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A Preliminary Virtual Study on the Feasibility of Transferring Muscular Activation Pattern Behaviors of Psychomotor Exercises

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Abstract: Research has demonstrated that Taekwondo training helps to enhance the coordination capabilities in people with developmental coordination disorders. These excellent results depend on many factors, including the behavior of the muscular activation patterns of psychomotor exercises during Taekwondo training. Our basic idea is to study the behavior of the muscular activation pattern of Taekwondo training (performed by athletes) and to apply the adapted behavior of the muscular activation pattern to other subjects with reduced coordination capabilities to enhance them, in line with the sustainable human development goals. This paper presents a preliminary feasibility study and a first step in this direction using a virtual simulation. First, the Taekwondo front-kick exercise was studied and reproduced using a virtual human model in OpenSim. Second, some perturbations were applied to the virtual human model to analyze the behavior of the muscular activation patterns. Third, functional electrical stimulation (FES) patterns were properly simulated to reproduce the same sequence (and value) of signals of muscular activation in another subject. The proposed methodology was conceived on the basis of a simple example of a Taekwondo kick by using a virtual human model, but its general application can fit all kinds of psychomotor exercises. If future works confirm the simulation results presented in this paper with real implementation, the methodology proposed here could be applied every time human capabilities must be increased with or without sports training (e.g., remaining seated on a chair or lying on a bed).

Keywords: Taekwondo; sport training; muscular activation; functional electrical stimulation; dynamic balance; human model; human–machine interaction; sustainability

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1. Introduction

The transfer of energy between two or more parts of the same human body or between the human body and the environment (or vice versa) is a very interesting and challenging research field, and it is very difficult to implement. The authors of [1] presented an algorithm developed for recruiting one-joint or both one- and two-joint muscles to perform a human movement. The authors of [2] presented an exoskeleton to reduce human efforts in lifting loads using arms. Another exoskeleton was proposed to transfer energy from a robotic structure to the human body in order to increase human motion capabilities [3].

The transfer of energy from one subject to another is only a beautiful dream, in part developed by using haptic interfaces [4] and tele-operated systems [5]. The idea presented in this paper introduces a new feasible challenge in the direction of the future of transfer energy and muscular activation from one subject (the athlete) to another (the patient).

Recent studies have highlighted the importance of practicing sports as a complementary therapy for people suffering from neuromuscular diseases [6,7]. Different types of sports have demonstrated the benefits of functional training in recovering motor-skill capabilities [8–13]. Research in multiple disciplines has analyzed how Taekwondo's training and exercises could improve the restoration of healthy muscle conditions, both increasing balance and coordination and assisting in the recovery of basic daily-life actions [14,15]. The authors of [16] studied the correlation between the speed and the impact of the target during the frontal kick execution of traditional Taekwondo in a pilot study. The authors observed that the speed of the kick decreases if more precision is needed for the target impact. This result may have been obtained because if the athlete would like to have more precision in a target impact, she/he should be more concentrated not only on the speed of the kick but also on other aspects, such as balance control, target impact, etc.

The authors of [17] presented a dataset of movements of martial artists for kinematic analysis, and the authors of [18] proposed a methodology applied to human actions analysis. In our work, we did not use human subjects and performed kinematic analyses and muscular activation using a 3D virtual human subject developed with an open-source simulator well known in the biomechanical sector [19].

The physical limitations of sports training (e.g., patient participation in training sessions and limited accessibility to hospital centers) necessitate the conception of novel home-care engineering rehabilitation systems [20] able to support patients' recovery and to increase their quality of life. In this regard, efficient home therapy systems should overcome the challenge of adapting clinical and cutting-edge technology to personal environments and autonomous applications [21]. On the ond hand, if advanced medical engineering systems require the support and supervision of qualified clinical personnel, home care solutions need simplified applicability to help patients, who have to use the system autonomously or with the partial help of caregivers. This requirement implies the development of innovative, smart, and portable systems that can be installed in the limited space of a home environment and the intelligent functionalities (e.g., fast setup, easy application) of which even out the inexperience of the final users (e.g., promoting user-friendly solutions). On the other hand, the economic budget and the rent policy, which strictly depends on the country's regulations of (private and public) healthcare services, should be taken into consideration [22]. A feasible home-care therapy system has to be low-cost, and, generally speaking, it should be lent to the patient by the healthcare provider. The proper balance of the above aspects should be the focus of the development of home-care rehabilitation systems able to earn users' approval (in terms of practical usability) while guaranteeing increased patient accessibility to the service.

In line with these considerations, this paper introduces a new feasibility study of a novel home-care functional rehabilitation system that aims to transfer the musculoskeletal activity pattern of one subject during a psychomotor exercise to another subject. The general idea is to analyze the execution of a psychomotor exercise, extract the human body's muscular and skeletal response during the movement, use this information to build physiotherapeutic recovery protocols, and apply them during rehabilitation sessions. The study presented in this paper is a first step forward with respect to the presented general idea. In the next sections, we evaluate the feasibility of the idea, analyzing muscular activation patterns (by using a virtual human model to perform tasks) and transferring muscular activation patterns to another virtual human subject (by using an electrical stimulation protocol).

