Different Robotic Structures Aiming To Help In Testing Neuroprosthesis Control Strategies

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Abstract: This paper presents some robotic structures and software components aiming to emulate human body motion, while a neuroprosthesis is supposed to provide certain control over the muscles of a disabled person during a rehabilitation process. A Simulink&Matlab model implements the human body model while certain muscles are electrically stimulated and the resulted motion of the human body is shown by controlling a humanoid-like robotic structure. The main feature of the proposed humanoid-like robotic structures is support for the training, development, implementation and testing of user defined control algorithms for a neuroprosthesis.

Keywords: Robot control, Neuroprosthesis, Functional Electrical Stimulation, Rehabilitation

1 Introduction

A motor neuroprosthesis has been proven as helpful in performing standing and even walking exercises in paraplegia [1], [2], [3] and [4]. Functional electrical stimulation (FES) provides a means of producing controlled contractions in muscles that are paralyzed due to a disease of the central nervous system. A so-called neuroprosthesis may be used to restore the motor function in paraplegic patients on the basis of FES. Improved performance of these neuroprostheses can be obtained through feedback control [5], [6] and [7]. In order to develop and evaluate different feedback controller schemes, a versatile closed-loop FES-based system for use in research laboratory is essential. The system needs to be easy to use, reliable, and it needs to ensure an easy implementation of any new proposed controller. Therefore, a lot of work has to be done prior to testing it on a patient in a clinical environment.

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During the last few decades, different control methods that aim at restoring standing have been proposed [2], [3], [5] and [6]. Generally, paraplegic subjects can control their balance by using hand supports as crutches or parallel bars, and their standing periods vary due to the adopted posture, muscles fatigue and strength. Therefore, the most suitable SCI (spinal cord injured) patients to perform standing exercises by means of these FES based control methods are those with a T7-T12 lesion level. Although open loop control strategies do not account for any changes in the muscles performance such as fatigue or load changes, they are still widely used in clinics due to their relative simple set-up. A good mathematical model of the human body [6] is required along with a program which allows easy implementation of different control strategies. In order to show the effectiveness of the proposed methods rather than by graphs and animations made by computer programs, it is much more interesting to show kinetotherapists, clinical engineers and master students how a neuroprosthesis control affects the human body posture. The robot-like human body needs joint variables (ankle, knee and hip angles, angular velocities and accelerations), which are the result of the simulation.

This paper presents some of our work dealing with human body modelling, simulation, control strategies for neuroprosthesis and human body motion emulation on different robotic structures.

