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Simplified Walking Simulation for Tuning a Passive Controllable Ankle Foot Orthosis

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Abstract: A passive controllable ankle foot orthosis (PICAFO) has been developed to treat foot drop on post-stroke patient by controlling the walking gait passively. PICAFO controls the gait by utilizing a proportional integral (PI) controller with an ankle velocity reference. The PI controller must be tuned before being implemented on PICAFO. However, controller tuning based on experimental trial and error is not suggested since it requires the user to use the untuned PICAFO. Therefore, a simplified walking simulation is developed to tune the PI controller using Simulink of MATLAB software. The simulation mainly consists of several parts, such as PI controller, brake model, ankle torque to velocity transfer function, ankle velocity reference, and constant external torque. The result shows that the PI controller can be tuned accordingly to subject's body mass index (BMI) and the brake model to meet the system specification. In this case, when the subject's BMI is 22.2 and the brake maximum torque is 1.938 Nm, the system can control the ankle velocity with settling time less than 20 ms. However, if there is an external torque that is outside the range of brake capacities, then the system cannot do the control task. Therefore, improvement in the brake design is necessary in the future to achieve ankle velocity control within wide range of external torque.

Keywords: PICAFO, Gait Control, PID, Walking Simulation, Ankle Velocity

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1. Introduction

Stroke is an illness which occurs when the blood supply to the brain is interrupted. It is so severe that the stroke deserves to be one of the top ten causes of death, as declared by World Health Organization (1). Despite that, there are also stroke survivors, called as post-stroke patient, whose lucky enough to avoid the death, but most of the time with disability. Typical disabilities are paralysis on the upper limb (2), paralysis on the lower limb (3) and speech difficulty (4). The disabilities also vary from short term to long term disabilities and mild to severe disabilities. Because of this, it is important to undergo rehabilitation gradually, if possible, with the assistance from the therapist (5).

The walking ability is important to be restored because it is the only means of moving for a person (6). Previously, the brain can send the movement signal to the foot, which enable the walking movement. However, the signal path is disrupted because of the stroke. The brain can identify new signal path, but it requires repetition of that particular motion (7). In other words, tedious training or rehabilitation is necessary so the brain can learn to send the movement signal to the foot once again. Previously, the research team has developed a passive controllable ankle foot orthosis, called as PICAFO to assist the walking rehabilitation of a post-stroke patient (8,9).

The PICAFO provides a passive assistance, such as the variable stiffness using the Magnetorheological (MR) Brake of the ankle joint to aid the walking gait. Unlike the traditional Ankle Foot Orthosis (AFO), the variable stiffness of PICAFO can achieve on demand assistance. For example, the stiffness is necessary during swing phase to lock the foot position, but unnecessary during the foot push-off (10). Optimizing the variable stiffness, which determined as per gait phases, to suit each individual is hypothesized can improve the outcome of rehabilitation. Currently, the PICAFO is designed to provide necessary stiffness to control the ankle velocity (8). If the ankle velocity surpasses a certain setpoint, then the MR brake will generate stiffness to decrease the ankle velocity.

The amount of the applied stiffness according to the error of the ankle velocity is determined using Proportional Integral Derivative (PID) control. Basically, the more the error, the higher the applied stiffness. Tuning the PID controller is compulsory to ensure smooth control of the ankle velocity. However, the PID tuning via trial-and-error approach was not feasible because the trial involves human where safety using untuned PID cannot be guarantee. Therefore, this paper proposes a simplified walking simulation for tuning the PID controller of PICAFO. The chapter 2 explains the PICAFO system in more details as well as the simulation methods. Chapter 3 discusses the simulation results. Meanwhile, the research is concluded in the chapter 4.

2. Materials and Methods

In general, the PICAFO controls the walking gait based on ankle velocity reference (ω_{ref}). The ankle velocity is estimated based on walking speed (WS) and body mass index (BMI), as shown in Figure 3.9. There are four ankle velocity references ($\omega1$, $\omega2$, $\omega3$, $\omega4$) for each of the four gait phases (P1 – P4), which has been explained in the previous work (8). P1 is started from initial contact (IC) to foot flat (FF). P2 is started from FF to heel-off (HO). P3 is started from HO to toe-off (TO). Then P4 is started from TO to the next IC. The MR brake at the ankle joint controls the ankle velocity to follow the control references. If the ankle velocity exceeds the control reference in the same direction, then the MR brake would apply appropriate damping stiffness to reduce the ankle velocity. On the other hand, the MR brake will do nothing if the ankle velocity is less than the control reference or in a different direction of the reference (ω_{ref}).

