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Online Usage of Biomechanical and Simulation Software in Analysis of Rehabilitation Robots Performances by Applying Simulation Technique

Maryam Khamar[1], Mehdi Edrisi[2], Saeed Forghany[3]

Original Article

Abstract

Introduction: Rehabilitation robots have the ability to assist the patients with paralysis and semi-paralysis. Besides, these robots are capable of being programmed to perform various rehabilitation methods. However, evaluating their functions and their effects on human's body are still two of the main challenges of theses robots. The purpose of the present study was to introduce a method for assessing the function of a rehabilitation robot in modifying the crouch gait to normal gait, by using online biomechanics and computational software.

Materials and Methods: Rehabilitation robot and human leg were simulated using Inventor (Autodesk, Inc.) and OpenSim (Stanford University) software. User's muscle strength was calculated according to a crouch gait. The system got the position of each joint and muscle strength as input, and determined the torque required for each hip and knee joints.

Results: The performance of rehabilitation robot on human body was evaluated by relating the simulation in biomechanical and computational software. The kinematic and kinetic effects of robots on model of human model with crouch gait pattern was confirmed. In addition, the error of tracking normal gait with wearable robot was less than 0.06 rad for user with crouch gait.

Conclusion: By using a simulation method and analyzing the motion data of a person gait pattern, an optimal path can be defined individually for each person, which reduces the risk and error of tracking while using the rehabilitation robot. It is also possible to change the mechanical and control structure of wearable robots in simulation without the cost and risk of laboratory evaluation.

Keywords: Wearable Robot; OpenSim Software; Teaching in walk cycle

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Introduction

A wearable robot is a type of wearable tools that wearing them allows the user to move and increase the power and efficiency of the limbs with a motor disorder (1,2). The use of rehabilitation robots provides appropriate feedback on patient's performance and progress (3). Despite the advancements in the wearable robots technology, the development of these robots is limited due to the lack of information about their impact on the user, such as the impact on muscles as well as the change in the length and strength of each muscle during robot use (4). In this regard, two approaches of experimental evaluation and simulation are often used to test and develop wearable robots. In the experimental (laboratory) evaluation approach, the wearable robot is worn by the user and its performance is examined by measuring the force, torque, position, and speed. In this case, it is not easy to measure the change in the length of the muscles and the force they exert. In addition, there is a possibility of damaging the user in the laboratory test mode (5). In this case, the risk is high and the reliability is low (6). For example, the information obtained from electromyography (EMG) only determines the muscle activation time, and the relationship between this stimulation and body

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movement, the effect of this stimulus on each organ, and the quantitative relationship between the stimulation and other variables cannot be measured (7,8). However, using a simulation approach reduces the cost, time, and risks of an experimental test, in addition to providing the ground to modify the overall structure of the robot or the controller designed for it at no cost (1,9,10). Another advantage of simulation is the accurate measurement of indicators and variables such as muscle force, length changes in each muscle, speed and position of joints, and other indicators that cannot be measured practically or require high costs (11,12). Using simulation, the amount of optimal force required to be applied to the user by the robot can be calculated and based on which, the appropriate electric motor can be selected, hence increasing the efficiency and intelligently and appropriately selecting the parts required by the robot (13).

The OpenSim software, a type of open source software, was introduced by Stanford University, Stanford, California (14). Due to its capability to access reference codes, this software has the ability to be developed and connected with other software (9,15), but is not capable of online simulating and analyzing the controllers used for biomechanical systems. In contrast, MATLAB software is a powerful computing tool that can simulate the desired controllers, but it is not easy to model biomechanical systems in this software. In a study by Afschrift et al., the relationship between MATLAB and OpenSim software was established and an online analysis was performed for a wearable robot (8). In a study performed by Mansouri and Reinbolt, the OpenSim software was employed to calculate system states, including the position and speed of the shoulder joint. The limitations of this study were on the use of the existing controllers in the OpenSim software, which is a simple proportional-integral (PI) controller, and could not design other advanced controllers (16). In another study, this problem was resolved and it was possible to add the desired controller. In this study, external forces were not modeled and it was assumed that the body would perform the desired activity without the help of these forces (17). In the present study, the force applied using the wearable robot motors was added to the human model with motor impairment (simulated by OpenSim software) and the possibility of online communication between the two software was established taking into account the effect of motor force on the kinematics of the joint movement.