2 Testing system

The overall system like neuroprosthesis requires technology that inclu-

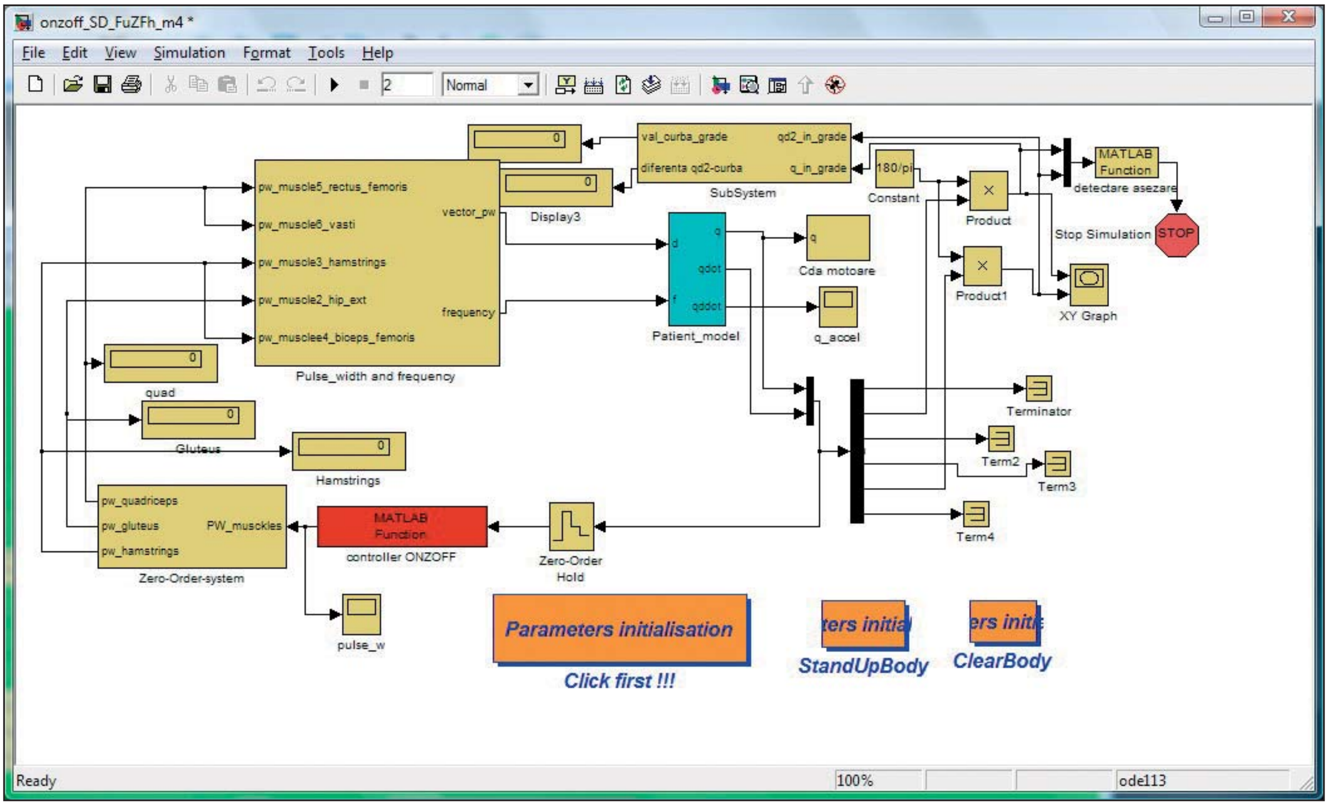

Figure 1. *The Simulink Matlab model of a human body and a FES-based controller block (red one)*

des stimulators, electrodes, sensors, lead wires and/or communication channels that connect them. Most of these components have to be mathematically modeled if it is of interest to emulate the human body motion, while a neuroprosthesis provides a controlled stimulation to the required group of muscles. Our proposed system contains a complex Matlab Simulink® model of the human body behavior, while the lower body muscles are considered electrically stimulated (see Figure 1) and different robot-like human body structures connected to the computer that performs a standing-up, standing and sitting-down chained motion as resulted in simulation.

2.1 Human body model

The considered Simulink model implements a three segmental model of a human body with nine mono- and biarticular muscle groups, as described in [6]. These muscle groups are modeled in the sagittal plane inducing moments about the ankle, knee, and hip joints. All muscle groups except monoarticular hip flexors can be activated in a real experiment by a proper arrangement of surface electrodes. Each modeled muscle group has its own activation and contraction dynamics. The inputs for the model are the stimulator pulse width and frequency. Muscle activation, muscle contraction and body segmental dynamics are the three main components of the implemented model. The forces computed for any of the nine muscle groups that are activated due to an applied electrical stimulus, are input to the body-segmental dynamics. The interaction (horizontal and vertical reaction forces) with a seat is modeled by means of a pair of nonlinear spring-dampers. The vertical shoulder forces are modelled as a function of measured knee angles by means of a fuzzy controller [8]. The implemented human body model will be provided with the electrical stimulus parameters (pulse width and frequency) for any selected muscle

Figure 2. *Robotic structures aiming to mimic the human body motion as induced by a neuroprosthesis (left – wood light structure superposed on a Lynxmotion robot arm, right – the humanoid Kondo robot)*

groups, in accordance with the desired control strategy of a motion task. The outputs are the angles, angular velocities and accelerations computed at the ankle, knee and hip joints levels, which can be conditioned and send out to the robot-like human body. A FES-based controller works on a half body, so in practice two controllers have to be tuned; one for each side. The control is performed in the sagittal plane, supposing that the patient arms will provide balance in the transversal plane.