Details on the control system is explained as the following. The PID controller used the feedback error, which was the difference between the ankle velocity reference (ω_{ref}) and ankle velocity (ω) feedbacks, to calculate the estimated current (I_{est}). Because I_{est} responsible for the damping stiffness generated by MR brake, I_{est} calculation should not produce wrong stiffness generation. For example, if ω was less than ω_{ref}, the controller should increase ω, so it reached ω_{ref}. However, increasing ω was not possible using actuators such as the MR brake. Even if the PID calculates I_{est} to increase ω, the resulted braking torque will always restrict the movement instead, which then defined as the wrong stiffness generation. There are activation conditions based on the current gait phases activated/deactivated the PID to anticipate the wrong stiffness generation. The activation condition on P1 – P3 was the ankle movement direction, such as plantarflexion ($\omega < 0$) or dorsiflexion ($\omega > 0$). Meanwhile, on P4, the activation condition was positive ankle position ($\theta > 0$), so the MR brake only locks the foot for toe clearance. Finally, the MR brake can generate the appropriate torque (τ) based on the I_{est}. Thus, it controls the walking gait based on ankle velocity.

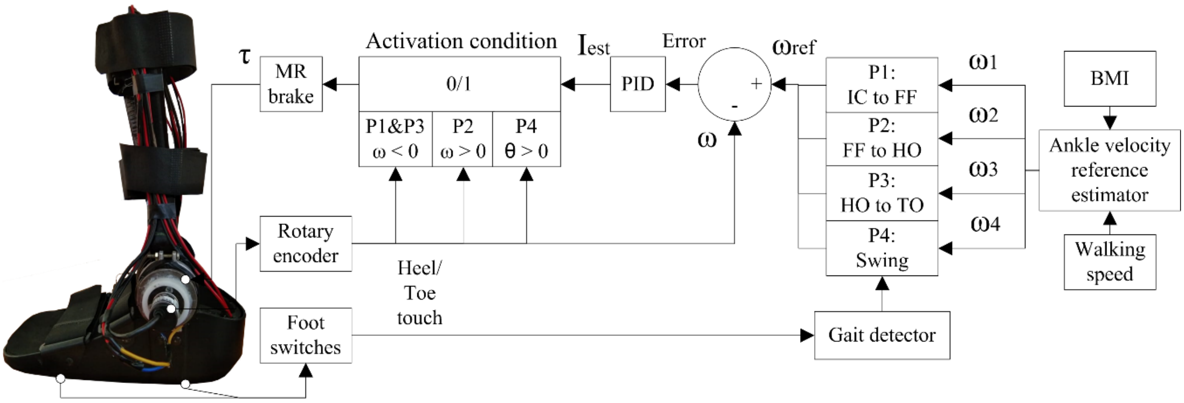


Figure 1. PICAFO control system (8).

The PID controller was developed and tuned using simulation on MATLAB simulink. Figure 2 shows the Simulink block diagram of a simplified scenario of the walking gait using PICAFO. In the simulation, two torques, namely external torque (τ_{ext}) and stiffness torque (τ_{brake}) were used. The external torque was the sum of torque from the lower limb muscle, body weight, and GRF (11). In contrast, the stiffness torque was the torque generated by the MR brake in a different direction of the external torque. In this simulation, the external torque had a constant value. For example, to simulate movement on P1, the external torque was negative 1 Nm because the foot moves in plantarflexion, as shown in Figure 3 (a). However, the external torque exceeded the MR brake capacity in most of the cases, while the higher external torque in Figure 3 (b) simulates this condition. The torque resultant ($\sum\tau$), is expressed as

