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Matlab/simMechanics based control of four-bar passive lower-body mechanism for rehabilitation[☆]

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Summary In recent times, use of wearable devices is becoming popular for providing precise ways of rehabilitation. The focus of this paper is to propose a passive lower body mechanism using a four-bar linkage, which can be actuated via the hip joint to move the other two joints at knee and ankle as well. Simulations are performed here by considering an average male human (height six feet) by modelling the gait cycle in CAD software and executing the control strategy in the SimMechanics, which provides a convenient way to study without use of detailed computational mathematics. The study of the controller aspects of the passive mechanism is presented with both PD and PID controllers with auto- and manual-tuned gains. Significant reduction in actuator torques is observed with the manually-tuned PID controller over automatically-tuned PID controller with marginal degradation in the overshoot and settling time.

Introduction

Cerebrovascular diseases, such as strokes, which occur due to poor blood flow to the brain. Survey taken in the first phase of twentieth century shows that 9.6% of the total death count was due to stroke worldwide which is increased up to 12% in 2013 (Lancet, 2015). After suffering a stroke, 10% of patients were found to recover completely with medicines, while the rest needed regular exercise to recover gait cycle. This cycle describes the motions of all the lower body joints (hip, knee and ankle) from initial placement of the supporting heel on the ground to the same heel contacting the ground for the next step (Novacheck, 1998). This process of recovery of gait cycle is called rehabilitation, which is normally done in hospitals or clinics with rehabilitation devices or equipments (Smith et al., 1981). Wearable robots have become popular for rehabilitation since they are able to remove almost every limitation of the traditional therapeutic devices (Rupal et al., 2016). Generally, four types of rehabilitation devices are used — Treadmill type,

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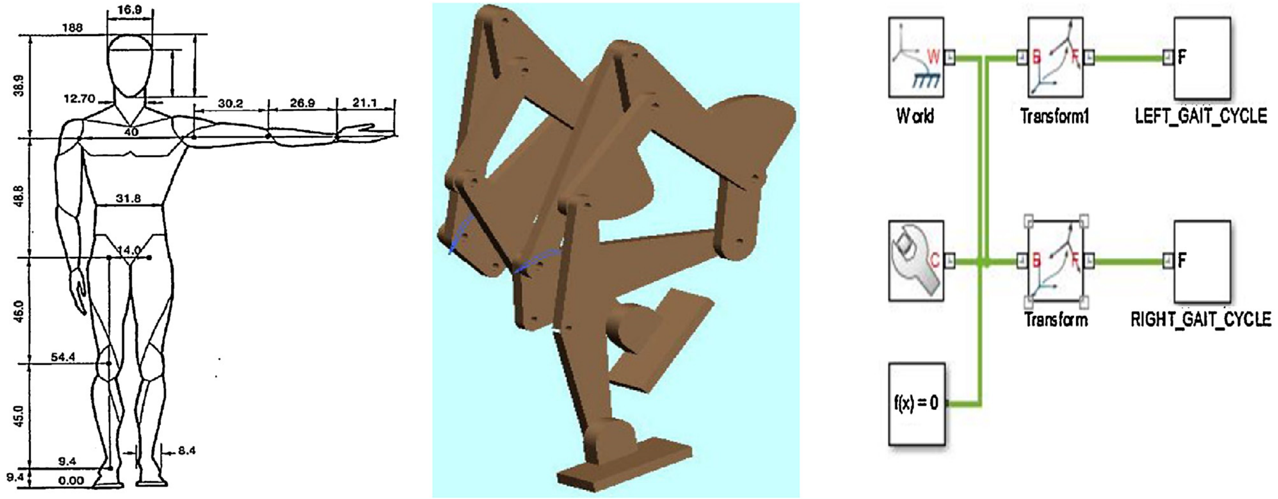

Figure 1 (a) Dimensions of average male human being (Singh et al., 2016), (b) CAD model pf the four-bar passive mechanism, (c) Four-bar passive mechanism.

Foot-plate based, Over-ground type and Stationary type gait trainers (Huo et al., 2014). Moreover, there are also some limitations of wearable robots related to their physical interaction, portability and energy requirements. Major limitations of the wearable robots are their heavy weight and high cost. Actuators and batteries contribute in a major way to both these limitations. In this respect, increasing the use of passive mechanisms could be one possible solution. Passive elements like springs, pulleys, link-mechanisms, etc. can be used to store or dissipate energy thereby reducing the overall energy needed to support the human motions (Valiente, 2005). Human powered products are also a good source to decrease the battery weight which further decreases the weight of wearable robots (Dhand et al., 2016). Link mechanisms like four-bar linkage systems are often used having one active and three passive links and are virtualized by using CAD tools like CREO, Solidworks, CATIA, etc. (Kostic et al., 2013). The integration of CAD software and Matlab/SimMechanics provides a convenient environment to perform detailed control design and dynamic simulations of complicated mechanisms without deriving complicated differential equations (Shaoqiang et al., 2008).