2.2 Robotic structures

The first robotic structure consists on a wood light cover superposed on the 3-DOF robot links (see Figure 2 – left side). Four pulse-proportional servos HITEC HS-422 (two for the ankle joint and one for each of the knee and hip joints) are used to control the posture of a half robot-like human body in accordance with the simulation results. The HITEC HS-422 servos (range: 0 to 180°, voltage: 4.8 - 6.0vdc, torque: 4.104 kg-cm, speed: 0.16s / 60 degrees) have been chosen to provide the desired speed and torque of the driven joints (Lynxmotion site). During simulation, a Lynxmotion SSC-32 controller board is used to provide the required pulse width to the servos in accordance with the angles and angular velocities provided by the Simulink&-Matlab human body model.

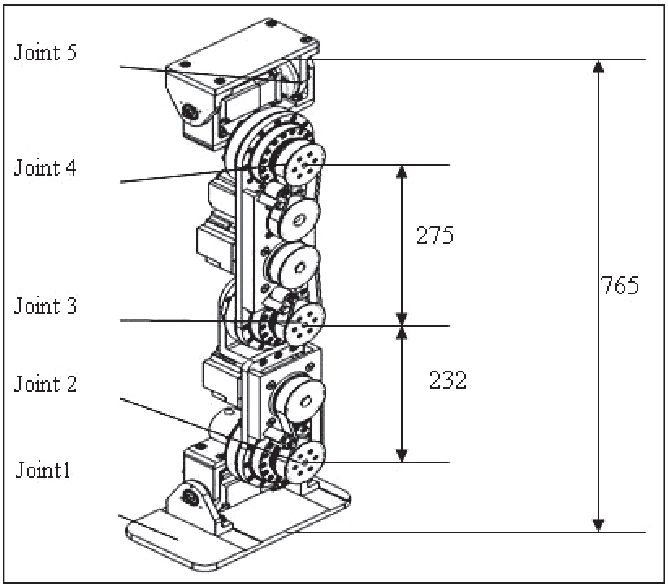

Figure 3. *The schematic structure of a mechatronic lower limb*

Figure 4. *The mechanical design of a mechatronic lower limb*

The second robotic structure (see Figure 2 – right side) is a seventeen degrees of freedom (DOF) Kondo robot which has been adapted to receive controls from the above presented Simulink model. Usually, it is driven by a RCB-3J control board with 24 PWM input/output and 3 analog input ports. Its KRS-788HV servos (range: 0 to 180°, voltage: 9.0 - 12.0vdc, torque: 10 kg-cm, speed: 0.14s / 60 degrees) makes it much more powerful than the first robotic structure and provides a much more challenging equipment in term of controlling standing-up, standing and sitting down.

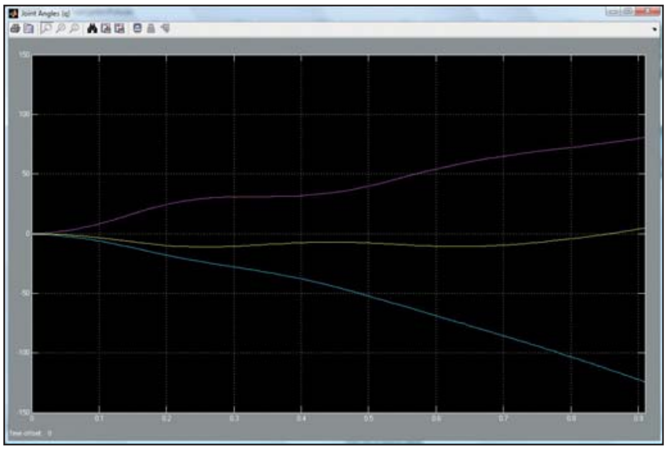

Figure 5. *Ankle (middle line - yellow), knee (top line - pink) and hip (bottom line - blue) joint angles during a sitting-down task (simulation)*