$$\sum \tau = \tau_{ext} - \tau_{brake} = \mathrm{I}\,\dot{\omega} \tag{1}$$

where I and $\dot{\omega}$ are foot inertia and ankle angular acceleration, respectively. The torque resultant went into the transfer function block to get the actual ankle velocity (ω), where the transfer function

$$\mathrm{T(s)} = \frac{\omega}{\sum \tau} = \frac{1}{Is} \tag{2}$$

was different from one subject to another because foot inertia is unique for each individual. Calculating foot inertia requires body mass and foot length, as suggested by Winter (11). In this study the transfer function corresponds to the foot inertia of a person with BMI of 22.2. The transfer functions are 1/0.000169186s and 1/0.000173s. The difference between an actual ankle velocity and reference defines the feedback error. The PID controller uses this feedback error to estimate the current that is being induced. There is a saturation block next to this process to restrict the current induced up to only 1 A maximum. The brake model

$$\text{MR brake torque} = 1.8\, i_{out} + 0.138 \tag{3}$$

converts the current out to become the MR brake torque, which is a linearization of the MR brake characteristics shown in the previous work (12). The maximum brake capacity can be calculated by inserting 1 A maximum current out to equation 3.8, which is 1.938 Nm.

The MR brake torque controls the ankle velocity according to the reference shown in Figure 3 (c). “Compared to zero” block defines activation condition in Figure 1, in which the brake only generates the stiffness torque in a different direction of the current external torque, and only when the actual ankle velocity exceeds the reference in that direction. For example, suppose the ankle velocity reference is -3 rad/s, while the actual ankle velocity is -2 rad/s. In this case, the reference and the actual ankle velocity are in the same direction, which is the plantarflexion. The controller will ignore this situation because the MR brake could not generate torque in the same direction to increase the actual ankle velocity, which is lesser than the reference value. After completing all the simulation block diagram, the PID tuner in the MATLAB control toolbox tunes the gains (P, I, and D) until the time response is equal or less than 20 ms (13).

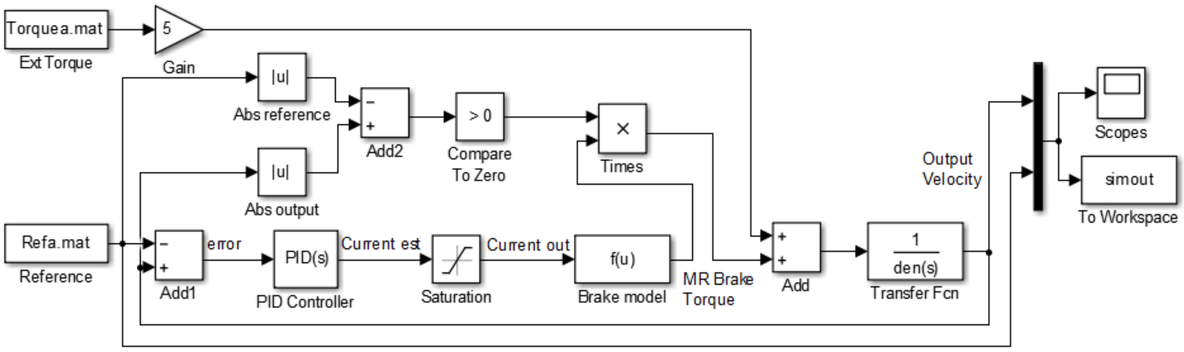
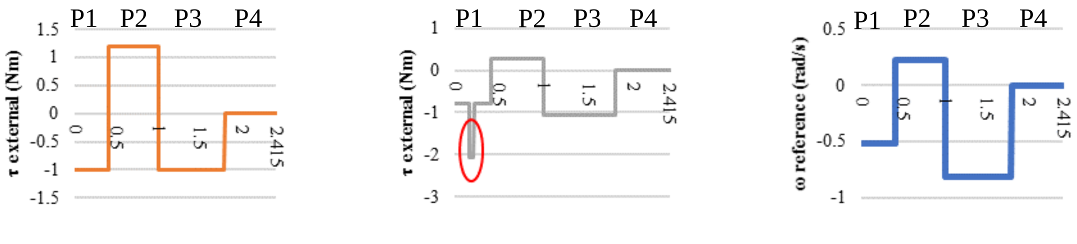


Figure 2. Simulation of the simplified walking gait to tune the PID controller.



