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Trajectory Planning and Simulation of 4-DOF Reciprocating Gait Orthosis

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Abstract

A development of trajectory planning and simulation for a four degree-of-freedom (DOF) biped reciprocating gait orthosis (RGO) for paraplegic is presented in the paper. Trajectory planning in joint space is developed using linear segments with parabolic blends (LSPB) method and presented graphically. The design of the RGO structure is developed in Solidworks and linked to MATLAB SimMechanics via xml mode. The input of generated model is fed according to the measured angular position trajectory of hip and knee joint actuator using Signal Builder block from MATLAB Simulink library and the simulation is shown graphically. The result of the simulation shows the RGO movement is imitating the desired trajectory quite similarly in each gait cycle and verified a normal walking gait pattern. The developed trajectory planning in this paper can be used as an input signal for the system in further advanced RGO control development.

Keywords: Reciprocating Gait Orthosis, Trajectory Planning, Simulation

1 Introduction

Paraplegic suffers dysfunctional lower extremities due to spinal cord injury. Numbers of researches, rehabilitation and equipment have been performed for paraplegics with non-permanent disabilities to walk again [4, 9]. Devices whether a stand-alone orthosis, treadmill-based or handheld have been studied and invented to aid paraplegics, e.g. Reciprocating Gait Orthosis (RGO), Walkabout Orthosis (WO), Hip-Knee-Ankle-Foot Orthosis (HKAFO), Hip Guidance Orthosis, etc. Studies show the orthosis consumed high amount of energy from the patient which would limit the efficiency of movement [1, 2, 5]. Thus, a simple automated biped RGO with 4 degree-of-freedom (DOF) is presented to assist rehabilitation with less energy consumption [7, 11].

The study of human walking gait has similar concepts with classic robotic topics which revolve around kinematics, dynamics and motion trajectory [8, 12]. There are advanced research developments on trajectory planning of biped robotics has been conducted and offering several approaches for walking stability such as inverted pendulum, zero moment point (ZMP) position, falling-based optimal foot trajectory planning method, the classical high-order polynomial method, low-order polynomial function in linear segments with parabolic blends (LSPB) [3, 6, 8, 10, 12, 13].

In this study, LSPB mathematical function application and simulation of the walking gait in MATLAB SimMechanics is performed to obtain, verify and present the position trajectory of the RGO in joint space with reference on normal waking gait pattern. The following are several sections describe the development of the trajectory of the biped RGO starting from overview of the human walking gait pattern, kinematics analysis; trajectory method, walking simulation and discussion of the RGO simulation result.

2 Trajectory Planning

Human walking gait pattern is studied to simulate the RGO movement similar to normal ambulation. Fig. 1 shows the human walking gait cycle in sagittal plane which is the dominant plane of motion during human locomotion. In this research, the walking gait started and end in stand-still (pre-swing) position within respective time frame. A full 100% walking gait cycle began and end at toe-off event of the right leg which is from time frame, T = 1 to 9. Between the heel strike of right leg and toe-off event of left leg, the overall leg is in double support sub-phase. During ambulation, it is observed that movement of right leg is recipcoral to the left side, which means the right leg is in swing phase and left leg is in stance phase simultaneously and when the right leg move to the next stance phase, the left leg is in swing phase.