2. Materials and Methods

2.1. Methodology

We can divide our methodology into four main functional blocks:

1. Study of functional movement;
2. Analysis of human body activation;
3. Definition of a physiotherapeutic protocol;

4. Application of the protocol in rehabilitation sessions.

Regarding point 1., considering the results obtained in [14,15], we decided to study the front-kick (FK) execution (a basic kick of Taekwondo practice) because it involves a high level of coordination of different muscle groups to maintain the body's balance while performing the kick. Consequently, since the possibility of transferring coordinated patterns in the form of muscle synergies has been demonstrated to positively affect the recovery of functional tasks for stroke patients [23,24], we believe that the FK exercise is an appropriate case study to evaluate the proposed training–rehabilitation methodology.

In order to perform a preliminary analysis to assess the feasibility of our system, we decided to analyze the FK by simulating its postures using a virtual human model designed with OpenSim [25]. Although alternative analyses can be conducted using surface electromyographic (sEMG) sensors, inertial measurement units (IMUs), and 3D motion capture systems (sometimes enhanced by artificial intelligence (AI) computing) [26–29] and by acquiring bio data to directly monitor Taekwondo athletes during performance, in this work, we preferred to focus on the simulation of the FK in order to examine the modelling and its response in detail, to limit the subject variability during movement execution, and to optimize the time–effort trade-off during this first preliminary analysis. Starting from these assumptions, we simulated the human postures of the FK (point 2.), also adding external perturbations to the static balance to study the response of the virtual muscles in restoring the equilibrium condition.

As regards point 3. and point 4., they should be analyzed together, considering their mutual behavior. Each rehabilitation technique follows precise physiotherapeutic protocols, which, in turn, need to be defined and optimized for the employed rehabilitation tool. Therefore, among the different procedures applied in functional recovery for people affected by neuromuscular disorders, we selected functional electrical stimulation (FES) [30] as the rehabilitative technique to effectively close the loop by providing functional restoration of motor tasks, i.e., reproducing the same behavior of the muscular activation pattern performed by the virtual human model in external subjects. Thanks to its extensive employment in physiotherapeutic clinical practices [31,32] combined with benefits in terms of quality-of-life improvements for people affected by neurodisorders [33–35], FES still confirms its essential role in rehabilitation practice. Moreover, looking at the recent state-of-the-art works, different FES control strategies could be implemented [36–40], making our intent of defining dynamic FES patterns (point 3.) modulated on the variation of the simulated muscle activation feasible, as confirmed by literature studies.

Figure 1 shows the high-level flow concept of our solution: from the left to the right, the FK movement is analyzed during its evolution, especially focusing on the body equilibrium phases; the human body is virtually reconstructed by using a musculoskeletal model in OpenSim software, also adding perturbations to the balance posture; muscle activation is obtained from the OpenSim simulation and consequently converted into FES patterns; and a subject (patient or athlete) applies the defined pattern to elicit a functional muscle contraction to restore or enforce the muscular structure.

Looking at the feasibility of the proposed methodology with respect to the defined standards for home-care therapy, we can see how it adequately fits the requirements listed above. Considering the four functional blocks (1. to 4.) of our process flow, only the last one (i.e., application of the protocol in rehabilitation sessions) is the step that effectively takes place in the home environment, while the other blocks (1. to 3.) are already implemented at this stage.

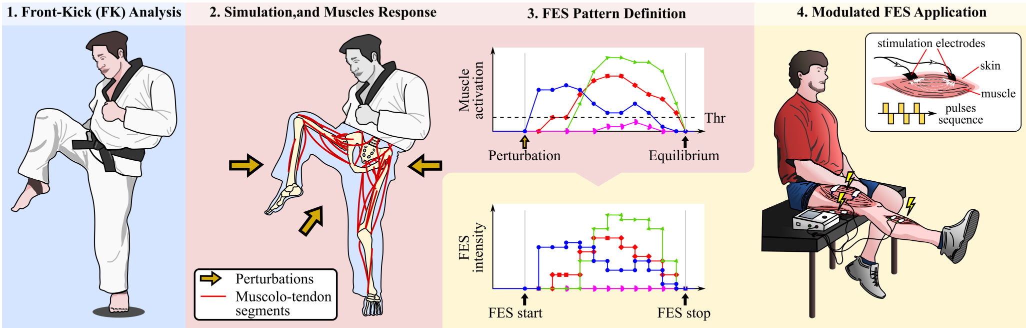

Figure 1. High-level process flow, from front-kick execution to FES pattern application.

2.2. *Process Flow to Transfer Muscular Activation Pattern*

Figure 2 shows the process flow developed in this paper, which can be described, summarized, and generalized as follows:

(1) A functional training exercise is selected; in this work, the Taekwondo front kick (FK) was considered as the reference movement, but it does not prevent the analysis of other Taekwondo movements (e.g., side kick or roundhouse) or psychomotor exercises related to other sports disciplines;
(2) A simulation implemented using OpenSim software [25] analyzes the phases of the movement, including external perturbation (if needed to study the restoration of the body balance from the equilibrium conditions), and obtains virtual muscle activation (e.g., by using the *Gait 2354* human musculoskeletal model [25]);
(3) If required, once the muscular patterns have been obtained, a further feature extraction process can be applied to obtain high-level information about the muscle activity;
(4) Control software developed in this study using the combination of MATLAB® and Simulink® environments is implemented in order to transform the value of the muscular activation into an FES pattern and communicate the desired command sequence (e.g., to enable stimulation with these computed pulse parameters) to the stimulator;
(5) An FES stimulator applies the processed stimulation patterns in order to promote the execution of functional movement generation by inducing synergetic muscle contraction.

