Title: A Hybrid-FES Based Control System for Knee Joint Movement Control: Controller Synthesis and Simulation

Authors: Mojdeh Rastegar, Hamid Reza Kobravi

1. Research Center of Biomedical Engineering, Islamic Azad University of Mashhad, Mashhad, Iran.

*Corresponding author: Hamid Reza Kobravi, Research Center of Biomedical Engineering, Islamic Azad University of Mashhad, Mashhad, Iran. E-mail: hkobravi@mshdiau.ac.ir

To appear in: Basic and Clinical Neuroscience

Received date: 2019/05/1
Revised date: 2020/04/25
Accepted date: 2020/04/27
This is a “Just Accepted” manuscript, which has been examined by the peer-review process and has been accepted for publication. A “Just Accepted” manuscript is published online shortly after its acceptance, which is prior to technical editing and formatting and author proofing. Basic and Clinical Neuroscience provides “Just Accepted” as an optional and free service which allows authors to make their results available to the research community as soon as possible after acceptance. After a manuscript has been technically edited and formatted, it will be removed from the “Just Accepted” Web site and published as a published article. Please note that technical editing may introduce minor changes to the manuscript text and/or graphics which may affect the content, and all legal disclaimers that apply to the journal pertain.

Please cite this article as:
Rastegar, M., & Kobra\v{r}i, H.R. (In Press). A Hybrid-FES Based Control System for Knee Joint Movement Control: Controller Synthesis and Simulation. Basic and Clinical Neuroscience. Just Accepted publication Jul. 7, 2021. Doi: http://dx.doi.org/10.32598/bcn.2021.173.3

DOI: http://dx.doi.org/10.32598/bcn.2021.173.3
Abstract

In this paper, a new control algorithm has been proposed which was designed based on a combination of functional electrical stimulation (FES) and an active mechanical actuator to control the knee joint movement. An adaptive controller and a PD controller have adjusted the motor torque and stimulation intensity, respectively. The FES controller was activated whenever a disturbance observer detected the presence of the external disturbance. In this manner, the occurrence of the muscle fatigue arises from the FES can be postponed. The simulation studies were carried out on a model of muscle-joint system along with a model of a servo-motor. The achieved results prove the ability of the proposed control strategy to not only reject the external disturbance but also compensate the muscle fatigue. In this research, the trajectories envisioned as the knee joint reference trajectory were designed using the recorded human data.

Keywords: FES, Hybrid Neuroprosthesis, Movement Control, Adaptive Controller, PID Control
1. Introduction

Neural system injuries often inflict untreatable disability on the afflicted patients. Thus, the rehabilitation can play an important and effective role in the maximal restoration of daily activities for such patients. One of the well-known technologies with expansive application is exoskeleton robots. These systems are wearable robots which can provide the required joint torques needed for human movement. In this manner the exoskeletons are used to rehabilitate people who suffer from a disability in a certain part of their body. These robots can be utilized for different parts of the body including the arms, the legs, the waist, etc. [1-3]. Many works have been conducted in the field of exoskeletons. Some of the reported works are focused on rehabilitation of the lower limbs [4-9]. Different categories of the adaptive and nonadaptive control strategies have been utilized for position control or torque control in the exoskeletons [4]-[10-15]. The servo-motors are usually are uses as the main actuators of such robots [16]-[17]. Some acceptable reported results convince the researcher to believe in the exoskeletons as a promising rehabilitation technology. Nevertheless, this technology faces some limitations.

Another group of the well-known tools for rehabilitation are technologies work based on functional electrical stimulation (FES). The FES based devices are delivering the electrical pulses to the involved muscle nerves to restore the movement. Many works have been focused on adopting the FES for movement control of the paralyzed limbs. Nevertheless, the rapid occurrence of the muscle fatigue and need for multidimensional control of the limbs are the main limitations of the FES systems [18].