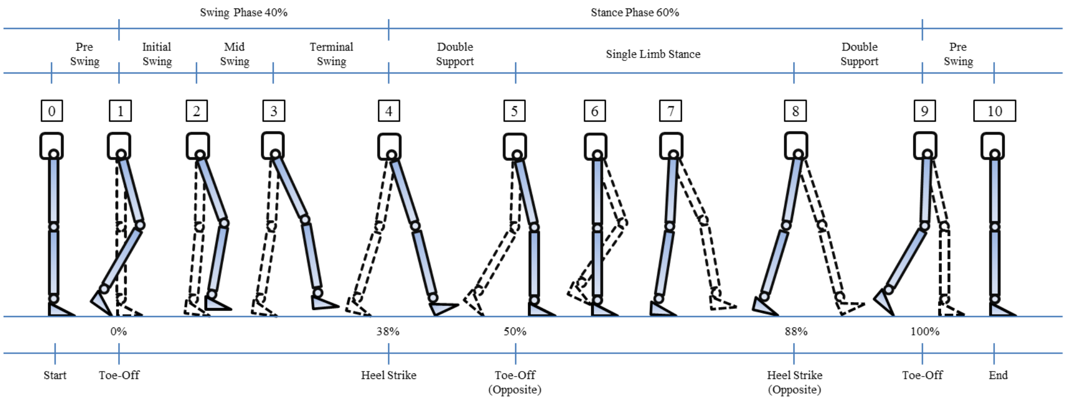

Fig. 1 Walking gait pattern of a normal person

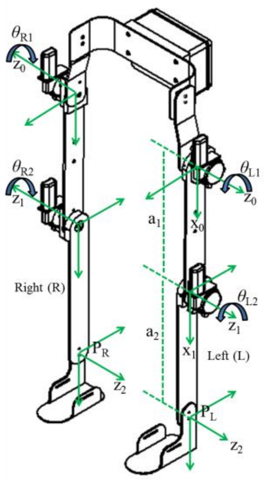

Fig. 2 Joint rotation direction and link parameter of the developed RGO

Fig. 2 shows the developed 4-DOF RGO which is designed in Solidworks software. The 4 (DOF) is divided into a 2-DOF per side of leg, i.e. 2 joint actuators located at hip and knee joints each side. Each hip and knee part is equipped with a DC motor acting as the joint actuator. The x-y-z frame is assigned to each joint using Denavit Hartenberg's (DH) algorithm to obtain the homogenous transformation matrix. The ankle joint part has no actuator and deliberately let free to rotate according to walking movement. The base (reference) frame and end effector (final frame) are located at hip joint and ankle position, respectively. Based on the DH parameters and homogenous transformation matrix, the following equation describes the position of the ankle:

$$P_x = -0.41c_1 - 0.41c_{12} \qquad P_y = -0.41s_1 - 0.41s_{12} \qquad P_z = 0 \tag{1}$$

where c_1, s_1, c_2, s_2, c_{12} and s_{12} represent cos θ_1, sin θ_1, cos θ_2 sin θ_2, cos $(\theta_1+\theta_2)$ and sin $(\theta_1+\theta_2)$ respectively.

The angular position θ_i of all joints is observed and measured during real walking and is shown in Table 1. Refer to Fig. 2, the angular position of any joint $\theta_i = 0°$ is when the RGO in standing position which is rotated about z-axis and in the direction of x-axis of corresponding joint frame.

Table 1 Angular position θ_i of all joints

Gait Cycle (Phase)		0% Toe-off (Right)			38% Heel Strike (Right)	50% Toe-off (Left)			88% Heel Strike (Left)	100% Toe-off (Right)	
Time Frame	0	1	2	3	4	5	6	7	8	9	10
Hip (Right)	0°	+15°	+20°	+25°	+20°	+15°	0°	-8°	-10°	-5°	0°
Hip (Left)	0°	0°	+5°	+8°	+10°	0°	-20°	-25°	-20°	-15°	0°
Knee (Right)	0°	-50°	-20°	-10°	-5°	-15°	0°	-10°	-15°	-35°	0°
Knee (Left)	0°	0°	+5°	+10°	+15°	+60°	+50°	+20°	+5°	+15°	0°

With the background of the measured angular position of the joints in Table 1 and if there is no obstacle in the work-space, the trajectory planning of each joint in joint space is developed using Linear Segment with Parabolic Blend (LSPB) method. In this approach, the trajectory in the each joint space is comprised three segments, as described in following equations:

$$\theta(t) = \begin{cases} \theta_0 + \dfrac{a}{2}t^2 & t_o \le t \le t_b \quad \text{Acceleration segment} \quad (2) \\ \dfrac{\theta_0 + \theta_f - vt_f}{2} + vt & t_b \le t \le t_f - t_b \quad \text{Constant velocity segment} \quad (3) \\ \theta_f - \dfrac{a}{2}t_f^2 + at_ft - \dfrac{a}{2}t^2 & t_f - t_b \le t \le t_f \quad \text{Deceleration segment} \quad (4) \end{cases}$$

$$v = \frac{\theta_f - \theta_0}{1 - t_b}, \qquad a = \frac{v}{t_b} \qquad (5)$$

where t_b, t_o, t_f, θ_o, θ_f, v and a represent blend time, initial time, final time, initial angular position, final angular position of joint, constant velocity and acceleration parameters, respectively.