In this paper, a four-bar passive mechanism structure is proposed for rehabilitation devices, which is designed to work with one actuator per leg. The paper is organized as follows: in Section 2, the modelling work in CAD software is presented, imported into Matlab using SimMechanics. In Section 3, two different combinations of proportional, differential and integral controllers with automatic and manual tuning are presented to study the control strategies of the passive mechanism. Finally, conclusions are drawn in Section 4.

Modelling of the passive mechanism

In this section, the solid model of the passive mechanism is developed using the Creo CAD software and simulated in Simulink. To transfer the model from Creo to Matlab & Simulink, the Creo model designed is embedded in SimMechanics. In order to make a realistic model, the dimensions of a six-feet tall male (Fig. 1a) are considered in this work (Singh et al., 2016). Aluminium alloy AL2014 is used as a reference material and weight of the passive mechanism per leg is calculated as 10.7 kg. The assembled part of whole mechanism is shown in Fig. 1b. It can be clearly seen that as the crank rotates at the hip joint, the appropriate joint motion trajectories are transferred to the knee and ankle joints using connecting rods and linkages. For simplicity, the ankle joint movement is not considered in this work. The modelling details of mechanism in CAD software and velocity analysis at knee, foot and hip joints are discussed in Singh et al. (2016). The CAD model file is converted to an XML file and imported to SimMechanics by the simmport inbuilt Matlab function. The block diagram model converted from CAD model is shown in Fig. 1c. It has two subsystems named LEFT_GAIT_CYCLE and RIGHT_GAIT_CYCLE, having equal number of blocks with symmetric pattern.

Controller design

In this section, two different controllers are used to control the passive mechanism. In the passive mechanism proposed here, there is only one active link in the four-bar linkage arrangement, i.e. the revolute joint between the knee link and the crank, which is sufficient to control the whole subsystem. SimMechanics provides the option to control the system with automatically-tuned controller gains, available in the Simulink library. Due to symmetry in the passive mechanism, the same controller can be applied to other subsystem. The block diagram of the RIGHT_GAIT_CYCLE subsystem (having same blocks as other subsystem mentioned above) with the controller is shown in Fig. 2. The PID block is used as the controller from the Simulink library, which gives the ability to choose any combination of proportional, differential and integral gains in order to control the system. The input to the closed loop system is the desired angular displacement of the crank and the outputs are the resulting moment and actuator torque. The control objective is to move the crank, i.e. the hip joint by 10° angular displacement. Both PD and PID controllers with auto- and manual-tuned gains are used to stabilize the system and the

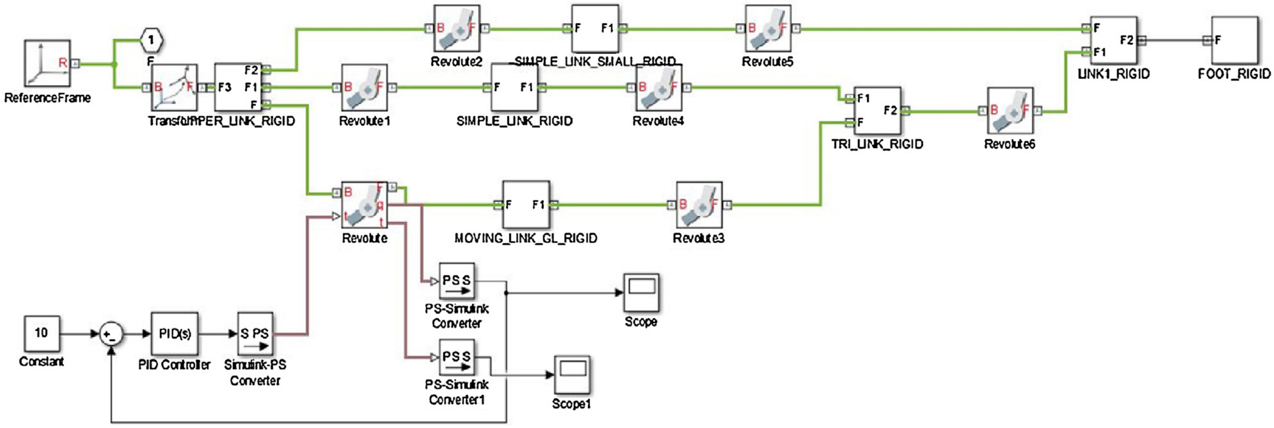

Figure 2 PID controller added to system.