Considering the strengths and shortcomings of exoskeletons and functional electrical stimulation, it seems that by combining these two technologies one can cover up the shortcomings related to each of them [7]. In this regard, some prominent studies have been conducted [4]-[6-8]. For example, the Kinesis robot was presented for people suffering from cerebral palsy [5]. It was designed in such a way to result in the least possible muscular fatigue for the patient. It uses concurrency mechanism between the robot and functional electrical stimulation. This robot offers both walking control and rehabilitation for the patient [5]. In another paper, a combinatory system composed of lower extremity limb exoskeleton and functional electrical stimulation was investigated for restoration of walking in people with paraplegia [6]-[19-20]. The important factor that must be considered is the presence of external and internal disturbance due to muscles and joints. Considering the presence of disturbance, an external rehabilitative robot based on
predicative control model and nonlinear predicative control has been proposed in the following researches [9-12].

As mentioned, the main limitation of the FES system is expediting the occurrence of the muscle fatigue. Therefore, in the FES-hybrid rehabilitation robots, activating the FES system in an optimal manner during a specific the time period can potentially postpone the occurrence of the muscle fatigue. In a recent work, two FES allocations were proposed [21]. Using these allocation scenario, the input efforts was allocated between motor and FES [21]. The desired input ratio was adapted as per the estimated fatigue [21]. But, accurate estimating the muscle fatigue can be a challenging process. Therefore, in this paper a control approach is proposed to use functional electrical stimulation intermittently along with an active actuator to control the knee joint position in a muscle-joint model. In the other word, the underlying idea of this study is intermittent applying the FES in a manner that not only the control performance can preserved but also the occurrence of muscular fatigue can be delayed.

2. Materials and Methods

2-1 The Proposed Control Approach

As mentioned previously, a proposed approach for movement control using functional electrical stimulation along with the active mechanical orthosis is presented. In this approach, two different controllers are used to determine stimulation intensity and provide motor torque, where PD controller is utilized to adjust the stimulation intensity and adaptive neural PID controller is used to determine the motor torque. The Figure 1, demonstrates the structure of the adopted control system.
According to the proposed strategy, the value of the exerted torque to the joint emerges from a synergetic cooperation between two closed loop controllers. In a manner that, a PD controller determines the electrical stimulation intensity and an adaptive PID controller determines the input current of the mechanical motor. According to the designed decision making algorithm, the electrical stimulation signals are delivered whenever an external disturbance is observed using an envisioned disturbance observer.

The performance of the control system was evaluated using a quantitative measure called root mean square (RMS) of the tracking error as the equation (1) shows.

\[
RMS = \sqrt{\frac{(\theta_{d1}-\theta_{t1})^2+(\theta_{d2}-\theta_{t2})^2+\cdots+(\theta_{dn}-\theta_{tn})^2}{n}}
\]  

(1)

Where \(\theta_d\) and \(\theta_t\) are the vector of the desired knee movement trajectory and the actual knee movement trajectory, respectively. The proposed closed loop control strategy will be elaborated in the following sections.

2-1-1 Muscle-Joint Dynamics

In this study a nonlinear and physiological model is used the muscle-joint model [21]. The used model describes the movement of the knee joint angle in the sagittal plane. The Figure 1, shows the used muscle-joint structure [21]. Three parts called muscle activation part, muscle
contraction part, and segmental dynamics part accounted for the main parts of the model [21]. The muscular part of the model describes the moment-velocity, moment-angle properties of the muscle, and the muscle recruitment curve describes the muscle activation property. The segmental dynamics part in fact describes the shank movement dynamics along with the mechanical properties of knee joint such as joint viscosity and joint elasticity. All model equations and model parameters were determined according to what was reported in the [22-23].

The used muscle-joint model does not simulate the process of muscle fatigue during the knee joint movement ensues from muscle electrical stimulation. In order to evaluate the control strategy in presence muscle fatigue, we multiplied the value of the total generated torque ($M_{\text{tot}}$, Figure 1) by a time decreasing exponential coefficient as follows:

$$M = M_{\text{tot}} \times e^{-t/125}$$

(2)

Where $M_{\text{tot}}$ is the total output torque (Figure 1), and $t$ shows the time.
2-1-2 Adaptive PID controller

As mentioned previously, an adaptive PID controller determines the input current of the mechanical motor. In this study, a neural PID has been used and its parameters were adjusted based on an error back-propagation mechanism [15]. The PID output is described as follows:

\[ u = kf(x) + B_h \]  

(3)

Where \( f \) is Hyperbolic tangent function, \( x \) is input of the controller, and the \( B_h \) and \( k \) are the bias weighting values of the output layer and hidden layer respectively [13]. In addition, the \( x \) as the controller input is as follows:

\[ x(k) = K_p(k) e_p(k) + K_i(k) e_i(k) + K_d(k) e_d(k) + B_t(k) \]  

(4)

Where \( K_p, K_i, K_d \) are the weighing values of the input layer and \( B_t \) is the bias value of the input layer, and \( e_p(k), e_i(k), \) and \( e_d(k) \) are the output tracking error, discretized derivative of the output tracking error, and discretized integral of the output tracking error.