3 Simulation

The design of the 4-DOF RGO which was developed in Solidworks software as in Fig. 2 is then being imported into Matlab Simulink Simscape through xml mode. The built model is based on actual length and position of the RGO's component links in world coordinate system. Fig. 3 represents the Simulink model for the developed RGO which was imported from Solidworks. Trajectory position of joints which were obtained from developed trajectory planning is tabulated in Signal Builder block, acting as the input signal. Each angular position input is fed into respective Revolute Joint block with additional corresponding first and second Derivative block to actuate all rotary joints and move the following links.

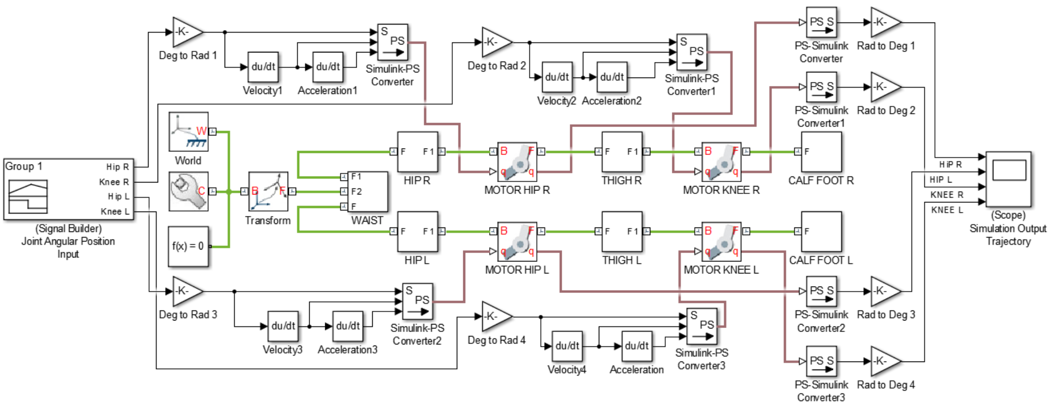

Fig. 3 Simulink model of the developed RGO using Simscape

4 Results and Discussion

The simulation of joints and links movement during walking of the RGO is shown in Fig. 4. The RGO is simulated in a complete full gait cycle within time frame began and ended in standing posture. The simulation run for about 10 seconds time frame. The right and left leg are denoted with green (turquoise) and red colour, respectively. The number above each simulated leg (value 0 to 10) denote the time frame of each gait in second unit.

A full 100% walking gait cycle began and end at toe-off event of the right leg which is from time frame T = 1 to T = 9. Between the heel strike of right leg and toe-off event of left leg (T = 4 to T = 5 and T = 8 to T = 9), the overall leg is in double support sub-phase. It is observed that ambulation of right leg is recipcoral to the left side, which means the right leg is in swing phase while the left leg is in stance phase simultaneously and when the right leg move to the next stance phase, the left leg is in swing phase. This simulation is executed several times and shows the same result.

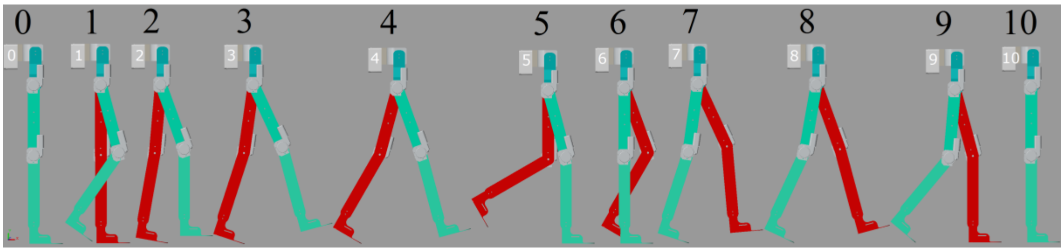

Fig. 4 Simulation of the walking RGO using the developed trajectory from time frame T=0 to T=10