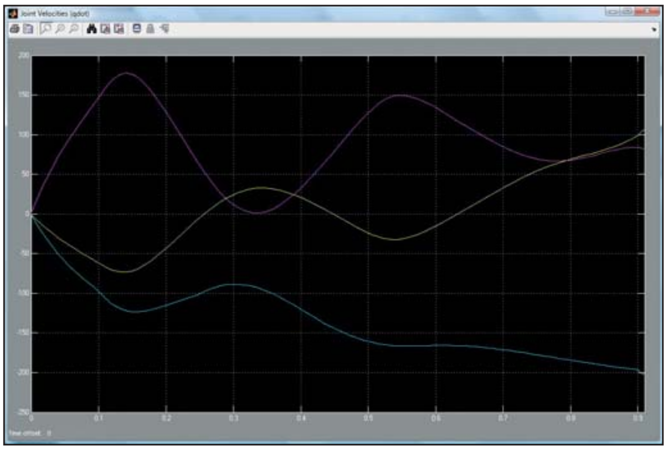

Figure 6. *Ankle (yellow), knee (pink) and hip (blue) joint angular velocities during a sitting-down task (simulation)*

The third robotic structure tries to replicate the human body lower limbs. The dimensions of the thigh and the shank were chosen in a 9/10 ratio, 402 mm for the thigh, and 362 mm for the shank.

The motors was chosen to provide sufficient torque and the required angular velocities in all the five joints. The joint two and three are provided with OMRON SGMPH-02AAA6CD-0Y brushless servomotors (rated torque: 0.637Nm /200W, speed: 3000 rpm, build-in 16 bits encoder, build-in 24 V brake). The joint two and three are provided with OMRON SGMPH-01AAA6CD-0Y brushless servomotors (rated torque: 0.318Nm /100W, speed: 3000 rpm, build-in 13 bits encoder, build-in 24 V brake). Each of them is driven by a servo driver (220Vac) allowing the position, velocity or torque control modes. Gearing reduction was provided via some harmonic gears (100:1 ratio, with a nominal torque of 31 Nm (maximum 143 Nm) for the joints one and five, and of 87 Nm (maximum 369Nm) for the joints two, three and four, respectively).

It is supposed that the overall designed structure will provide a better control of the required joints angles, angular velocities and accelerations.

3 Results and Conclusion

Performing FES-based standing exercises is of great interest for paraplegic people. We have focused on the control of a chained motion standing-up, standing and sitting-down. The simulation results are provided to real equipment, which emulates human body motion as it is supposed to be under control of a neuroprosthesis.

Figures 5 and 6 show the evolution of the ankle, knee and hip joints angle, and angular velocities. The knee and hip angles are measured anticlockwise relative to the shank and thigh, respectively, while the ankle angle is measured relatively to a vertical line. The sitting position is reached at the moment when the knee joint angle equals 80° (see Figure 5). Figures 7 and 8 show the shoulder forces as estimated for the patient and the ground forces, respectively. In that case the control strategy for sitting down allows the virtual patient to support only a small percent of its body weight, while the ground forces graphs prove that a large amount of the body weight is supported by the lower legs due to electrical stimulation technique.

Figure 9 shows the pulse width values, which have to be applied over the quadriceps, hamstrings and gluteals by a neuroprosthesis, in accordance with the ONZOFF sitting-down control strategy [3]. The ONZOFF (ON-Zone-OFF) controller, works according to a switching curve in knee angle against knee angular velocity state-space, but with a gradual increase or decrease in stimulation pulse width (see Figure 9) between the ON and OFF subspaces, the so-called 'zone'.