The parameters of the controller can be tuned in an online manner using the fast learning back propagation (FLBP) algorithm. The extracted updating laws are as follows [13]:

\[ K(k + 1) = K(k) - \eta_p e_p(k) \Delta O(k) \]  

(5)

\[ K_p(k + 1) = K_p(k) - \eta_p e_p^2(k) \Delta K \frac{2e^{-x}}{(1+e^{-x})^2} \]  

(6)

\[ K_i(k + 1) = K_i(k) - \eta_i e_p(k) e_i(k) \Delta K \frac{2e^{-x}}{(1+e^{-x})^2} \]  

(7)

\[ K_d(k + 1) = K_d(k) - \eta_d e_p(k) e_i(k) \Delta K \frac{2e^{-x}}{(1+e^{-x})^2} \]  

(8)

\[ B_t(k + 1) = B_t(k) - \eta_{Bi} e_p(k) \Delta K \frac{2e^{-x}}{(1+e^{-x})^2} \]  

(9)

\[ B_h(k + 1) = B_h(k) - \eta_{Bh} e_p(k) \Delta \]  

(10)

Where \( \eta_p, \eta_i, \eta_d, \eta_{Bi}, \) and \( \eta_{Bh} \) are the learning rates, \( O(k) = f(x(k)) \), and \( \Delta = \frac{dy(x)}{du(x)} = 0 \).
2-1-3 Disturbance Observer and Decision Making Process

As mentioned previously, the electrical stimulation signals are delivered whenever an external disturbance is observed using an envisioned disturbance observer. The quantitative effect of the external disturbance has been considered as an added term in equation of the state space model of the system as follows [12]:

\[
\begin{align*}
    \dot{x}(t) &= f(x(t)) + g_1(x(t))u + g_2(x(t))d(t) \\
    y(t) &= h(x(t))
\end{align*}
\]

(11)

where \( x \in \mathbb{R}^n, u \in \mathbb{R}, d \in \mathbb{R} \) represent the state variable, the system input, and external disturbance. The \( f(x), g_1(x), g_2(x), \) and \( h(x) \) describe the nonlinear dynamics of the system states, system inputs, external disturbance, and the output signal, respectively. Besides, it is assumed that a linear model describes the disturbance dynamics. The equation (12) demonstrates the external disturbance dynamics as follow:

\[
\begin{align*}
    \dot{\xi} &= A\xi + l(x)(\dot{x} - f(x) - g_1(x)u - g_2(x)d) \\
    \dot{d} &= C\xi
\end{align*}
\]

(13)

\[
C = 1, \ A = 4
\]

A disturbance observer has been used to detect the disturbance. The dynamics of the disturbance observer are described by equation (13-15).

\[
\begin{align*}
    \dot{\xi} &= A\xi + l(x)(\dot{x} - f(x) - g_1(x)u - g_2(x)d) \\
    \dot{d} &= C\xi \\
    l(x) &= \frac{ep(x)}{\delta x} \\
    p(x) &= KLf^{-1}h(x)
\end{align*}
\]

(14)

(15)

where \( \xi \in \mathbb{R}^n \), is state variable of the state space model of the disturbance, \( \dot{d} \in \mathbb{R} \) is the observed disturbance, and \( A \) and \( C \) represent the parameters of the state space model of the disturbance. Also, \( L \) is the derivative of the function \( f \), and the \( K \), as the gain, is equal to 10.

After observing the disturbance and according to the value of the disturbance, the PD controller is activated whenever the value of the observed disturbance is bigger that a specific value. In the
other words, the electrical stimulation is delivered to the muscle and the PD controller determines the stimulation intensity. According to the utilized decision making mechanism, the PD controller, as the FES controller, is activated whenever the observed disturbance ($\hat{d}$) is bigger than 5.

