

Introduction

At the Human Neuromechanics Laboratory at the University of Michigan, an artificial foot orthosis (AFO) has been developed to assist with rehabilitation for patients with partial spinal cord injuries or stroke. The orthosis produces a regulated torque at the ankle of the patient, using a pneumatic muscle as an actuator [1]. The control algorithm used to actuate the exoskeleton greatly influences the response and learning ability of the user. Subjects relying on myoelectric control adapted to the exoskeleton by altering their muscle activity and using the artificial muscle to their advantage, whereas the group using a simple kinematic footswitch to activate the muscle had a much harder time doing the same thing [2]; many users do not have sufficient muscle activity to control the exoskeleton with myoelectric signals [3].

Our goal

We are seeking an alternative adaptive control method and control algorithm that does not rely on myoelectric control, but does allow versatile, stable control which mimics the user's natural neurophysiological pathways. This would allow the system to entrain to the needs of the patient and recover from small perturbations. Our current approach is to use an artificial neural oscillator (Figure 1).

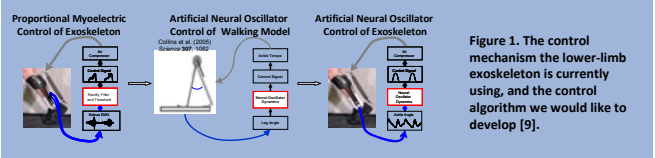


Figure 1. The control mechanism the lower-limb exoskeleton is currently using, and the control algorithm we would like to develop [9].

Approach and Methods

We are first testing this approach using the Webots software developed by Cyberbotics and the Biologically Inspired Robotics Group (BIRG) at the École Polytechnique Fédérale de Lausanne in Switzerland. We have first searched the parameter space of a simple pendulum, with slight damping at the base. The torque applied to the base of the pendulum was governed by the Hopf oscillator equations:

$$\dot{x} = (\mu - r^2)x - \omega y$$

$$\dot{y} = (\mu - r^2)y + \omega x + \varepsilon F$$

- Where:
- ω is the frequency of oscillations in rad-s⁻¹ is the amplitude of oscillations
 - ε is the coupling constant, or the strength of the feedback signal F (angle of pendulum)
 - Feedback is on the y variable as suggested by [4], to ensure a smooth output of x
 - $x(t)$ used as the torque applied to the pendulum
 - μ and ω were systematically changed throughout the search

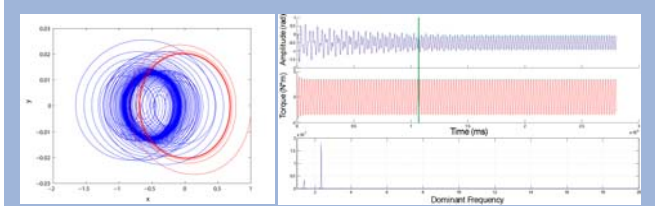


Figure 2. Phase space of the position (blue) and torque (red) oscillations. With time, the two signals tend towards a stable limit cycle.

Figure 3. The servo position (amplitude), servo force (torque) and dominant frequency output for values $\omega = 1.5$ and $\mu = 0.1$. The points indicate peaks, and the vertical line shows where the system reached entrainment. The dominant frequency of the system is at 2.34Hz.

Entrainment analysis

We searched for entrainment between the natural frequency of the pendulum and the oscillator signal driving it (Figure 2). Entrainment between two oscillating signals leads to a constant phase difference between them. To determine whether entrainment occurred, we analyzed the phase drift between the torque output and the angle of the pendulum.

Finding phase drift

- Position of pendulum (rad.) and applied torque (N*m) were recorded by Webots every 2 ms.
- Using MATLAB, we found peaks in the torque and position (Figure 3).
- We calculated the phase difference between each position and the subsequent torque peaks.

Comparing parameter sets

- To compare iterations, we used the following analysis of phase drift over time (Figure 4):
- We took the derivative of the phase drift
 - Peaks in the derivative were identified
 - We defined entrainment as the time at which ten consecutive peaks differed from the preceding peak by <5% (Figure 3).