The current study is carried out with the aim to introduce a method to assess the performance of a wearable robot in modifying the lower extremity gait cycle of a person with crouch gait impairment with the online use of biomechanical and computational software. First, the robot and user modeling was performed using the OpenSim and Autodesk Inventor software. To test the robot performance in correcting the gait cycle, the controller was implemented using the MATLAB software and the connection between the OpenSim and MATLAB software was established online.

Materials and Methods

This study was of a simulation and modeling type performed using biomechanical and computational software. In this study, the motor data of an individual with crouch gait impairment were simulated along with a rehabilitation robot. The use of rehabilitation robots to modify motor patterns for individuals with mobility disorders has attracted the attention of researchers. In recent years, some robots have been developed for this purpose (2,18), but what is important in the development and construction of these robots is to pay attention to the pattern of movement of each user and examine the exact performance of the robot using simulation methods before clinical testing (7). In this way, in addition to reducing the risk of using the robot, it is possible to predict the effect of the robot on the user in some way, and accordingly, the occupational therapist can determine the treatment protocol with a better quality.

The OpenSim software (OpenSim SimTK 3.3, Stanford, USA) was exploited to model the user's anatomy. This software has the ability to model the anatomy of the body with features such as height, weight, and other characteristics of a real user. It also has robot and user modeling capabilities and the ability to analyze forces and communicate with MATLAB software. In the OpenSim software, it is possible to enter the user's walking pattern, which was recorded using motion analysis cameras, and examine and analyze it dynamically and kinematically (19).

The two OpenSim and MATLAB software were used in modeling and analysis of biomechanical systems in the present study due to their capabilities. The robot and user modeling using the proposed method had been previously performed in the study by Khamar et al. (20). The rehabilitation robot is used for both legs in practice, but in order to reduce the complexity and volume of computations, it was modeled only to simulate one leg, as the analysis can be performed for both legs by applying the pattern of movement of the left leg and right leg separately. For this purpose, the robot model was created using the Autodesk Inventor software for one leg (Figure 1).

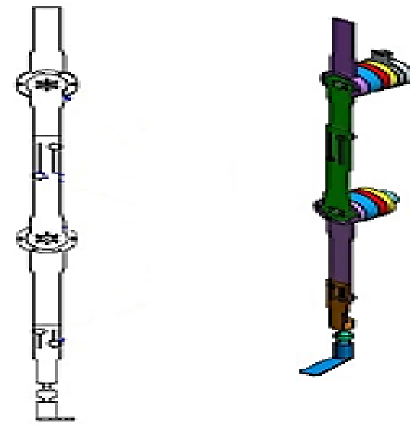


Figure 1. Wearable robot three-dimensional and real models

After adding the robot, the force applied by it was created using the robot-user model reference. In order to enter the user information and his movement pattern, the movement information of an individual with a movement disorder recorded by 3D motion capture cameras was used. The user model created in the OpenSim software consisted of three joints (a pelvis, a knee, and a wrist) that could move on the sagittal plane. The model also included 16 muscles: "soleus, long head of biceps femoris, middle gastrocnemius, vastus medialis, rectus femoris, short biceps femoris, tibialis anterior, and gluteus maximus", the information about which is presented in table 1. Two engines in the pelvis and knee joints were added to the model. The wrist joint did not have a motor and it was assumed that the robot did not have a role in the movement of this joint. It should be noted that information on natural gait is available in the OpenSim library.

Using the motor data of a subject with a motor disorder and the ground reaction force (GRF), the data were analyzed using software. The outcome of this analysis was the calculation of muscle force and movement pattern for each joint. The robot reference trajectory was then determined for each joint by analyzing the data by the occupational therapist. The robot's task at this stage was to follow the reference trajectory. Therefore, the robot controller was designed in a way to be able to travel this path considering the individual's muscle's force. The control block diagram, which was designed for the robot as the study by Khamar and Edrisi (21), is shown in figure 2.