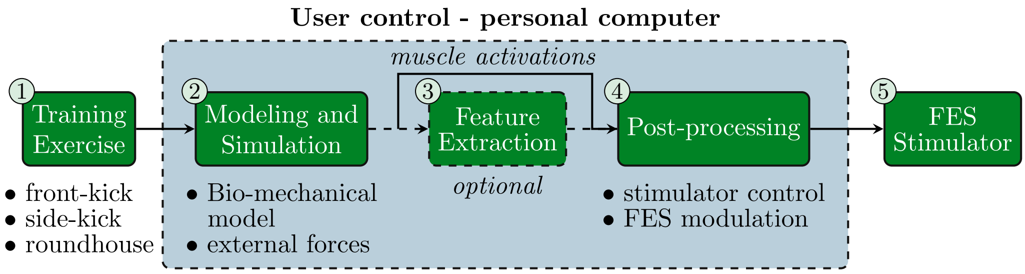

Figure 2. Flow chart of the proposed process for the definition of the front-kick virtual training protocol.

Since this work represents a preliminary analysis to evaluate whether the above pipeline can effectively define and generate FES patterns starting from human model simulations, we limited the application of point (5) to the virtual generation of the stimulation profiles. Future experimental validations of this approach will be carried out by studying how the stimulation performs when applied to human subjects, following the same procedures already employed in [34,40,41].

All the above considered, if the concept proposed in this paper can be applied in a real domain, many advantages for human safety, adaptive sports, sports, and home-care rehabilitation can be underlined. This approach is particularly recommended when are sport benefits are reduced by external causes like the pandemic situation [42].

The convenience of having a virtual training system able to increase human performance (“at home” or “alone”) without external contact with other individuals has many advantages for the health of people in our society. Social interaction is a fundamental aspect, and the methodology proposed in this paper may help society and the sports sector to overcome the difficulties related to the restrictions imposed by dangerous problems like COVID-19 [42].

2.3. Virtual Human Model: Analysis and Design

Many works report analytical studies about balance and posture, applying perturbation analyses to human subjects [43–46] and evaluating how artificial dynamic balance can be achieved for human-like robots [47–53] and biped exoskeletons [54]. Generally, every perturbation in the human subject creates a disturbance in her/his posture, generating instability. In response, the human brain is able to find a novel balance posture, synchronizing all body parts (head, arms, trunk, legs, and feet) and skeletal muscles. Given these considerations, this paper aims to introduce a method for the extraction of muscle activation by simulating a simple exercise using a virtual human model (under the application of unbalance forces) and consider how these activations could be used to control FES therapy (Figure 2).

2.3.1. Case Study: Front Kick in Taekwondo

In this first study, we decided to analyze a basic martial arts kick: the front kick (FK). In particular, this study focuses an Olympic martial arts sport, namely Taekwondo [55].

The sport objective of different martial arts, like Taekwondo, is to land kicks and punches in the opponent’s scoring zones. Practitioners undergo complex training to reach the adequate elasticity, flexibility, and leg power needed to perform these movements [56]. As underlined in [14,15], Taekwondo training increases humans’ motor capabilities, and training in this discipline (like sports training in general) may be used to recover dynamic balance capabilities in people with motor disorders. For this reason, the main idea of this work is to analyze the synchronization of muscular activation in a virtual human model during a psychomotor exercise in order to reproduce the sequence of muscular activation of one subject in another subject. The final aim is to increase human motor capabilities. This work is a first step in this direction, and the analysis of the virtual human model during the front-kick exercise, including external perturbations, is shown in the following sections.

Among different exercises and movements, kicks (e.g., front, side, and roundhouse) are strictly related to the single-leg stance ability. Focusing on the FK, its balance can be divided into four main static positions [57] (see Figure 3):

- Phase 1: From a standing position (both feet on the floor), the right knee is raised to its flexion, with the thigh oriented approximately horizontally and ready to kick;
- Phase 2: Maintaining the knee at its highest point, the leg is completely extended to execute the kick;
- Phase 3: The kicking leg is bent toward the body, returning to the equilibrium position of phase 1;
- Phase 4: The right leg is lowered to the ground, reassuming the standing position.

Generally, the supporting leg is maintained stationary on the ground during the entire kick duration, and a small rotation on the axis perpendicular to the ground is permitted for the foot.

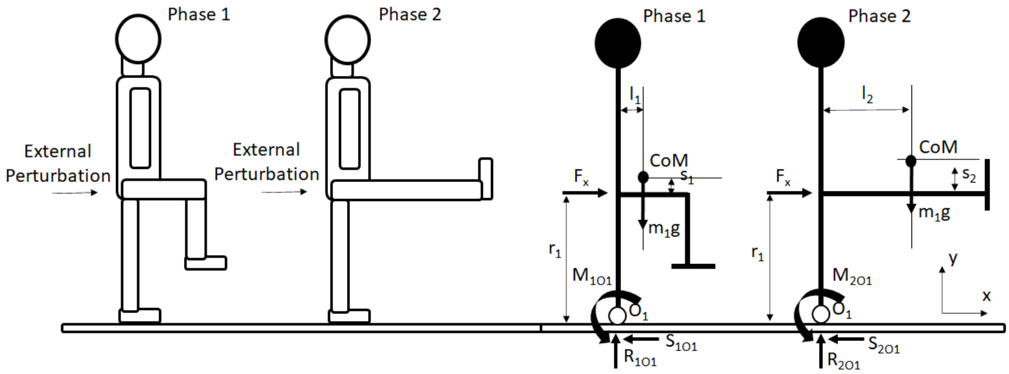

Figure 3. Front-kick (FK) model: sketches of the first two phases (**left**) and a simplified free body diagram of the model using only the ankle torque to maintain balance (**right**).