The ω and μ variables in the Hopf equations were varied from 0 to 1.9 and from 0 to 1.0 respectively, with increments of 0.1

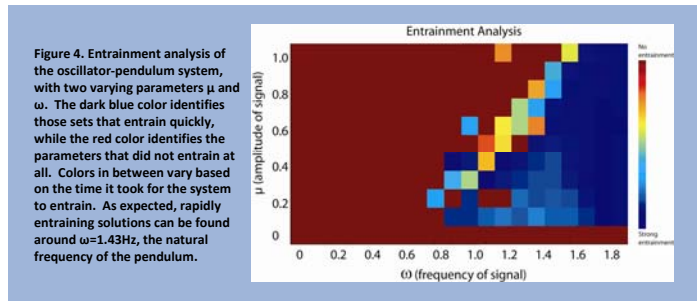


Figure 4. Entrainment analysis of the oscillator-pendulum system, with two varying parameters μ and ω . The dark blue color identifies those sets that entrain quickly, while the red color identifies the parameters that did not entrain at all. Colors in between vary based on the time it took for the system to entrain. As expected, rapidly entraining solutions can be found around $\omega=1.43$ Hz, the natural frequency of the pendulum.

Passive Walker

Since our final goal is to control a walking robot with an oscillator, our next logical step was to create a simple walking robot as a study platform. We have constructed in the Webots software a passive walker, with two legs and knees, similar to the prototypes developed by [5] and [6]. Both of the doubled legs behave in an identical manner as their partner leg, but act to provide passive lateral stability. The ankles are currently fixed. The first iteration took several steps on simulated blocks and seven steps down a slope (Figure 5, A, B, C).

We have also coupled a Hopf oscillator with a phase dependent frequency to drive the hip torque of the walker, using the angle between the legs as the feedback signal F . The oscillator, as described by [7], allows us to independently regulate the swing and stance phase durations:

$$\dot{x} = (\mu - r^2)x - \omega y$$

$$\dot{y} = (\mu - r^2)y + \omega x + \varepsilon F$$

$$\omega = \frac{\omega_{stance}}{e^{-by} + 1} + \frac{\omega_{swing}}{e^{by} + 1}$$

In preliminary attempts to couple the walker with oscillator-based actuation, we found the system extremely sensitive to the level of damping at the hip and knee, and the walker only made several asymmetric steps. Tuning the walker is difficult due to the large amount of parameters, but we hope to constrain some of them to minimize the parameter search space. Eventually, we would like to couple this oscillator to the ankle joint to simulate the lower limb exoskeletons.

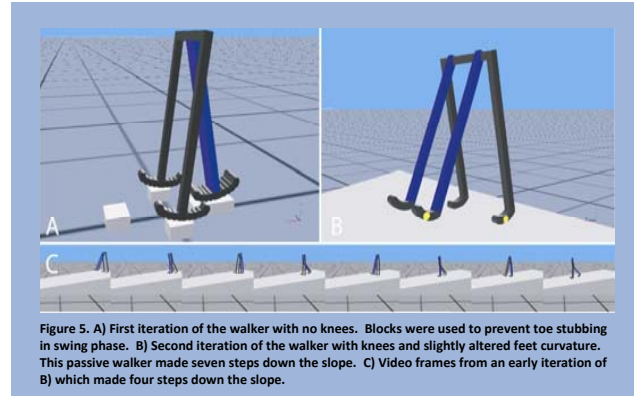


Figure 5. A) First iteration of the walker with no knees. Blocks were used to prevent toe stubbing in swing phase. B) Second iteration of the walker with knees and slightly altered feet curvature. This passive walker made seven steps down the slope. C) Video frames from an early iteration of B) which made four steps down the slope.

Discussion

We have so far coupled a simple pendulum with an artificial neural oscillator to study the behavior of the system, constructed a passive walker in the Webots software and coupled an adaptive frequency Hopf oscillator at the hip. We would like to develop a control algorithm to control the ankle torque produced by a lower-limb exoskeleton. To make the walker more stable and reliable, we would still like to:

- Look into the effects of the hip and knee damping constants on the walking and stability of the passive walker, using a systematic gridded parameter search
- Use Fourier decomposition for rapid analysis of entrainment. Entrainment will occur when the dominant frequencies of the torque and the angle data the same or an integer multiple of each other.
- Compare the stability and energetic cost of walkers actuated at the hip versus the ankle, as well as the difference in using the position (angle) or the ground contact force as the control feedback.
- Compare the stability and energetic cost of alternative control strategies and nonlinear oscillator models.

Acknowledgements

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