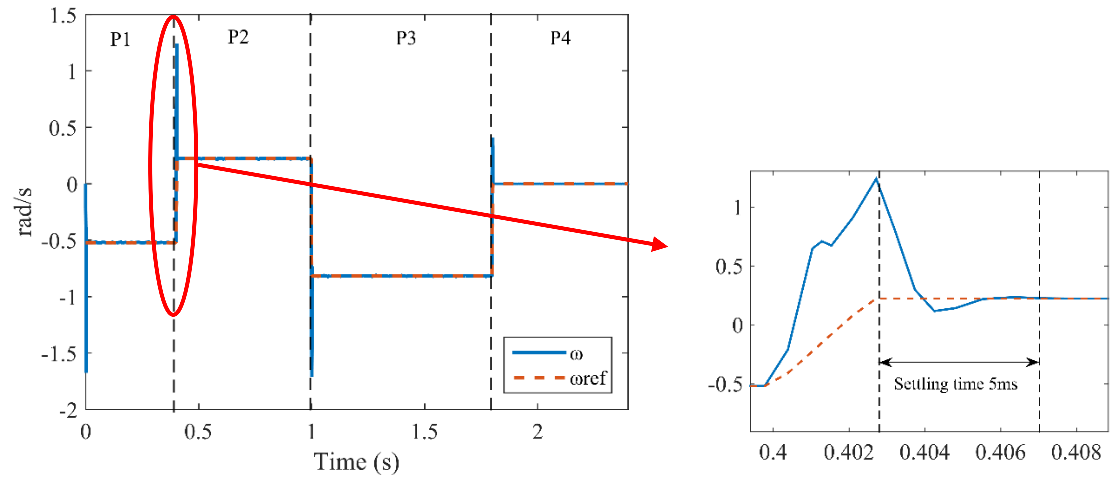
(a) (b) (c)

Figure 3. External torque and ankle velocity reference for the simulation of walking gait: (a) external torque less than brake capacity, (b) external torque more than brake capacity, (c) ankle velocity reference.

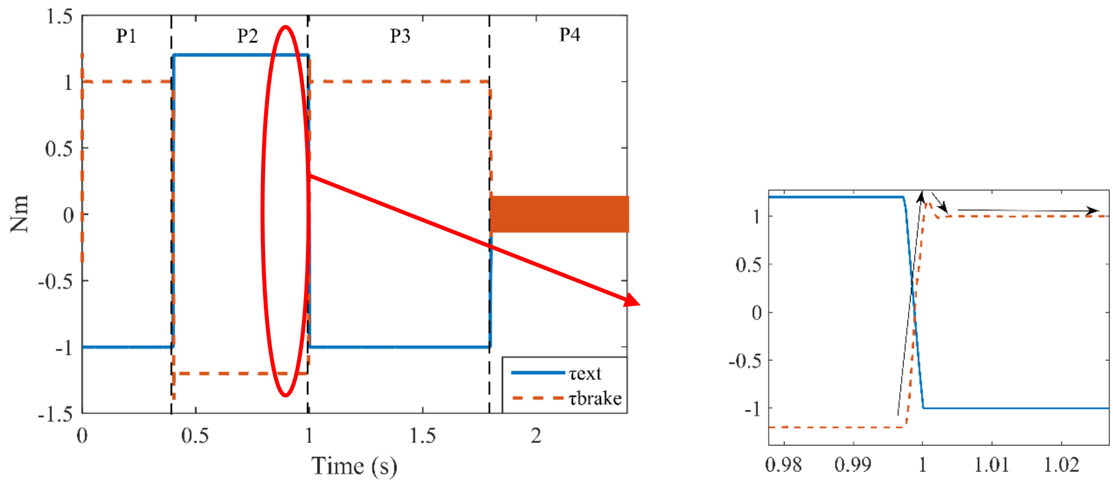
3. Result and Discussion

The simulation has been conducted and the results are the followings. After tuning PID using the PID tuner in MATLAB control toolbox, the finalized PID gains are P = -0.24, I = -466, and D = 0, which is more to PI controller than PID controller. The PI configuration reduces the rise time, reduces the steady-state error, and increases the overshoot. Combined with the D gains, the overshoot will reduce, and so will the settling time (14). However, the use of D tends to make the system unstable in real life because the derivative response is highly sensitive to noise. Apart from that, in the PICAFO system, the overshoot is not an issue since the actuator is only the MR brake, which cannot generate any movement, but only restricting the movement. Therefore, the D gains are less important while the controller development focused on PI configuration.