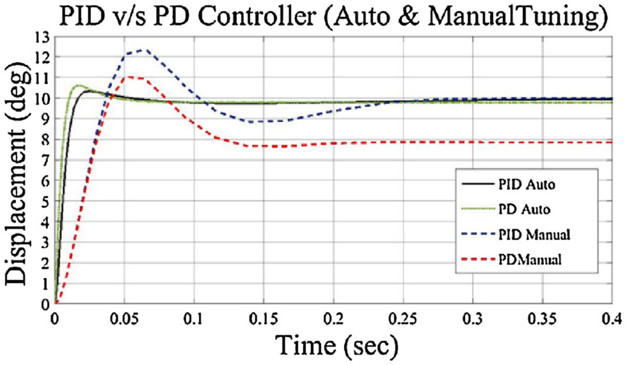

Figure 3 Auto and manually tuned PID v/s PD controllers.

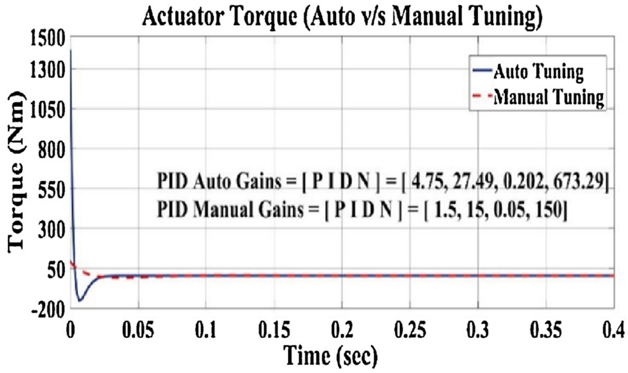

Figure 4 Controller actuator torque for auto and tuned gains.

relative performance of both the controllers are shown in Fig. 3. It can be observed that with auto-tuned PD controller results, the maximum overshoot is 0.6° with settling time of 0.3 s. Moreover, the PD controller is unable to deliver the zero steady-state error, which is found to be 0.2° as the crank displacement settles to 9.8°.

In order to eliminate the steady-state error, the auto-tuned PID controller was used. As can be seen in Fig. 3, this yields an overshoot of 0.37°, which is 0.23° less than the PD controller. Further, the settling time of PID controller is slightly more at 0.38 s but the steady-state error has been eliminated. Next manual tuning controller gains were considered. Similar trends are observed in that the PD controller results in 1° overshoot and has a settling time of 0.2 s, whereas the PID controller gives 2.3° overshoot and 0.27 s for the settling time. Further, the steady-state error using the PD controller is 2.14° which is reduced to zero with PID controller.

From these final results, it looks like that the auto-tuned controller works better than the manual-tuned controller which is a wrong interpretation. This wrong interpretation can be corrected by comparing the actuator torques as shown in Fig. 4. It can be seen that the auto-tuned PID controller torques have high values with the maximum value being 1410 Nm at start-up, whereas the manual-tuned PID controller torques are much lower with only 90 Nm as the maximum torque value. It looks physically unrealizable in auto-tuned PID controller as it requires either a very heavy actuator or multiple gear trains. Thus, it is concluded that manual-tuned PID controller results in 93.6% of torque reduction with a marginal degradation in overshoot and settling time.

Conclusions

The paper has presented modelling and control studies for a passive mechanism designed to be used for lower-body rehabilitation applications of patients recovering from a stroke. The passive mechanism uses a four-bar mechanism, which can result in actuation of all the three primary joints (hip, knee and ankle) by driving only the crank at the hip joint. The mechanism is shown to work well and is able to track normal human walking gait cycles and hence can be used to retrain a person learning to walk again. Creo software has been used to model the mechanism and then exported to Matlab/SimMechanics to control. It has been found that control of complicated and multi-body systems can be effectively performed on SimMechanics, without developing the complicated equations of motion. Controller design for the passive mechanism has been performed using PD and PID controllers, with automatically- and manually-tuned gains. Finally, it has been shown that PID controller works better than PD controller in achieving zero steady-state error with a marginal penalty on the size of the overshoot and longer settling-time. It has also been also shown that the manually-tuned PID controller is able to achieve the desired performance with much lower actuator torques.

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