The human body model is initialized with statistically general dimensions for shank, thigh and upper body (0.45 m, 0.5 m and 0.8 m), seat high (0.45 m), link mass (3.5 kg, 10 kg and 23.7 kg) and center of mass (0.279 m, 0.244 m and 0.4685 m) for each of the three links. The values of angles and angular velocities of the ankle, knee and hip joints are con-

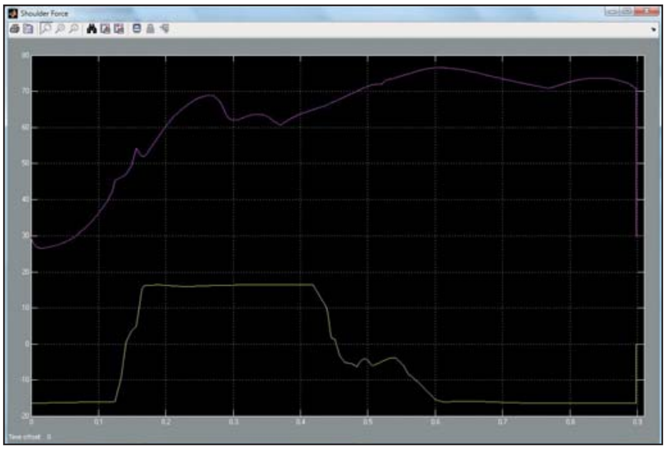

Figure 7. *Vertical (pink) and horizontal (yellow – sagittal plane) components of the shoulder forces*

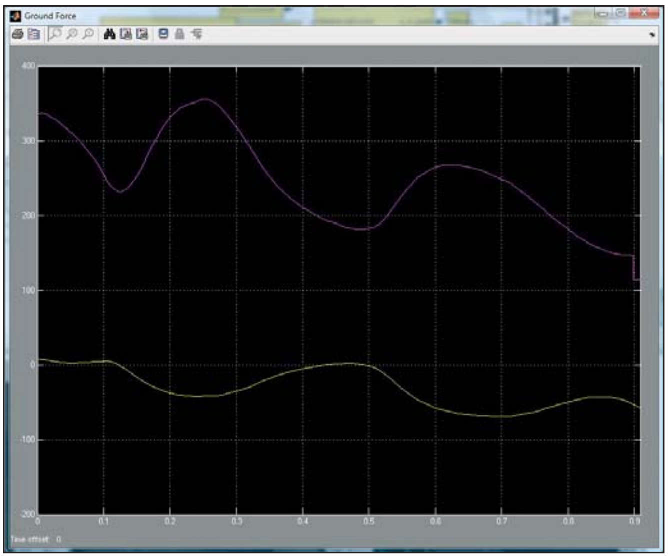

Figure 8. *Vertical (pink) and horizontal (yellow – sagittal plane) components of the ground forces*

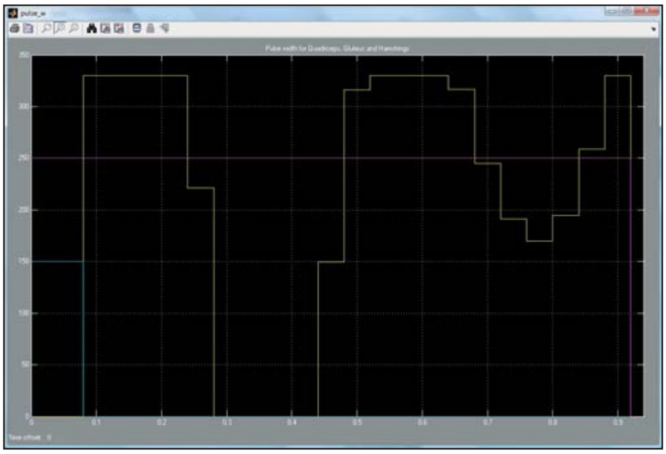

Figure 9. *The controller output (pulse width of the electrical stimulus) for quadriceps (yellow), hamstrings (blue) and gluteals (pink) muscles*

