2.22
Settling Time (s)	1.33	1.3	1.34	1.35	3.75	3.75	3.75	3.75
Overshoot	1.689°	2.533°	3.378°	5.774°	0°	0°	0°	0°
Steady-state error	−1.719°	−2.579°	−3.438°	0.1008°	0.7076°	0.6821°	0.658°	0.18°

3.2. Muscle torque response due to non-linearity effects

The muscle non-linearity effects that influence muscle torque, which include fatigue, spasticity, stiffness and time delay, are shown in Figure 10. Figure 10(a) demonstrates the muscular torque on fatigue. The rate at which the muscle torque diminishes accelerates with the intensification of the fatigue effect. Figure 10(b) illustrates the spasticity torque, which exhibits positive and negative values, causing a disturbance to muscular torque in the presence of spasticity non-linearities. The positive values of the spasticity torque will be added to the muscle torque generated from the FES device, leading to an increase in total torque. By contrast, the negative values will decrease muscle torque. Figure 10(c) shows the stiffness torque, which elicits resistance to muscular torque. Initially, the stiffness effect is at its maximum at a zero knee angle. As the angle increases, the stiffness effect decreases until it reaches 35° of elevation, thereby reducing the stiffness torque. Figure 10(d) demonstrates the time delay effect on the muscle torque. Notably, the time delay effect on the muscular torque can cause instability and oscillation issues in the closed-loop system.

3.3. Knee angle response with non-linearity effects

Figure 11 depicts the knee angle response at four reference angles (20°, 30°, 40° and 76°) with fatigue Figure 11(a) and spasticity Figure 11(b) non-linearities. As shown in Figure 11(a), the PID controller performs at low reference angles (20°, 30° and 40°) when fatigue non-linearity is incorporated into the knee model. However, the performance of the PID starts to degrade around 6 s for the high reference angle of 76°. As indicated in Figure 11(a), the knee angle trajectory begins to drop substantially at around 6 s. The drop in knee angle trajectory after 6 s indicates that muscle fatigue markedly affects the knee angle trajectory at a high reference angle (76°). Consequently, the steady-state error substantially increased after 6 s, reaching a value around 30° (76° − 46° = 30°) at the reference angle of 76°, as shown in Figure 11(a). Details of the performance of critical parameters are tabulated in Table 2.

The knee angle responses of the PID with spasticity at four different reference angles (20°, 30°, 40° and 76°) are shown in Figure 11(b). The spasticity effect causes the knee response to oscillate at reference angles of 20° and 76°. The oscillation of the knee response for the PID controller is highly prominent and substantial at the low reference angle (20°) and the high reference angle (76°). The PID controller exhibits poor performance, with remarkable knee response oscillation at small and high reference angles (20° and 76°, respectively). The PID controller demonstrates steady-state error around 2° to 3° at high and small reference angles (76° and 20°, respectively). The knee-angle trajectory oscillating response behaviour indicates that the PID controller cannot compensate for the effect of spasticity, especially at small and high reference angles (20° and 76°, respectively). The PID is considered capable of control only at the middle reference angle (30° and 40°), but the result is unsatisfactory at low and high reference angles (20° and 76°, respectively). These outcomes indicate that the presence of spasticity lowers the PID control bandwidth.