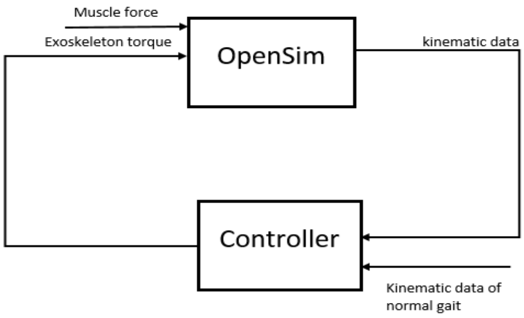


Figure 2. General block diagram of robot-user simulation

The force applied by the robot was based on the force applied by the user and aimed at tracking the reference trajectory. The system operated in such a way that the data associated with the path recommended by the occupational therapist were used as the reference data for the controller. Then, having the reference trajectory for each joint and the joint path at each moment, the controller in MATLAB software determined the motor torque and applied it to the model created in the OpenSim software. In order to track the desired path by the robot in the present study, the controller introduced in the study by Khamar and Edrisi (21) was utilized. The block diagram of this controller is illustrated in more detail in figure 3. As stated in the study by Khamar and Edrisi, this controller is capable of tracking the path, taking into account the uncertainty of the indicators and the force applied by the user, and can well follow the reference trajectory (21). Therefore, this controller was used for the simulation.

Table 1. Specifications of muscles modeled in OpenSim software (8)

Muscle name	Optimal length of a unit muscle (m)	Tendon looseness length (m)	Maximum isometric force (N)
Long head of biceps femoris	0.119	0.326	2700
short biceps femoris	0.173	0.089	804
Gluteus maximus	0.147	0.127	1819
Rectus femoris	0.114	0.310	1169
Vastus medialis	0.107	0.116	5000
Tibialis anterior	0.098	0.223	4000
Soleus	0.080	0.220	3000
Middle gastrocnemius	0.090	0.360	2500

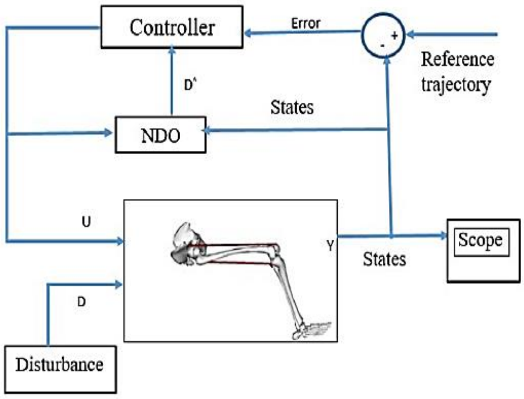
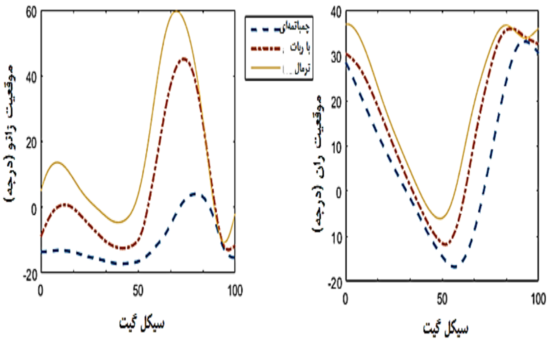


Figure 3. Control block diagram proposed in Khamar and Edrisi (21)

Results

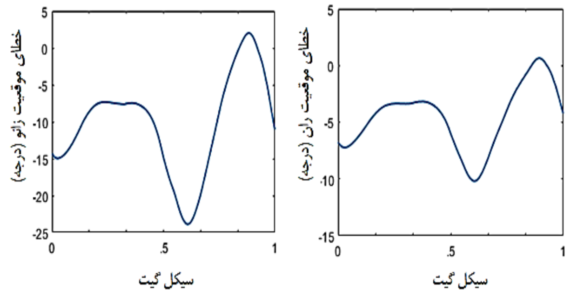
With the reference trajectory and muscle force, the controller calculated the amount of force that had to be applied by the motors to the hip and knee joints and applied it to the model. Then, using the OpenSim software, the position of the joints was calculated online and transmitted to the controller as feedback to determine the motor torque value based on the tracking error and muscle force. The simulation was performed in two modes of with and without using the robot, and the results were compared with the natural mode. In the first case, the natural walking path was applied to the robot, and in the second case, using the results of motor data analysis and according to the occupational therapist's opinion, the appropriate path of the patient was determined for each joint. Figure 4 depicts path tracking with the help of the controller.