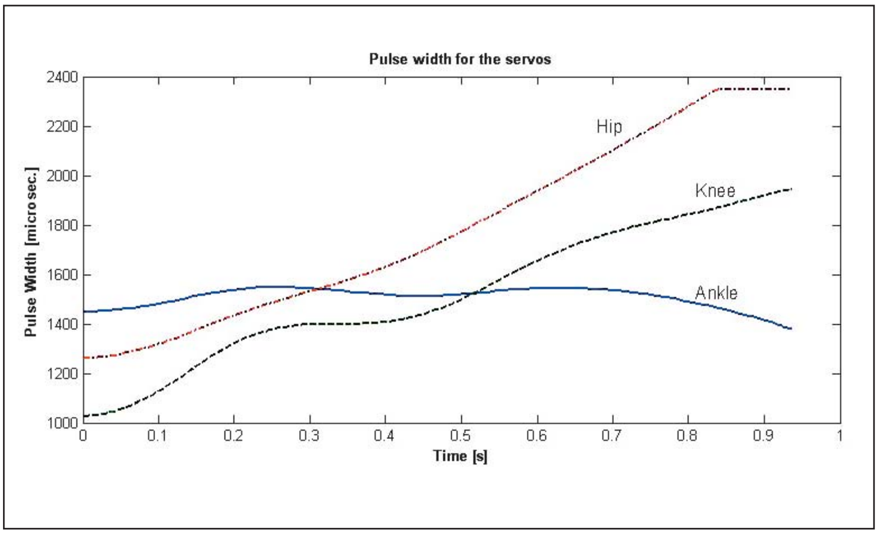

Figure 10. *Pulse width for the driven servos of the wood covered robot-like human body structure*

verted into inputs for the mechatronic devices which mimic the human body motion.

For the first robotic structure (light wood structure with servomotors – see Figure 2 – left side) a SSC-32 controller, which drive the servomotors, has to be provided with the values of the pulse width of the PWM signal to be applied to the joint servomotors. The pulse widths for the driven servos are shown in Figure 10, and are related to the simulation results which are presented in Figures 5 to 9. This robotic structure has some limitations related to the knee and ankle angular velocities limitations and also on the provided torques. Due to the limited torque provided by the servos at the ankle level, the robotic structure, which resemble a pendulum, may develop some unwanted small oscillations at the beginning of the sitting-down phase.

The humanoid Kondo structure (see Figure 2, right side) has more powerful servomotors and overcomes this problem, still keeping some limitations in terms of the available range of angular velocities, which can be imposed to that robotic structure. It offers a much more challenging control problem, while the upper body also has to be mathematically modeled and controlled in order to ensure the equilibrium. The third robotic structure overcomes all the problems encountered at the first two human-like robotic structures and provides enough torque in any required joint and comes with more degrees of freedom at the ankle and hip joints. It was provided with a Trajexia-OMRON control system which may incorporate all the simulation programs and can even be programmed to accept outputs from a neuroprosthesis. The main idea is that a neuroprosthesis, which has been programmed to support FES-based standing in paraplegia can be tested on that robotic leg prior to use on human users. Once the expected results are achieved, it will be possible to continue with clinical trials. Less required trials are expected since a neuroprosthesis is fitted to a patient.

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Robotske naprave za razvoj vodenja ortotičnih sistemov FES

Razširjeni povzetek

Članek predstavlja robotske naprave in programska orodja za pomoč in emulacijo gibanja človeškega telesa pri uporabi vodenja mišične aktivnosti s pomočjo funkcionalne električne stimulacije (FES) paraplegičnih oseb.

S pomočjo ortotičnih sistemov FES je možno paraplegičnim osebam povrniti nekatere motorične funkcije. Zaprtozančna regulacija vodenja izboljšuje delovanje sistemov električne stimulacije, vendar so danes v kliničini praksi uveljavljeni le preprosti načini tovrstnega vodenja. S funkcionalno električno stimulacijo podprta vadba vstajanja, stoje in usedanja lahko pripomore k hitrejši rehabilitaciji.