2-1-4 Active Mechanical Actuator

In this study the modeled mechanical motor, as an active mechanical actuator, has been used is an AC servo motor comprised of two parts: servo driver and feedback encoder [15]. The used servo motor had three states including position control, speed control and torque control. The Figure 3, shows the structure of the used model as the AC servo motor.

![Figure 3: The block diagram showing the structure of the model used as the permanent magnet synchronous servo motor [2].](image)

As the Figure 3 demonstrates, the parameters of the model are as follows [2]:

- $U_q$ = input voltage (Ω)
- $R$ = winding equivalent inductance (V)
- $L$ = equivalent inductance (H)
- $K_c$ = torque coefficient
- $T_c$ = torque (Nm)
- $P_n$ = number of pole pairs
- $\phi_f$ = rotor flux field equivalent (wb)
- $T_L$ = load torque (Nm)
- $J$ = moment inertia (kgm$^2$)
- $\omega_r$ = rotor angular velocity (rad/s)
All parameters of the motor model were determined according to what has been reported in [2].

2-2 Knee joint Movement Trajectory

The reference trajectory of knee joint movement control was envisioned using recorded human data. Data was recorded from 5 healthy subjects. Table 4 shows the information related to the participants. After preparing the subjects, data recording commenced. The subjects were asked to take 9 steps on the designated sheet, irrespective of time and conforming to their natural speed. In other words, no restrictions were imposed on gait length or walking speed. The kinematic information of the knee joint angle was recorded using a motion analyses system. The sampling frequency was 100 Hz. Figure 4 shows how the markers used for motion analyses were located on the leg.

Table 1. The Information related to the participants

| Subject no. | Gender | Age | Height   |
|-------------|--------|-----|----------|
| 1           | Male   | 23  | 178 cm   |
| 2           | Female | 24  | 165 cm   |
| 3           | Female | 26  | 175 cm   |
| 4           | Female | 29  | 168 cm   |
| 5           | Female | 24  | 168 cm   |

Figure 4: Placement of the located markers used for motion analyses.
3- Results of the Simulation Studies

3-1 Evaluation without Presence of the Disturbance

In the first section of simulated studies, we assessed the control strategy under the conditions which no external disturbances were applied. In such context, the electrical stimulation is not delivered. In the other words, only the PID controller has been activated. At first a nonadaptive PID and then an adaptive PID were used.

3-1-1 Evaluation Using Nonadaptive PID

As it can be seen In Figure 5, there exists considerable tracking error and phase delay between the reference knee joint trajectories and the obtained actual. The calculated RMS of the tracking error is 202 degrees. It can be deduced that may be owing to the nonlinearity of the model, even when no disturbance is applied to the system, appropriate or acceptable efficiency is not achieved.

Figure 5: The reference and actual knee angle trajectory elicited due to using the nonadaptive PID controller

3-1-2 Evaluation Using Adaptive PID

As it can be seen In Figure 6, even when using adaptive control still there exists considerable tracking error and phase delay between the reference knee joint trajectories and the obtained actual. Though the tracking performance has been improved apparently, but the calculated RMS of the tracking error is 20 degrees. Such unacceptable performance can be attributed to the some system nonlinearity which the controller couldn’t cope with them.
In the next step, for improving the performance of the adaptive PID, a PD compensator was added. In fact, the control signal is aggregation of the two control signals. One is the adaptive PID output and the other is the compensator output as the Equation (16) describes.

\[ U = U_{pd} + U_{pid} \]  

As can be seen from figure (7), adopting the PD compensator along with the adaptive PID has improved the performance significantly. The computed RMS of the tracking error is 3. Since the range of knee angle variation is about 80 degree, such value of the tracking error can be acceptable. In the other words, such result can be construed as a sign of good performance of the control strategy. Besides, as it was expected, the FES controller is disactivated during the control process. Because, no disturbance was applied during the control process.