Knee joint position (degree)-Hip joint position (degree)
Gait cycle

Figure 4. Reference trajectory and traced path of the hip and knee joints in the first case

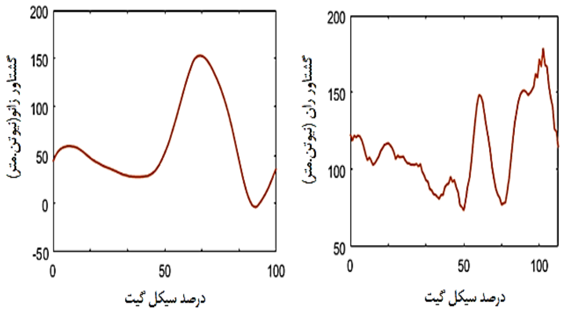
To check the tracking accuracy, the tracking error of the first case is shown in figure 5.



Knee joint position error (degree)-Hip joint position error (degree)
Gait cycle

Figure 5. Tracking error of the reference trajectory of the hip and knee joints in the first case

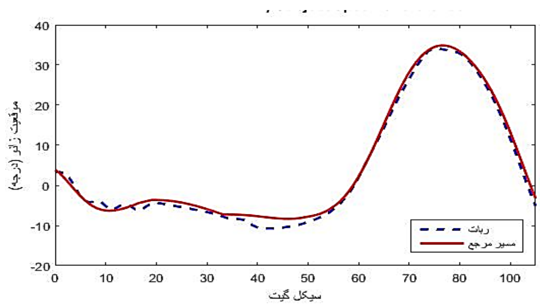
Besides, the force applied by the robot in this case is shown in figure 6.



Knee torque (N.m)-Hip torque (N.m)
Gait cycle percentage

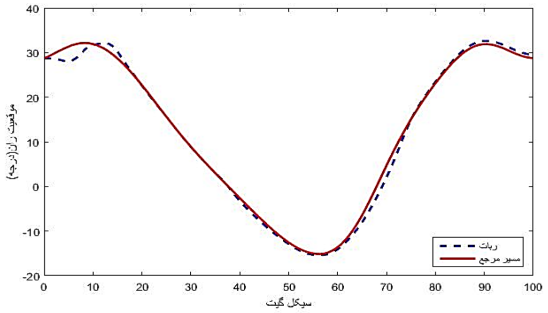
Figure 6. Robot force applied to the hip and knee joints in the first case

In the second case, the desired path for each joint was determined according to the occupational therapist's opinion and applied to the robot. The results of tracking the position of the knee and hip joints are demonstrated in figures 7 and 8, respectively



Knee joint position (degree)
Gait cycle

Figure 7. Reference trajectory and the traced path of the knee joint in the second case



Hip joint position (degree)
Gait cycle

Figure 8. Reference trajectory and the traced path of the hip joint in the second case

Discussion

Today, OpenSim software allows developing and connecting with other software due to its open source nature. Nevertheless, it does not have the ability to online simulate and analyze the controllers used for biomechanical systems. In contrast, MATLAB software is a powerful computing tool that can simulate the desired controllers, but it is not able to model biomechanical systems.

In their study, Mansouri and Reinbolt used OpenSim software to analyze a wearable robot with one degree of freedom of movement, but their model did not work online, and the external forces applied were stored in an XML format. They also used inverse dynamics tools for analysis (16).

In the study by Stanev, the connection between MATLAB and OpenSim software was established and the analysis was performed online for the wearable robot. In their study, the controller available in OpenSim software was used and only one disturbance input was generated using MATLAB software and the connection between the two softwares was established through S-function (17).

The limitation of this study was the use of controllers available in the OpenSim software, which is a simple PI controller and it is not possible to design other advanced controllers in this software. In addition, external forces were not modeled, and it was assumed that the body would perform the desired activity without the assistance of these forces (17), but in the present study, the applied force was added to the human model with motor impairment using wearable robot motors and the online communication between the two software was established taking into account the effect of the motor force on the kinematics of movement of the joints. The results suggested that this connection was well established and without delay, the kinematics of movement was calculated using the OpenSim software and imported to the MATLAB software to calculate the motor force and apply it to the wearable robot-user model.