2.3.2. Physical Modeling and Dynamic Balance of the Subject

Figure 3 shows the first two phases of the FK execution when a perturbation is applied. The position of the total center of mass (CoM) changes between the FK phases because of the different positions of body segments, as shown in Figure 4. If the perturbation always has the same value and the whole system is in a static condition using only the ankle torque to maintain balance, the following equations may be written:

$$F_x r_1 + l_1 m_1 g = M_{1O_1} \tag{1}$$

$$F_x r_1 + l_2 m_1 g = M_{2O_1} \tag{2}$$

where r_1 is the distance of the perturbation from the ground; l_1, l_2 represent the horizontal distances of the CoM; g is the gravity; m_1 is the total mass on the CoM; and M_{1O_1} and M_{2O_1} are the resultant ankle torques generated by the muscles and calculated with respect to the ankle (point O_1), respectively, for the two FK phases.

According to (1) and (2), Equation (3) is obtained, which underlines how, in the two phases, the difference between the resultant torques of the muscular activation is proportional to the difference in the CoM position if the same perturbation (F_x) is applied in the two FK phases.

$$M_{1O_1} - M_{2O_1} = (l_1 - l_2) m_1 g \tag{3}$$

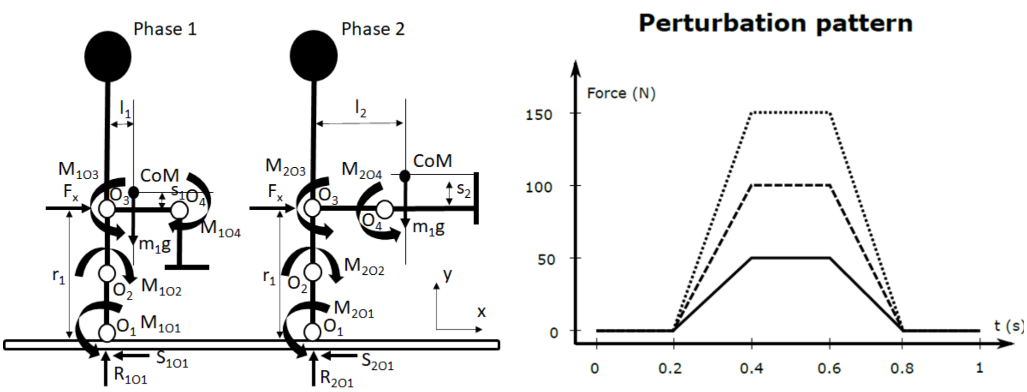

Figure 4. Front-kick (FK) model: free body diagram of the multibody model with five links (**left**) and the perturbation pattern used for muscular activation (**right**).

If the perturbation pattern of F_x is the same in the two phases and if it is not constant, the calculation of the dynamic balance condition is more complex to perform. An example of the dynamic analysis of a human model in a standing position with an external dynamic perturbation is shown in [44,46]. In this paper, the same simplified models were used to adapt the CoM location shown in the two phases above. However, the resultant torques calculated with respect to point O_1 do not provide much information about muscular activation. For this reason, a more detailed analysis was performed using a biomechanics multibody model. In particular, the simulations were carried out using OpenSim software due to its widespread employment in the dynamic simulation of a wide variety of movements related to the modeling of the musculoskeletal system [25].

In the simplified free body diagram shown in Figure 3, only the ankle joint is used to maintain balance. It is essential to underline that the simplification required to consider only the ankle torque must be confirmed by a more detailed analysis of muscular activation. Figure 4 (left) shows a more complex free body diagram in which the human model comprises five links, each with a mass. In the case of Figure 4 (left), the unknown resultant torques are applied to four joints (O_1, O_2, O_3, and O_4) each with different values in phase 1 ($M_{101}, M_{102}, M_{103}$, and M_{104}, respectively) and phase 2 ($M_{201}, M_{202}, M_{203}$, and M_{204}, respectively). In order to obtain a resultant torque in a joint, many muscles and their activation percentages must be considered.

2.3.3. Virtual Human Model Design

The three-dimensional *Gait 2354* model was chosen for our scope because it features 54 musculotendon actuators (representing the torso and the lower extremities) combined with 23 degrees of freedom, assuming the default physique characteristics of 1.8 m height and 75.16 kg mass [25].

The FK poses for phases 1 and 2 were reproduced in the OpenSim environment, where perturbations were included as imbalance forces applied to the head of the left femur (supporting leg), with their force vectors located in the XZ plane (parallel to the ground). The orientation of the forces follows tat of the X and Z axes (both positive and negative), therefore acting as pushing forces from four different points. The forces were generated using a symmetrical pattern (Figure 4, right). In a 1 s simulation, the force starts increasing its value after 0.2 s, maintains its maximal value in the 0.4 s to 0.6 s interval, and finally decreases to zero until 0.8 s. Three different maximal force amplitudes were tested, i.e., 50 N, 100 N, and 150 N, in order to evaluate how muscle activations may differ depending on this value.

3. Results

3.1. Muscular Activation in Virtual Human Model

Before the analysis of FK execution, a preliminary evaluation of the muscle contributions during the two-leg stance posture was performed to obtain an activation reference. In this way, by defining a global muscle activation threshold of 30% of the previous posture, which muscles contract as a consequence of the FK poses was determined.