The RMS of the tracking error while the recorded trajectories related to different subject were used as the desired trajectory, were computed. The Table2 shows the computed values. The computed average value is 2.6±0.36. It can be claimed again that since the range of knee angle variation is about 80 degree, such value of the tracking error can be acceptable.

| Table 2: The RMS of the tracking error while the recorded trajectories related to different subject (without presence of disturbance) |
|---|---|---|---|---|---|
| Subject no. | 1 | 1 | 3 | 4 | 5 |
| RMS (Degree) | 3.5 | 2.3 | 2.3 | 2.6 | 2.3 |
| Average RMS ± Std: | 2.6±0.36 |
The desired trajectory is related to human data. Since the human gait is a rhythmic and not periodic, we expect that the controller parameters do not converge to the fixed level. The Figure 6 shows the variations of the adaptive PID parameters during the process. Clearly, the controller parameters did not converge to the fixed values. Besides, whenever the slope of the desired trajectory changes the dynamics of parameters variations change. It shows the ability of the controller to adapt its behavior according to the different dynamics of the reference trajectory.

3-2 Evaluation in Presence of the Disturbance without Considering the Muscle Fatigue

In the next step of the research, an external disturbance, as an additive torque was applied to the knee during two different time interval. Each time interval lasted two seconds. As explained previously, the disturbance dynamics was as equation 12. Without presence of the disturbance, using the adaptive PID along with the PD compensator led to the best results. Therefore, in this step only the adaptive PID along with the PD compensator has been evaluated. The Figure 11 shows a sample achieved result. Firstly between 2 to 2.2 s and secondly between 4 to 4.2 s. The
external disturbance was applied during two separate time period. Clearly, as it was expected the FES controller has been activated exactly during applying the disturbance. In fact, the elicited torque aroused from delivering the electrical stimulation to the muscle has provided the torque which was not generated using the active motor. Once the external disturbance was removed, the stimulation signal reduced to zero again. The RMS of the tracking error while the recorded trajectories related to different subject were used as the desired trajectory, were computed. The Table 3 shows the computed values. The computed average values of the RMS seem to be acceptable if one consider the range of knee joint motion (80 degree).

Table 3: The RMS of the tracking error while the recorded trajectories related to different subject (In presence of disturbance)

| Subject no. | 1  | 1  | 3  | 4  | 5  |
|-------------|----|----|----|----|----|
| RMS (Degree)| 3  | 3.5| 2.5| 2.6| 3.5|

Average RMS ± Std: 3.2±0.38

As it can be seen in Figure 9, once the elicited torque aroused from the FES has been increased, the generated torque by the active motor has decreased significantly. It shows that using the FES yields need for low mechanical power servo-motor for annihilating the disturbance. Though during applying the disturbance the FES has provided the necessary torque, but the stability of the control system should also preserved. Therefore, as the Figure 9 shows the variations of the adaptive PID parameters were not stopped even when the FES controller was active.

Figure 9: Knee joint trajectory, FES controller output and the generated torque using the servo-motor.
3-3 Evaluation in Presence of the Disturbance and the Muscle Fatigue

Muscle fatigue is a limiting factor in FES [16]. It is expected that in the FES-Hybrid system incorporating the FES in a manner that the FES system is activated only during a specific time intervals may lead to postpone the occurrence of the muscle fatigue. As it was explained previously, in the proposed control approach the FES controller (A PD controller) is activated only when an external disturbance is observed. Therefore, it is expected that the muscle fatigue can be compensated using the proposed control strategy.

As explained previously, we used a decreasing exponential coefficient in the muscle model to simulate the muscle fatigue process. The Figure 11 shows a sample achieved result. As it can be seen, despite the presence of the muscle fatigue the performance of the controller has not been degraded. Besides, the trend of the motor torque is increasing. It shows the ability of the adaptive PID controller to compensate the muscle fatigue due to gradual increasing the level of the mechanical motor torque.

The RMS of the tracking error while the recorded trajectories related to different subject were used as the desired trajectory, were computed. The Table 4 shows the computed values. The computed average values of the RMS seem to be acceptable if one consider the range of knee joint motion (80 degree).
Table 4: The RMS of the tracking error while the recorded trajectories related to different subject (In presence of disturbance and muscle fatigue)

| Subject no. | 1   | 1   | 3   | 4   | 5   |
|-------------|-----|-----|-----|-----|-----|
| RMS (Degree)| 5   | 5   | 5   | 3   | 3.5 |

Average RMS ± Std: 4.3±0.92

Figure 11: Knee joint trajectory, the trend of the servo-motor torque in presence of the muscle fatigue.