Figure 4 establishes the simulation result during one gait step with an external torque that is lower than the MR brake stiffness (Figure 3 (a)) and external torque, which is suddenly higher than the MR brake (Figure 3 (b)). The controller successfully keeps the ω (solid blue line) by following the ω_{ref} (orange dash line) with a settling time of 5 ms, which is less than 20 ms. The simulation of the MR brake behavior can also be seen in Figure 4. The brake generates τ_{brake} after the ω exceeds the ω_{ref}, thus reducing the ω. The stiffness is initially larger than the τ_{ext} to reduce the ω, and then it becomes equal as the τ_{ext} in the opposite direction. In the case of high external force, which is larger than the MR brake maximum stiffness, it is not possible to keep the ω to follow the ω_{ref}, as shown in Figure 5. However, the ω follows the reference again after the external control becomes less than the MR brake maximum stiffness. Therefore, the simulation result shows that the MR brake can still partially support the walking gait during the real walking experiment where the τ_{ext} may fluctuate randomly and exceed the MR brake capability at the same time.



(a)



(b)

Figure 4. Simulation of ankle velocity control using MR brake: (a) ankle velocity when controlled; (b) MR brake stiffness compare to an external torque

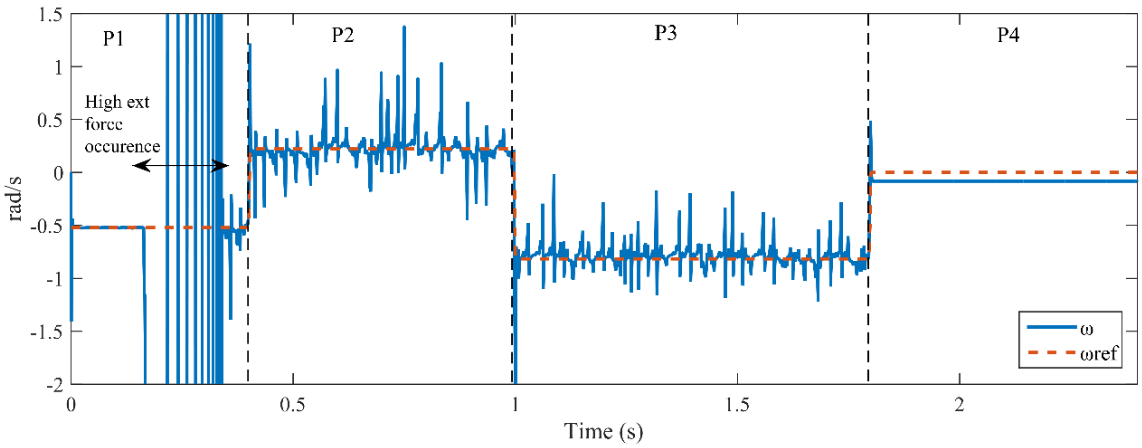


Figure 5. Simulation of ankle velocity using MR brake for sudden higher external torque.

4. Conclusion

All in all, this study shows a simulation of simplified walking simulation of a person walking with PICAFO. The PID controller of the PICAFO system is tuned through simulation attempt. The PID tuner generates the PID gain according to the required specification, which in this case, the settling time should be less than 20 ms. The PID gain was tested in the simplified walking simulation of a person with 22.2 BMI. Result shows that if the external torque is in the range of the brake capacities, then the ankle velocity can be controlled well. But, if the external torque is outside the range of brake capacities, then the PICAFO could not control it. The PICAFO can only give partial support within the braking torque capacities, whsich can be improve through the brake design. Later on, this simulation can be used tuned the PID accordingly by just inserting the foot inertia depends on the subjects BMI. In case of change in the brake design, then the brake model can be changed accordingly.

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