Pred preverjanjem delovanja ortotičnega sistema FES v kliničnem okolju je delovanje priporočljivo preveriti s simulacijo. Namensko simulacijsko okolje posnema gibanje človeškega telesa, ki se giblje s pomočjo električne stimulacije. Šele, ko je shema vodenja preverjena in je možno predvideti učinke, se lahko prične klinično testiranje. Pristop s predhodno simulacijo zmanjša število potrebnih testiranj za prilagoditev sistema pacientu, s čimer je lažja tudi namestitev in uporaba. V delu so predstavljene tri robotske naprave za simulacijo delovanja algoritmov vodenja ortotičnih sistemov FES. Vsaka mehatronska naprava za posnemanje gibanja človeškega telesa, ki se giblje pod vplivom vodenega sistema FES v laboratorijskem okolju, lahko prispeva k boljšemu razumevanju delovanja in uporabe ortotičnih sistemov FES pri paraplegičnih osebah v klinični praksi.

Simulacijski model človeškega telesa je razvit v programskem okolju Matlab Simulink®. Model posnema gibanje telesa, ko so spodnje ekstremitete vodene z električno stimulacijo. Model je zgrajen kot trisegmentni model, ki vključuje devet mono- in biartikularnih mišic. Mišične skupine so modelirane v sagitalni ravnini in delujejo v sklepih gležnja, kolena in kolka. Vsaka mišična skupina je modelirana z lastnim modelom dinamike aktivacije in kontrakcije. Vhod v mišični model sta širina in frekvenca stimulacijskih impulzev. Simulacijski model tako združuje modele mišične aktivacije, mišične kontrakcije in dinamike gibanja segmentov. Dvižne sile, ki delujejo v ramenskem sklepu, so modelirane s pomočjo mehkega regulatorja kot funkcija merjenega položaja kolena. V praksi na vsako polovico telesa deluje svoj sistem FES, zato je potrebno uglaševanje vsakega sistema posebej. Oseba s pomočjo opore rok dodatno zagotavlja ravnotežje v transverzalni ravnini.

Prvi predstavljeni robotski mehanizem je sestavljen iz treh lahkih segmentov, ki ponazarjajo segmente človeškega telesa. Za pogon segmentov so uporabljeni štirje pulznoširinsko vodeni servoaktuatorji HITEC HS-422, pri čemer dva v skladu z rezultati simulacije poganjata sklep gležnja, po eden pa sklep kolena in kolka. Drugi robotski mehanizem je robot Kondo s sedemnajstimi prostostnimi stopnjami gibanja, tretji mehanizem pa je trisegmentna struktura, ki ponazarja človeško nogo. Robotski krmilnik je prilagojen za vodenje preko modela Simulink. Dinamika gibanja robotskih mehanizmov je omejena z maksimalnim navorom in maksimalno hitrostjo gibanja v sklepih. Dimenzije segmentov so bile izbrane v razmerju 9/10 glede na človeško telo. Tako znaša dolžina stegna 402 mm in dolžina goleni 362 mm. Pogonski motorji so bili dimenzionirani glede na zahteve dinamike gibanja človeškega telesa. Za vodenje motorjev je uporabljen krmilni sistem Trajexia-OMRON, na katerem lahko hkrati tečejo simulacijski algoritmi, vhod pa je lahko tudi jakost stimulacije sistema FES.

Razvite mehatronske naprave in programska orodja omogočajo, da je ortotični sistem FES za oporo pri stoji ali hoji paraplegičnih oseb ustrezno preizkušen pred uporabo na pacientu. Ko rezultati ustrezajo pričakovanim, je možno eksperimentiranje v kliničnem okolju. Razviti sistem zmanjšuje potrebno število preizkusov za prilagoditev sistema FES uporabniku. Razvita oprema lahko koristno služi tudi kot pedagoški pripomoček pri razlagi vodenja ortotičnih sistemov FES študentom magistrskega študija smeri biomedicinskega inženirstva.

Ključne besede: funkcionalna električna stimulacija, zaprtozančno vodenje FES, robotski mehanizmi, ki posnemajo gibanje človeka

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