4. Discussion

- The Effect of the Knee Reference Trajectory on the Controller Performance

As was seen, the reference trajectory of knee movement was designed using the human data. Since the situation of the patients may be different in reality, individualizing the exoskeleton make them more efficient. Therefore, in this simulation studies the controller performance was evaluated while different trajectories related to the different human subjects were used as the desired knee movement trajectory. Since the specifications of the gait dynamics in each subject differ from the others, the evaluation of the controller under such conditions could elucidate the ability of the proposed control strategy to control the exoskeleton movement in an individualized manner. According to the obtained results, the controller performance was not degraded owing to changing the knee reference trajectory (Table 2-4). Such promising results can hearten us about the prospective application of this control strategy.
• **The Using the FES and Muscle Fatigue**
In this study, the FES was used along with the active actuator to compensate the effect of the external disturbance. But, the main limitation of the FES system is expediting the occurrence of the muscle fatigue. Therefore, a decision making approach has been applied to activate the FES controller only whenever a designed disturbance observer detects the presence of an external disturbance. In this manner, the presence of the FES is not only effective but also the occurrence of the muscle fatigue can be postponed as much as possible. The achieved results certify the underlying idea. Because, the value of computed RMS of the tracking error in the presence of the muscle fatigue and the corresponding value computed without presence of the muscle fatigue are comparable (Table 3, Table 4). Such results can prove that the proposed decision making strategy prevented the rapid occurrence of the muscle fatigue. Besides, during applying the disturbance the elicited torque by FES could provide the needed torque. This shows that a low mechanical power motor can be enough to provide the needed torque to annihilate the external disturbance. This is a considerable benefit, because low mechanical power motor is low weight with small size which can be useful for implementing an FES-Hybrid exoskeleton with proper weight and size.

• **The Effect of the PD compensator**
According to the results, using the adaptive PID instead of nonadaptive PID did not improve the controller performance. But, adding the PD compensator significantly improved the controller performance. It shows that the controller could not cope with some nonlinear dynamics due to adaptive laws. It can be attributed to the structure of the defined Lyapanov function which the adaptation laws were derived using it. The only variable of the defined Lyapanov function is the square value of the tracking error. Accordingly, it can be suggested that the Lyapanov function should be a function of not only the square of error but also a function of the estimation errors of the controller parameters. However, a PD compensator could overcome the mentioned impediment.

• **Future works**
Future works can focus on evaluating the proposed control strategy for multi-joint control system. In the other words, concurrent controlling the knee joint and hip joint is one of the next important works. In addition, evaluating the proposed control strategy for controlling the joint
movement with different speed is the next step of the future works. Also, practical implementation of the proper setup for experimental studies is one of our prospective works.

5. Conclusion

In this paper, a hybrid-FES control system has been proposed to control the knee joint movement. The simulation studies on a model of muscle-joint system showed the promising performance of the proposed control strategy. Without presence of the external disturbance, the adopted adaptive PID controller along with a PD compensator could acceptably control the mechanical torque generated by the active actuator. Because, the knee joint movement was controlled with an acceptable value of the tracking error. Besides, during applying the external disturbance a PD controller could control the muscle stimulation intensity in a manner that the disturbance can be rejected and the value of the tracking error was comparable with the situation which no disturbance was applied. In addition, the utilized decision making strategy led to cope with the muscle fatigue aroused from the FES delivering.
Reference

[1] Ghaddar, Raed, and Mohammad AS Mohammad. "A Review of Lower Limb Exoskeleton Assistive Devices for Sit-To-Stand and Gait Motion." (2019)

[2] Yeem, Sungjun, et al. "Technical Analysis of Exoskeleton Robot." *World Journal of Engineering and Technology* 7 (2019): 68-79.

[3] Mohammadi, E., H. Zohoor, and S. M. Khadem. "Design and prototype of an active assistive exoskeletal robot for rehabilitation of elbow and wrist." *Scientia Iranica. Transaction B, Mechanical Engineering* 23.3 (2016): 998.

[4] del-Ama, Antonio J., et al. "Characterization of a Dual PID-ILC FES Controller for FES-Robot Control of Swing Phase of Walking." *Replace, Repair, Restore, Relieve—Bridging Clinical and Engineering Solutions in Neurorehabilitation*. Springer, Cham, 2014. 341-349.