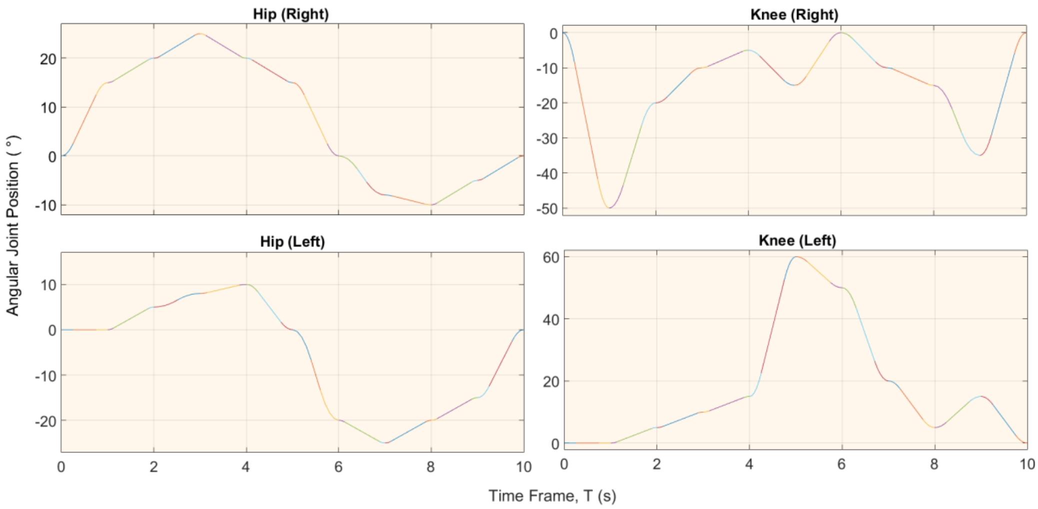

Fig. 5 The result of trajectory planning in joint space

The result of the simulation can be represented into a graph which is obtained from the scope in Simulink model. Fig. 5 shows the result of the simulation by using the developed trajectory planning. Comparison between normal walking analysis in Fig. 1 and the result in Fig. 4 and Fig. 5 shows that the developed trajectory planning and the simulation of RGO ambulation are similar to human walking gait pattern.

In trajectory planning, the issue concerned is related to the quality of the trajectory, for example the smooth time function and the equation parameters such as blend time (t_b), initial time (t_o), final time (t_f), initial joint angular position (θ_o), final joint angular position (θ_f), constant velocity (v) and acceleration (a) of each time frame and joint space. In developing a good trajectory planning, the maximum value of constant velocity, v and acceleration, a of the joint actuator are related to blend time, t_b of each time segment and these parameters must be considered in its ratio so that the joint can accelerate, move constantly and decelerate to its desired position point and satisfied the gait pattern requirement.

Finally, the final position of the ankle (end-effector) can be calculated by using forward kinematic analysis in Eq. (1). Table 2 shows the position of ankle based on joint coordinate system. Although the calculation of kinematics is not for determination of the length of walking stride, the position of ankle in each time segment can be known briefly.

Table 2 Position of ankle based on joint coordinate system in time frame

	0	1	2	3	4	5	6	7	8	9	10
Right Px (m)	-0.820	0.682	-0.577	-0.095	0.144	-0.098	-0.820	-0.211	-0.062	0.157	-0.82
Right Py (m)	0.0	-0.442	-0.374	-0.212	-0.641	-0.267	0.0	0.097	-0.277	-0.088	0.0
Left Px (m)	-0.820	-0.820	0.227	-0.211	-0.062	-0.019	-0.231	-0.523	0.144	-0.098	-0.820
Left Py (m)	0.0	0.0	0.616	-0.097	0.277	0.125	0.779	-0.447	0.641	0.267	0.0

5 Conclusion

Trajectory planning in joint space and simulation of walking RGO biped leg is developed and presented in this paper. Human walking gait overview, design and forward kinematics analysis has been studied and implemented. The trajectory in joint space is performed by using linear segments with parabolic blends (LSPB) approach consists acceleration, constant velocity and deceleration segment in each joint and time frame. A simple four degree-of-freedom (DOF) biped RGO has been designed in Solidworks and linked into Matlab Simscape for simulation. The input signal to perform the walking simulation is determined from the developed trajectory. The simulation result shows that the walking RGO with developed trajectories imitated quite similarly to the human walking gait pattern. Therefore, the trajectory planning developed in this paper can be used in further advanced development to design the control system of the automated RGO in the future.

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