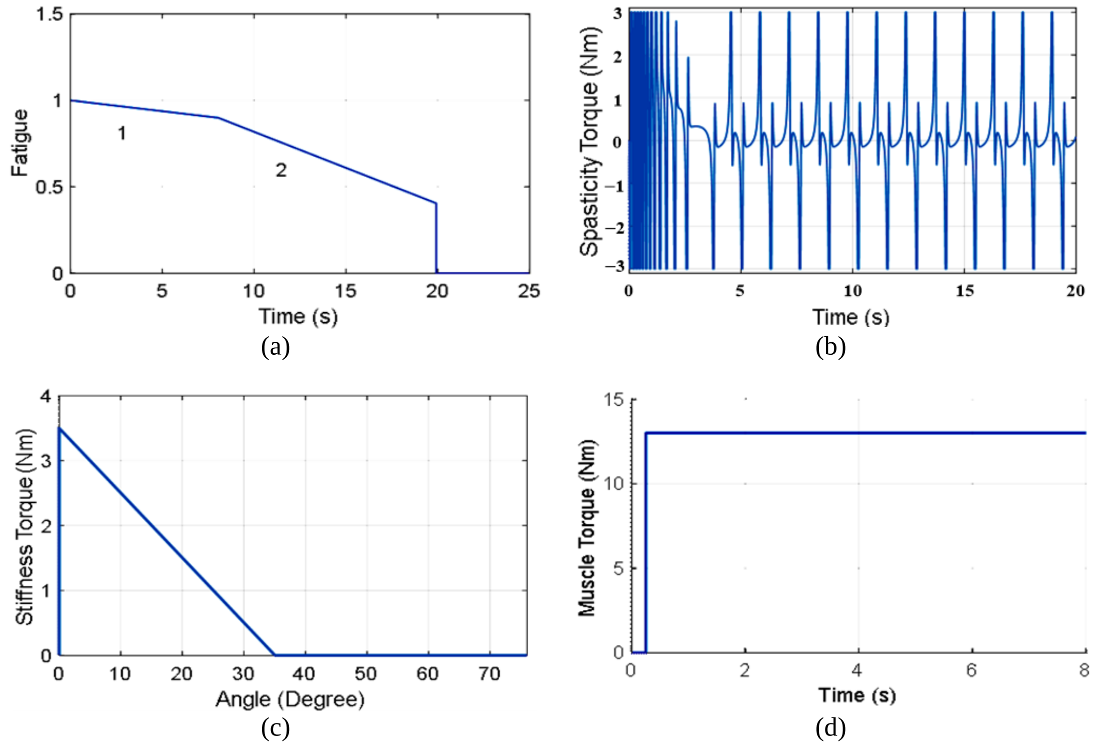


Figure 10. Muscle torque response due to non-linearity effect, (a) effect of fatigue non-linearity, (b) effect of spasticity, (c) effect of stiffness, and (d) effect of time delay

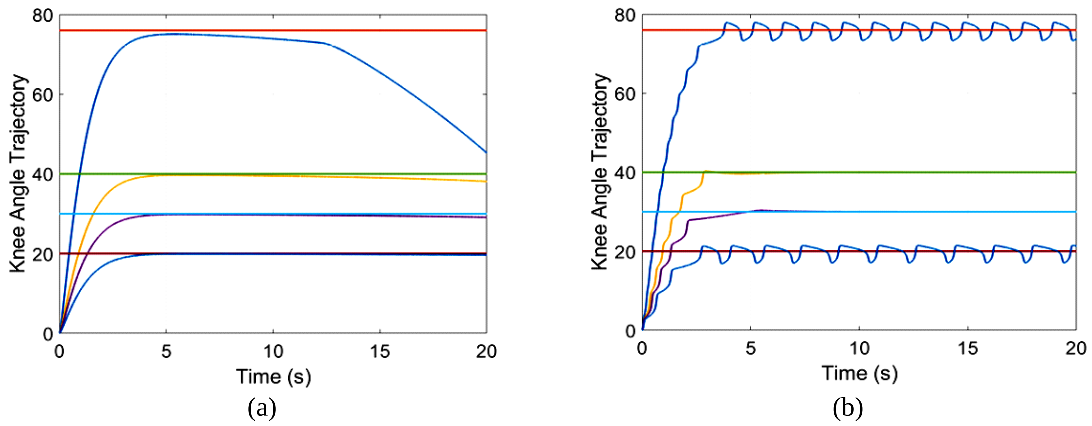


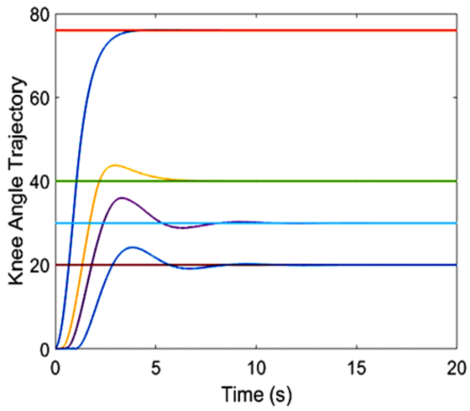
Figure 11. Knee angle response with non-linearities (fatigue/spasticity), (a) Knee angle response with fatigue non-linearity and (b) Knee angle response with spasticity non-linearity. The reference angle (ref) and knee response (resp) are represented in different coloured lines as follows: (i) ref 76°: orange and resp: blue; (ii) ref 40°: light green and resp: yellow; (iii) ref 30°: light blue and resp: purple; (iv) ref 20°: red and resp: blue

Table 2. Fatigue and spasticity non-linearities

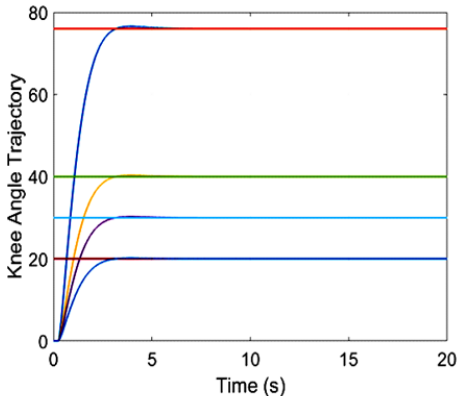
Non-linearity	Fatigue				Spasticity			
Ref. Angle	20°	30°	40°	76°	20°	30°	40°	76°
Rise Time (s)	2.22	2.23	2.23	2.24	2.52	1.96	2.34	2.69
Settling Time (s)	3.81	3.85	3.88	4.05	2.74	4.23	2.83	3.69
Overshoot	−0.075°	−0.16°	−0.279°	−0.9327°	1.458°	0.3178°	0.3285°	1.93°
Steady-state error	0.243°	0.2975°	0.3946°	0.988°	3.041°	−0.3163°	0.3457°	2.076°