[5] del-Ama, Antonio J., et al. "Hybrid therapy of walking with kinesis overground robot for persons with incomplete spinal cord injury: a feasibility study." *Robotics and Autonomous Systems* 73 (2015): 44-58.

[6] Ha, Kevin H., Spencer A. Murray, and Michael Goldfarb. "An approach for the cooperative control of FES with a powered exoskeleton during level walking for persons with paraplegia." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 24.4 (2016): 455-466.

[7] Bortole, Magdo, et al. "The H2 robotic exoskeleton for gait rehabilitation after stroke: early findings from a clinical study." *Journal of neuroengineering and rehabilitation* 12.1 (2015): 54.

[8] Ren, Yong, and Dingguo Zhang. "FEXO Knee: A rehabilitation device for knee joint combining functional electrical stimulation with a compliant exoskeleton." *5th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics*. IEEE, 2014.
[9] Chen, Gong, et al. "Mechanical design and evaluation of a compact portable knee–ankle–foot robot for gait rehabilitation." *Mechanism and Machine Theory* 103 (2016): 51-64.

[10] Parsa, Mohsen, and Mohammad Farrokhi. "Robust nonlinear model predictive trajectory free control of biped robots based on nonlinear disturbance observer." *2010 18th Iranian Conference on Electrical Engineering*. IEEE, 2010.

[11] Wittmann, Robert, et al. "Real-time nonlinear model predictive footstep optimization for biped robots." *2015 IEEE-RAS 15th International Conference on Humanoid Robots (Humanoids)*. IEEE, 2015.

[12] Chen, Wen-Hua. "Disturbance observer based control for nonlinear systems." *IEEE/ASME transactions on mechatronics* 9.4 (2004): 706-710.

[13] Kirsch, Nicholas, Naji Alibeji, and Nitin Sharma. "Nonlinear model predictive control of functional electrical stimulation." *Control Engineering Practice* 58 (2017): 319-331.

[14] Shen, Dongbin, Weijie Sun, and Zhendong Sun. "Adaptive PID formation control of nonholonomic robots without leader's velocity information." *ISA transactions* 53.2 (2014): 474-480.

[15] Huy, Anh Ho Pham, Huan Tran Thien, and Nam Nguyen Thanh. "Novel Robust Walking for Biped Robot Using Adaptive Neural PID Controller." *2014 International Conference on Automatic Control Theory and Application (ACTA-14)*. Atlantis Press, 2014.

[16] Zhang, Dingguo, et al. "Cooperative Control for A Hybrid Rehabilitation System Combining Functional Electrical Stimulation and Robotic Exoskeleton." *Frontiers in neuroscience* 11 (2017): 725.

[17] Gilbert, Masengo, Xiaodong Zhang, and Gui Yin. "Modeling and design on control system of lower limb rehabilitation exoskeleton robot." *2016 13th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*. IEEE, 2016.

[18] Franken, Henry M., et al. "Fatigue of intermittently stimulated paralyzed human quadriceps during imposed cyclical lower leg movements." *Journal of Electromyography and Kinesiology* 3.1 (1993): 3-12.
[19] Tu, Xikai, Jian Huang, and Jiping He. "Leg hybrid rehabilitation based on hip-knee exoskeleton and ankle motion induced by FES." 2016 International Conference on Advanced Robotics and Mechatronics (ICARM). IEEE, 2016.

[20] Anaya, Francisco, Pavithra Thangavel, and Haoyong Yu. "Hybrid FES–robotic gait rehabilitation technologies: a review on mechanical design, actuation, and control strategies." International Journal of Intelligent Robotics and Applications 2.1 (2018): 1-28.

[21] Kirsch, Nicholas A., et al. "Model-based dynamic control allocation in a hybrid neuroprosthesis." IEEE Transactions on Neural Systems and Rehabilitation Engineering 26.1 (2018): 224-232.

[22] Ferrarin, M., Palazzo, F., Riener, R., & Quintern, J. (2001). Model-based control of FES-induced single joint movements. IEEE Transactions on Neural Systems and Rehabilitation Engineering.

[23] Riener, Robert, and Thomas Edrich. "Identification of passive elastic joint moments in the lower extremities." Journal of biomechanics 32.5 (1999): 539-544.