Consequently, static optimization analysis was started to extract muscle activation when perturbations were applied. The outcomes are reported in Table 1, which summarizes the muscles featuring significant contributions in at least one case study (e.g., force magnitudes and orientations). For example, considering the *biceps femoris long head* muscle, the table shows overthreshold activation on the left limb (**l** in table) during both FK-phase 1 (1) and FK-phase 2 (2) when Z+ and X− forces are applied.

In order to provide a visual outcome of the OpenSim simulation, Figure 5 graphs the muscle activations (reported as the relative percentage of the static two-leg activation) associated with a force of 50 N applied along the X+ direction, during FK phase 1. Only nine muscles (i.e., the ones listed in the **[X+, l]** column of Table 1) among the 54 muscles simulated by the *Gait 2354* model are activated to balance the external force, among which just 4 present a strong activation over the defined 30% activation threshold. Based on these results, the following analysis (for this configuration) consider the contribution of the *biceps femoris (short head)*, *gluteus medius*, *iliacus*, and *psoas* muscles. As visible, muscle activations follow the applied perturbation pattern, each proportional to the balance activity of the corresponding muscle (in the case of no force application, muscle activations are maintained constant during simulation).

Table 1. Summary of analyzed muscles from the *Gait 2354* model for FK static optimization analysis with and without perturbations.

	No Force		**Z+**		**Z−**		**X+**		**X−**	
Muscle	**r**	**l**	**r**	**l**	**r**	**l**	**r**	**l**	**r**	**l**
adductor magnus				1, 2						
biceps femoris long head				1, 2						1, 2
biceps femoris short head	1	1, 2		1, 2		1, 2		1, 2		
gemellus								1, 2		
gluteus maximus						1, 2				1, 2
gluteus medius		1, 2		1, 2		1, 2		1, 2		1, 2
gracilis				1, 2				1		
iliacus	1, 2	1, 2		1, 2		1, 2		1, 2		
medial gastrocnemius	2									
piriformis						1, 2		1, 2		
pectineus				1, 2						
psoas		1, 2		1, 2		1, 2		1, 2		
rectus femoris	1, 2									
sartorius	1, 2					1, 2		1, 2		
tensor fasciae latae						1, 2		1, 2		

1: FK phase 1; 2: FK phase 2.

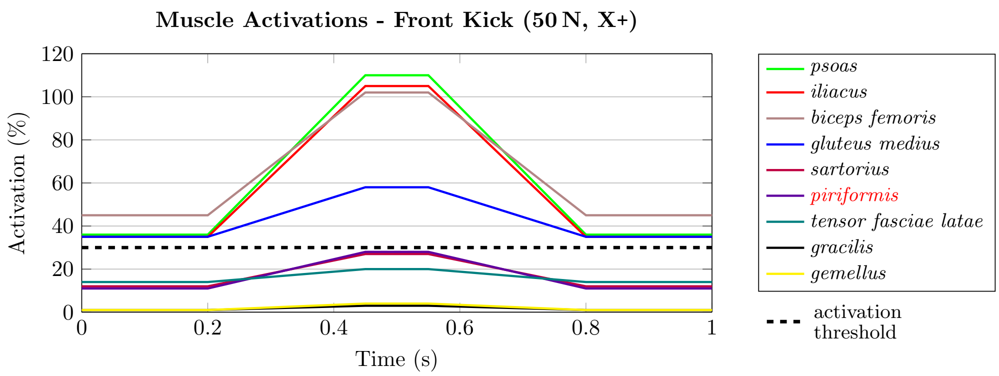

Figure 5. Muscle activations during FK, phase 1, 50 N force applied along X+. The muscle responses follow the pattern of the generated perturbation. The 30 % threshold is crossed only by the muscles presenting strong activation during balance restoration.

The same typology results were obtained for sweeping force magnitude (0 N, 50 N, 100 N, 150 N), orientation (Z+, Z−, X+, X−) and when simulating both FK postures.

When forces are applied, the area under the curve of each activation is computed as a proportional measure of each muscle contribution based on OpenSim results. As reported in the matrix shown in Table 2, the *iliacus* and *psoas* contributions are collapsed into the *psoas* contribution, since they represent the two muscular bellies of the *ileopsoas* muscle. Afterward, the total area covered by each force intensity was calculated, and their sums and percent conversion were considered as the resultant force for all orientations, as represented in Figure 6. The maximal activation percentage provides information about how each muscle contributes to balance the resultant external force.

Table 2. Simulation results for the most significant muscle activations balancing external force during FK phase 1 in terms of area under the curve.

		+			—		
		50 N	**100 N**	**150 N**	**50 N**	**100 N**	**150 N**
Z	*glueteus medius*	0	0.0108	0.0396	0.1008	0.2019	0.5036
	biceps femoris	0	0.0035	0.0141	0.0537	0.1074	1.6170
	psoas	0	0.0106	0.0379	0.0426	0.0855	1.1290
X	*glueteus medius*	0	0	0	0.0369	0.0937	0.4962
	biceps femoris	0.0858	0.1719	0.2455	0	0	0
	psoas	0.1110	0.2220	0.5567	0	0	0