Figure 12 depicts the knee angle response at four reference angles (20°, 30°, 40° and 76°) with stiffness Figure 12(a) and time delay Figure 12(b) non-linearities. Table 3 summarises the critical parameters of the PID performance. As shown in Figure 12(a) and tabulated in Table 3 (column stiffness), the PID with stiffness non-linearity causes high overshoot around the value of 3.7° to 5.9° in the knee response, especially at low reference angles (20°, 30° and 40°). The PID controller can also control the stiffness non-linearity only at a high reference angle (76°). However, the results are unsatisfactory at low reference angles (20°, 30° and 40°). Therefore, the presence of stiffness non-linearity lowers the PID control bandwidth.

The knee angle responses of the PID with a time delay of 250 ms at four different reference angles (20°, 30°, 40° and 76°) are shown in Figure 12(b). A detailed summary of critical parameters of the PID performance is tabulated in Table 3 (column time delay). The knee response for the PID controller is relatively smooth without oscillation at all reference angles. Thus, the PID can control all reference angles, indicating high control bandwidth in the presence of time delay non-linearity despite the presence of small overshoots at all reference angles.



(a)



(b)

Figure 12. Knee angle response with non-linearities (stiffness/time delay), (a) Knee angle response with stiffness non-linearity, and (b) Knee angle response with time delay non-linearity. The reference angle (ref) and knee response (resp) are represented in different coloured lines as follows: (i) ref 76°: orange and resp: blue; (ii) ref 40°: light green and resp: yellow; (iii) ref 30°: light blue and resp: purple; (iv) ref 20°: red and resp: blue

Table 3. Stiffness and time delay non-linearities

Non-linearity	Stiffness				Time Delay (250 ms)			
Ref. Angle	20°	30°	40°	76°	20°	30°	40°	76°
Rise Time (s)	1.24	1.26	1.26	1.69	1.64	1.64	1.64	1.64
Settling Time (s)	2.82	2.37	2.16	3	2.75	2.75	2.75	2.75
Overshoot	4.177°	5.978°	3.767°	0.07°	0.1561°	0.2342°	0.3123°	0.5933°
Steady-state error	0.112°	0.051°	−0.031°	−0.012°	−0.1151°	−0.211°	−0.2923°	−0.5892°

3.4. Comparative analysis of PID controller performance

The performance of the tuned PID controller was further investigated and compared with other PID tuning methods reported by other researchers, which include Neto *et al.* [29], Lynch and Popovic [28] and Benahmed *et al.* [5]. Table 4 compares the performance characteristics of the tuned PID controller utilising the pole placement method to those reported by other researchers using different tuning methods such as PID–ZN [29], piecewise-affine (PID–PWA) [29] and trial-and-error methods [5], [28]. Notably, this comparison was based on the knee extension model at a reference angle of 40° without any non-linearity effects. The tabulated results indicate that the rise time of the PID–ZN tuning method (0.2 s) is the smallest, followed by the PID–PWA tuning method (0.32 s). The rise times of pole placement and trial-and-error tuning methods are almost similar, around 2.2 s. Although the PID–ZN tuning method has the shortest rise time, the PID controller has the latest settling time (10.99 s) and the highest overshoot (50.8°). By contrast, the proposed PID with pole placement tuning method has the fastest settling time (3.75 s) and zero overshoot (0°). The steady-state error of the PWA–PID is the smallest (0.3°), followed by the proposed pole placement PID tuning method (0.65°). Overall, the designed PID controller using the pole placement tuning method demonstrated the best performance compared to other tuning methods. This finding is due to the fastest settling time (3.75 s), zero overshoot (0°) and reasonable small steady-state error (0.65°) of the designed PID controller for the reference angle at 40°. Zero overshoot and small steady-state errors ensure stability in the system and the absence of overstimulation. Additionally, the small value of steady error indicates that the PID controller can provide an accurate stimulus charge to reach the target angle. Although the proposed PID controller using the pole placement tuning method has a slower rise time (2.22 s) compared to the PID–ZN (0.2 s) and PID–PWA (0.32 s) tuning methods, the value is still acceptable and reasonable for knee extension exercise. Fast rise times do not represent the overall performance, and the uncontrolled fast rise time may induce oscillation, resulting in a long settling time. Additionally, fast rise time may contribute to overshoot effects. The most important criteria for the closed-loop FES knee extension exercise are that patients can maintain the target angle for a specific duration and perform the exercise repeatedly for an extended period according to their conditions [10]. Therefore, low steady-state errors and small overshoots are essential to prevent overstimulation and early fatigue.