After modeling and simulating the robot and the user with the online use of biomechanical and computational software, the effect of the robot on the user was examined. As expected, the use of the robot led the user's gait to approach the normal state. During the simulation, the user's muscle force was considered as an additional force, and the robot followed this path considering this force, indicating that the robot was resistant to external forces. The cause of the error emerged was the limited force applied by the robot and consideration of the maximum force tolerated by the user. To reduce this error, it is recommended that the reference trajectory be defined in accordance with each user's movement data and approach it to the reference trajectory over time according to the therapist. For this purpose, simulation was performed for two modes. What is important in rehabilitation robots is to consider the movement pattern of each individual and adjust the robot in accordance with the individual's own data. The simulation results showed that by defining the reference trajectory according to the occupational therapist, it is possible to reduce the tracking error and on the other hand, prevent the user from applying unbearable pressure and force and reduce the risk of using the robot.

Limitations

One of the limitations of the present study was that for simplicity, the robot ankle joint model was considered to be free, but in future studies, it is recommended that the control of the ankle joint movements be considered. Another limitation of the study was the use of the normal model for modeling the anatomy of the user's body.

Recommendations

In the present study, the wearable robot was tested on only one person and in future studies it is recommended that it be performed on other motor disorders and on a larger number of subjects. Additionally, it is better to create an anatomical model of the user using radiographs so that the structure of the model is closer to the real state.

Conclusion

Wearable robots have the ability to precisely control multiple joints simultaneously, enabling them to create more real-time activity-based exercises for the patient. In the present study, the effect of the robot on the user was examined using a simulation approach.

The use of the rehabilitation approach determines the reference trajectory for the robot in accordance with the user's own information, hence leading to an increase in the quality of the rehabilitation. Moreover, the application of the simulation approach reduces the cost, time, and risks of the experimental evaluation and reduces the risk of possible errors due to improper robot performance. Another advantage of simulation is the accurate measurement of indices and variables such as muscle force, changes in the length of each muscle, speed and position of the joints, and other indicators that are not measurable practically or require a high cost.

Acknowledgments

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Authors' Contribution

Maryam Khamar: Study design and ideation, attracting financial resources for the study, supportive, executive, and scientific study services, providing study equipment and samples, data collection, analysis and interpretation of results, specialized statistics services, manuscript preparation, specialized manuscript evaluation in terms of scientific concepts, confirmation of the final manuscript to be submitted to the journal office, responsibility for maintaining the integrity of the study process from the beginning to publication, and responding to the referees' comments; Mehdi Edrisi: Study design and ideation, attracting financial resources for the study, supportive, executive, and scientific study services, providing study equipment and samples, data collection, analysis and interpretation of results, specialized statistics services, manuscript preparation, specialized manuscript evaluation in terms of scientific concepts, confirmation of the final manuscript to be submitted to the journal office, responsibility for maintaining the integrity of the study process from the beginning to publication, and responding to the referees' comments; Saeed Forghany: Study design and ideation, attracting financial resources for the study, supportive, executive, and scientific study services, providing study equipment and samples, data collection, analysis and interpretation of results, specialized statistics services, manuscript preparation, specialized manuscript evaluation in terms of scientific concepts, confirmation of the final manuscript to be submitted to the journal office, responsibility for maintaining the integrity of the study process from the beginning to publication, and responding to the referees' comments.

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The present study was based on the analysis of part of the information extracted from the doctoral dissertation with the code of ethics IR.UI.REC.1398.027, approved by the University of Isfahan.

Conflict of Interest

None of the authors had a conflict of interest. Dr. Saeed Forghany is a faculty member of the Department of Orthoses and Prostheses, School of Rehabilitation Sciences, Isfahan University of Medical Sciences, and Dr. Mehdi Edrisi is a faculty member of the Department of Electrical Engineering, School of Engineering, University of Isfahan. Maryam Khamar is a PhD Student, Department of Electrical Engineering, School of Engineering, University of Isfahan.

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