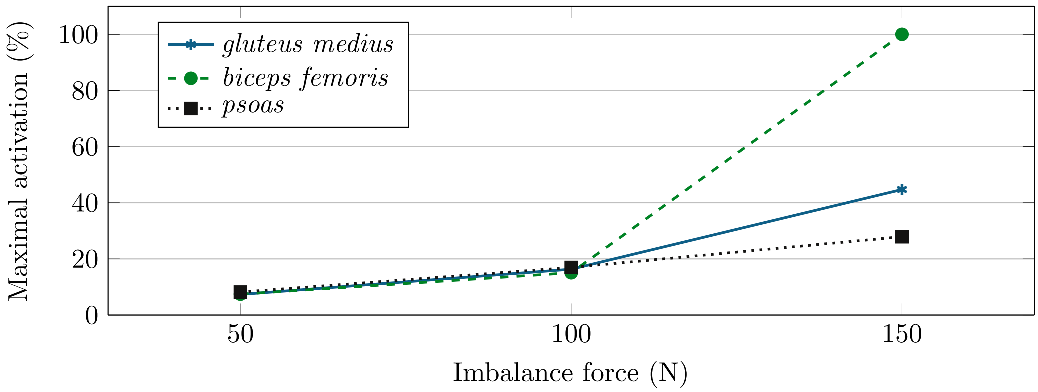

Figure 6. Total muscle activation (calculated as the covered positive area) for the front kick, phase 1.

3.2. Hardware and Software Considerations and Implementation of FES Control

Among the commercial and certified stimulator devices, the RehaMove® [58] matches our intent because it features enhanced user controllability, allowing users to define complex and time-varying FES profiles. In particular, this device permits the user to control up to eight channels simultaneously, with the possibility of individually setting the pulse parameters (i.e., amplitude, pulse width, and frequency) for each one, thus enabling the stimulation of different muscles groups concurrently and, consequently, the generation of synergistic movements. Considering our specific case, the above features are essential for the FK stimulation. As discussed in Section 3.1 and represented, e.g., in Figure 5, a multichannel and dynamic FES approach is fundamental to efficiently reproduce the muscular patterns in the stimulated subject (i.e., whose intensities depend on the considered muscle with variation over time).

Passing now to the software requirements, the control unit must comply with a biomedical application's technical specifications. In our situation, the two requirements that best describe the system functionalities are (1) real-time FES definition and modulation of pulse parameters from the muscle activation patterns and (2) operating software reliability to minimize failure probability and ensure user safety. In these regards, the RehaMove® stimulator can be interfaced with an external device by means of the ScienceMode 2 bidirectional protocol [59], which, beyond the implementation of a dedicated application programming interface (API), was developed to achieve both fast updating of the FES parameters during the ongoing stimulation and multiple safety checks. In particular, considering the last point, the ScienceMode 2 protocol constantly verifies the proper communication between the stimulator and the control unit (through a *watchdog* approach), and the RehaMove® itself performs skin-impedance measurements to check if the stimulation electrodes are adequately connected to the body, instantaneously presenting an error message if the matching condition is not verified.

With all the above considerations in mind, we implemented our control software in the MATLAB® and Simulink® intercommunicating environments. Starting from a third-party library and Simulink® block [60], which provides a basic interface with the stimulator API, we added our custom module for the definition of the FES profiles [34,40]. In particular, by means of a lookup table (LUT) structure, we link the simulated muscle activation patterns with the pulse features (i.e., amplitude, pulse width, and frequency), thus obtaining the newest FES patterns every time the muscle activation groups are processed.

Figure 7 shows the structure of our Simulink® model, which is basically divided into two main parts: the stimulator interface and the logical control block. The former is characterized by three time-variable inputs for pulse characterization, i.e., stimulation current, pulse width, and mode (which manages the timings for families of pulses), and some pre-run settings for serial communication. Linking these inputs to the MATLAB® workspace variables, e.g., the muscle activation patterns obtained from OpenSim simulation, direct control of the stimulation definition can be achieved. Moreover, in order to ensure online modulation of these inputs, a logical control block was implemented. Every time the simulation time (supervised by means of a *clock* object block) is equal to the user-defined *update time* (depending on application; 100 ms in our case), the *assertion* block is enabled, consequently pausing the simulation and running the MATLAB® custom script for the LUT-based FES parameter update [34,40].

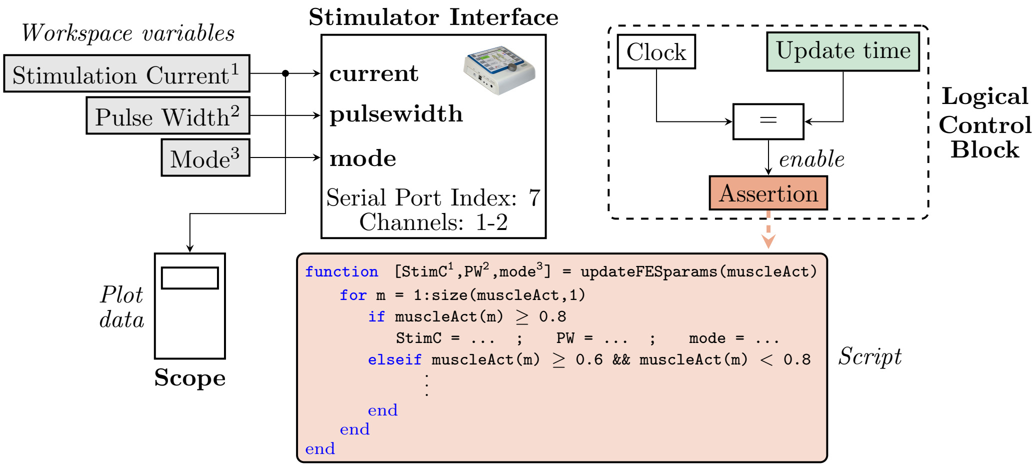

Figure 7. Simulink® model for the online control of the RehaStim 2 FES stimulator. The stimulation parameters are updated by running a MATLAB® script every (Update time) .