Table 4. Comparison of PID feedback controller performance from other research work

Proposed by	Type of Controller	Ref Angle (Deg)	Rise Time (s)	Settling Time (s)	Overshoot (Deg)	Steady State Error (Deg)
Neto, *et al.* [29]	ZN–PID	40°	0.20	10.99	50.8°	0.9°
Neto, *et al.* [29]	PWA–PID	40°	0.32	9.5	14.4°	0.3°
Lynch and Popovic [28]	PID (Trial and error)	40°	2.24	5.0	0°	11.07°
Benahmed, *et al.* [5]	PID (Trial and error)	40°	2.20	7.69	5.72°	16.31°
Current work	PID (Pole placement)	40°	2.22	3.75	0°	0.65°

3.5. Summary of analyses

Overall, the PID controller can effectively control the closed-loop system for the knee model without non-linearity. This performance can be attributed to PID, which is a linear feedback controller that can work well with a linear system. However, the PID controller has some limitations in controlling knee models with non-linearities, which include fatigue, spasticity and stiffness. For fatigue non-linearity, the PID controller has demonstrated good performance at lower reference angles (20°, 30°, and 40°) and degraded performance at a higher reference angle of 76°. For stiffness, the PID demonstrated good control performance at a higher reference angle (76°) and degraded performance at lower reference angles (20°, 30°, and 40°). For spasticity, the PID controller demonstrated reasonable control at the middle reference angles (30° and 40°) and poor control performance for the lower and upper reference angles (20° and 76°, respectively). These failure occurrences were predominantly due to unknown non-linear parameters that were fed into the non-linear equations. These unknown parameters resulted in an inaccurate equation for fine-tuning PID controller settings. Two methods can be implemented to address the non-linearity problems. The first method is to employ system identification to determine the non-linearities and then update the equations and define a new PID controller [30]. The second method incorporates feedforward and direct torque control (DTC) in the PID controller to cater to specific issues such as stiffness and spasticity. Determining the gain settings of the PID controller is difficult because three parameters must be determined without knowing the particular points, areas and ranges for these parameters. The trial-and-error method requires a lengthy duration to obtain optimised gain parameter settings. By contrast, pole placement enables a shorter duration to obtain the optimised PID gain parameter settings, producing satisfactory results. Hence, the pole placement method is suitable for initial or first-stage tuning, providing references to the tuning range for further optimisation using GA, GD and PSO. The performance of the PID controllers was further investigated by comparing them with other tuning methods reported in other studies. The proposed PID controller demonstrated good control performance and stability by displaying the fastest settling time, zero overshoot and reasonably small value of steady-state error compared with other studies when tested with a knee extension model without non-linearity effects.

4. CONCLUSION

Overall, this study exhibits the application of a pole placement technique to optimise PID controller parameters within a simulated environment. The enhanced performance of the PID controller when applied to a knee extension model was demonstrated through rigorous evaluation. The outcomes confirm the efficiency of the pole placement method in effectively controlling the knee extension system. Additionally, when comparing the proposed PID controller using the pole placement tuning method with other PID tuning methods, the proposed PID was found to be more effective than other tuning methods in terms of stability, fast settling time and low steady-state error. However, when non-linearities were present and extreme to the controller, the performance of the PID controller varied in accordance with the type of non-linearities. For some, such as time delay, the PID controller worked satisfactorily at all reference angles; for others, stiffness worked only at higher reference angles (76°) and spasticity at middle reference angles (30° and 40°), which lowers the PID control bandwidth. For fatigue non-linearity, the PID controller worked fine at the early transient response but degraded at the end due to fatigue effects, especially at a high reference angle (76°), which degraded early at 6 s. The PID performance can be further enhanced by employing feed-forward control and DTC to control specific non-linearities such as stiffness and spasticity. The results acquired strongly demonstrated the effectiveness of the pole placement method, highlighting its optimisation of the PID control and enhancing the closed-loop FES system for peak performance. The pole placement tuning method provided early insights into PID controller performance before further detailed optimisation using GA, GD or PSO. Furthermore, using the pole placement tuning method reduced the tuning range and duration required to determine the gain settings of the PID controller. Overall, the pole placement tuning method facilitates the establishment of initial tuning range settings and accelerates the overall tuning process for the gain settings of the PID controller.

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