In our specific LUT implementation, the MATLAB® script, which is recalled by the *assertion* block, can be defined ad hoc depending on the user's requirement, making this solution suitable and general for different configurations and applications.

4. Discussion

FES: Application Definition and Discussion

Now that the software pipeline and architecture (from the OpenSim simulation to the RehaMove® FES communication) have been described, this section discusses the FES application possibilities of this approach. As introduced in Section 1, this analysis was restricted to evaluating whether the muscular information process flow is suitable to generate appropriate FES patterns. For this reason, this preliminary experimental investigation was conducted by simulating the FES definition process but excluding the real application of FES pulses on human subjects, which will be left to future works. Although a complete and more detailed description of the performance of the approach requires additional confirmations, some generalizations can be considered and discussed.

Therefore, depending on the extracted features (i.e., raw muscular patterns vs. post-processed features), the model proposed in this paper can fit two different FES real-case scenarios:

1. The stimulation parameters are defined in the beginning setup phase and do not change during the ongoing simulation. This situation is generally applied when unique data representing the entire history of muscle activation, e.g., the measure of total area (Figure 6), are available;
2. The stimulation parameters are continuously updated during the ongoing stimulation on the basis of the variation of muscle activation information over time (e.g., Figure 5).

In order to provide an application example, the graphical panel in Figure 8 represents the simulation current amplitude of the pulses inherent to *gluteus medius*, *biceps femoris*, and *tensor fascia lateae* muscles (obtained from the Simulink® model using a *scope* block, Figure 7) related to a 1 s stimulation duration (to be consistent with the perturbation timing). In [61], the *tensor fascia lateae* muscle was proposed for stimulation instead of the *psoas* muscle due to its major accessibility and participants' comfort during the FES application, while maintaining a good hip flexion motion. The definition of the proper stimulation current (minimum and maximum values) for the three cited muscles depends on different subjects' body conditions (e.g., age, muscle mass, fiber conductivity, and fat layer) [62]; however, without any loss of generality, 0 mA to 40 mA was set as a suitable range, since these current values, if correctly applied, allow such muscles to adequately contract [63].

As shown in the graphs in Figure 8a–c, the predefined stimulation parameters are directly proportional to the activation state of muscles and, consequently, to the applied force. In this case, a constant stimulation current is injected through muscle fibers, promoting the proper muscle-body contraction for at least 1 s (i.e., the simulation time).

In the other case, when the modulation of the FES parameters is directly obtained by the time-varying muscle activation coefficients, current profiles present the waveforms as reported in Figure 8d,e. This configuration enhances the adaptability of pulse amplitude with respect to the previous case, since the FES current evolves similarly to the force path (i.e., 0 s to 0.2 s, almost constant; 0.2 s to 0.4 s, increasing; 0.4 s to 0.6 s, maximal value; 0.6 s to 0.8 s, decreasing; and 0.8 s to 1 s, constant). It is interesting to notice that during the null-force phase, the stimulation current is proportional to the muscle activation that maintains the single-leg stance.

As introduced, this first work focuses on a preliminary study of the definition of a processing pipeline that applies the FES practice by using the simulation results related to martial arts exercises in general and Taekwondo as a particular case. Therefore, despite the simplicity of the movement (i.e., front kick) reported herein, the proposed approach may be an adequate solution to accomplish this task. However, evolving from this simulation method to the real scenario involving healthy and pathological subjects will allow us to evaluate and validate the proposed system. Moreover, more complex exercises (e.g., a sequence of different kicks), which are associated more detailed simulations, will permit us to enrich and improve the martial arts–FES relationship.

To the best of our knowledge, no other studies have been reported in the literature on the subject presented in this paper. However, some references related to this study can be found in [64,65], underlining the need for, usefulness, importance, and applicability of our proposed approach. Many steps must be performed to pass from an idea to a clinical application (i.e., ethical procedures, analysis, design, development, implementation, etc.). After performing these and many other steps, clinical tests can be performed. Many processes should be implemented before evaluating the impact of clinical tests. These complex and long phases may be more important if a simulation confirms the initial hypotheses before starting the process. This is our case. We did not perform experiments on humans, and only on a virtual human model used in open-source software [65], which helps us to validate the feasibility of our idea. This software has been used many times to compare clinical experiments with human model simulations. Our idea/approach seems feasible from the virtual point of view. This is the first step, but the research must be improved in clinical situations. The next step will be performed after a positive evaluation in simulation as reported in this paper. We are not able to evaluate the clinical impact in this paper, but begin by proposing a first hypothesis with respect to a new era of clinical tests. If our hypothesis is confirmed in a real context, our idea may result in a breakthrough procedure able to increase the quality of life of patients with reduced mobility. This could have a great impact on our society, enabling physical exercises and sport in human subjects with different pathology to maintain physical health.

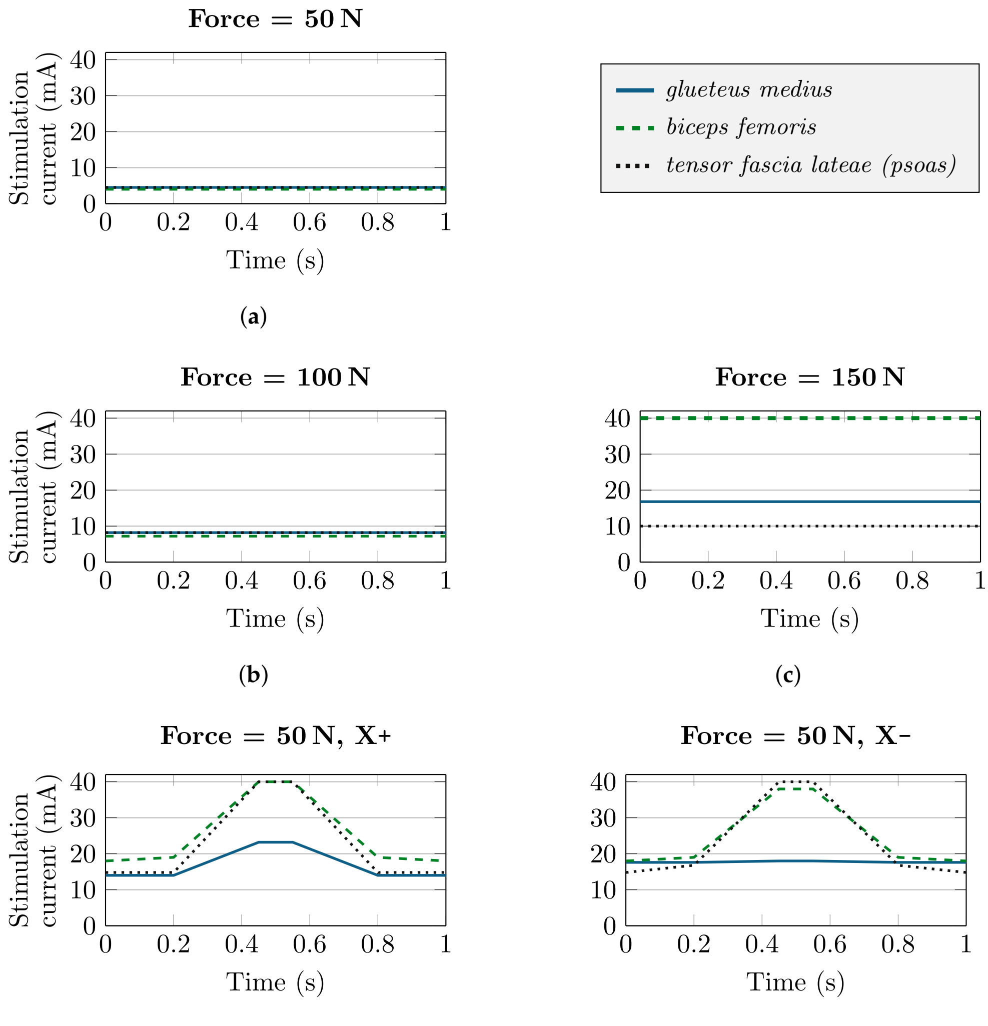

Figure 8. Stimulation pulse current amplitude modulation. Graphs (**a**–**c**) represent the static FES definition when the pattern is determined considering unique measurement information, i.e., the total area under the curve (Figure 6) for different amplitudes of the external force during FK poses. Current values are initialized before the stimulation session and remain unchanged during the execution. An increase in the force module corresponds to an increase in the current injected through the electrodes in order to obtain a static balance. On the other hand, graphs (**d**,**e**) show how online current modulation is achievable when the FES parameter definition is directly based on muscle activation. In this way, the features of the pulses follow the profile of the applied force. A significant variation of the current values can be observed during the 0.2 s to 0.8 s application of force (proportional to each muscle activation), while the static balance is clearly visible from 0 s to 0.2 s and from 0.8 s to 1 s.

5. Conclusions

This paper presents a preliminary virtual study of the feasibility of transferring muscular activation patterns of the front-kick exercise using functional electrical stimulation (FES). By using OpenSim as a virtual simulator, we extracted the static balance muscle activation of a virtual human model during the main phases of a front kick. The simulation results and their processing were used to define and modulate the FES patterns during the ongoing (simulation) stimulation. The FES application requires a minimal hardware setup to work: an FES stimulator, which usually needs to be situated near the user in order to connect the stimulation cable to the electrodes and which preloads all protocol profiles needed for the rehabilitation session, as well as space to move the body freely during stimulation, making this system portable and suitable for use outside of the clinical environment. As regards the prestimulation setup, the subject, with the help of a second person (if required), needs to place the stimulation electrodes on the skin surface (above the muscles of interest) and to configure the stimulator in the proper modality. The guidelines to successfully accomplish this task can be provided to the users with a short training session before releasing the system at home.

This conceptualized system could improve the restoration of functional motor tasks for subjects affected by neuromuscular disorders (e.g., development coordination disorders), in addition to solving the subject–participation difficulties encountered during rehabilitative sessions. Furthermore, the proposed virtual training system may also be used to increase the muscle performance of people without disabilities and practicing other sports. The study presented in this paper is a first step forward in the direction of virtual sport and, proposing a useful application for the society of the future. Many clinical implementations should be applied to validate the hypothesis presented in this paper, but a first feasibility step is simulated with our study. We performed a virtual analysis using a virtual model that is used in biomechanical sector to reproduce human behavior; however, clinical protocols should be performed to validate our approach. Future works should be oriented to demonstrate system functionality in real-case scenarios involving healthy and pathological individuals, with a complete and detailed validation of the approach proposed in this paper.

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Abbreviations

The following abbreviations are used in this manuscript:

API	Application programming interface
CoM	Center of mass
FES	Functional electrical stimulation
FK	Front kick
LUT	Lookup table

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