Chapter 5
Movement Models

Experiment 5.1 Self-organization in dynamic systems

Purpose and Background

The purpose of this experiment is to investigate dynamic systems theory as revealed by self-organization of neural systems with mechanical systems.

Self-organization means that a system, in this case the human body, attempts to find a stable performance level or is “attracted” to perform in a characteristic way under certain circumstances. It also means that a stable state, known as an attractor state, occurs when multiple systems working together are stable, not just a single system. Stability is generally indicated by consistent performance that is resistant to perturbation but can also be measured by efficiency. In this experiment, you will look at the interaction of neural pattern generators and mechanical systems. Specifically, you will look a preferred walking cadence (strides per second) as a neural mechanism and the relationship of cadence to the pendular actions of the legs and of the whole body during walking.

The figure below illustrates that during walking, the legs swing as pendulums and the whole body sways as an inverted pendulum. A pendulum has a natural or resonant frequency at which it swings or oscillates. If you find a relationship between the natural pendulum movement and the cadence at which one walks, it provides evidence that the mechanical and neural systems work together to stabilize gait.

Under normal circumstances each person has a preferred walking speed that is highly repeatable. You might hypothesize that this preferred walking speed depends on some innate dynamic system that is built into the human body. Specifically, you might speculate that the mechanical and anthropometric makeup of the body—e.g., height, weight, and inertial properties
of the legs— influences one’s preferred speed. If so, then one’s preferred walking speed should correlate to these anthropometric measures.

How fast one walks can be measured in several different ways, such as velocity (e.g., meters per second) or the number of strides per second. Most important to this experiment is the number of strides per second, which is also called stride frequency or walking cadence. For this experiment, you will measure leg and whole-body anthropometrics and compare them to walking cadence. Because of large variability in these measures, it is imperative that many individuals, at least ten, be tested. You may share data with other students in your class.

**Methods**

**Equipment**

- Cloth measuring tape
- Stadiometer to measure height
- Scale to measure weight
- Stopwatch
- Open space (50+ feet) to walk

**Procedures**

**Anthropometrics**

1. Measure the length of the dominant leg, from the greater trochanter of the femur to the lateral malleolus. Record all data, in centimeters, on the data sheet. The trochanter can be located by rotating the leg at the hip. Take care with this measurement, as it is easy to miss the trochanter.
2. Measure height in centimeters, shoes off, on the stadiometer.
3. Measure weight in kilograms.
4. Record all anthropometric data in the table.
5. Record data from at least five individuals, preferably fifteen to twenty or more.

**Preferred/Actual Walking Cadence**

1. Have the subject walk at a comfortable, preferred pace for at least 20 strides in an open space or long hallway. Follow several paces behind with a stopwatch to gather the time it takes the subject to take 10 strides. The subject should look straight ahead and walk with an external target in view. This will help to prevent the subject from walking aimlessly or shuffling along.
2. Wait until the subject has taken three or four steps to get up to his or her preferred pace. Once the subject is walking at this pace, start the stopwatch on a heel strike and count zero (“0”). On the next heel strike of the same leg, count one (“1”). This is one stride (see the figure below). Continue until the tenth heel strike, at which time you should stop the stopwatch. This is the time it takes the subject to complete 10 strides. Repeat and calculate the mean of the two trials. Calculate stride frequency (Hz) using the following formula:

\[
\text{stride frequency} = \frac{\text{number of strides}}{\text{time}} \quad \text{(that is, 10/time)}
\]
Record the time and the cadence in the table.

Predicted Walking Cadence

1. Use the formula below to calculate a predicted walking cadence based on your anthropometric measurements (for information on this formula, see Holt et al., 1990). This formula assumes that your legs act like pendulums swinging from the hip, and therefore the natural rate of swinging (oscillation) is dependent on the size and weight of the pendulum. This formula also assumes that your whole body, upon heel strike, acts like an inverted pendulum pivoting on the foot.

\[
f = \frac{1}{2\pi \sqrt{\frac{L}{2g}}}
\]

where:
- \( f \) = stride frequency
- \( \pi \approx 3.1416 \)
- \( L \) = simple pendulum equivalent length of the leg (see below to calculate)
- \( g = 9.81 \) m/s/s (gravitational acceleration)

To calculate \( L \), use the following formula:

\[
L = \frac{I}{M \times D}
\]

where:
- \( D \) = Center of mass distance in lower leg. (length, in meters, of greater trochanter to lateral malleolus \( \times 0.447 \))
- \( M \) = Mass of lower leg system, or (body weight, in kg, \( \times 0.161 \))
- \( I \) = Inertia of lower leg system, or \( M \times (\text{leg length} \times 0.560)^2 \)

Record walking data in the table.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Leg Length (cm)</th>
<th>Time for 10 Strides (s)</th>
<th>Actual Cadence (Hz)</th>
<th>Predicted Cadence (Hz)</th>
</tr>
</thead>
</table>
Questions

1. Describe the relationship between the actual cadence and the predicted cadence. To do so, create an x-y scatterplot graph of actual cadence (x-axis) versus predicted cadence (y-axis). Use a graphing program to calculate a regression line (trend line or best fit line) and a Pearson correlation coefficient ($r$). Use the correlation value as well as visual inspection of the numbers to help answer the question.

2. What is the functional significance of the preferred walking rate being similar to what would be predicted if the legs acted like a simple pendulum? Why is this important? Explain your answer from a dynamical systems viewpoint, including concepts of metabolic efficiency and degrees of freedom. See the following articles for help with your answer:


Experiment 5.2  Dynamic systems, self-organization, and transitions

Purpose and Background

The purpose of this experiment is to investigate dynamic systems theory as revealed by transitions from one stable state to another.

In this experiment, you will examine the stand-to-walk transition, the walk-to-run transition, and the run-to-walk transition. As one goes from standing to walking and then walk faster and faster (in this case on a treadmill speeding up), one will reach a point at which one transitions from a slow walk to a normal walk and then from a normal walk to a run. Of course, one can make the shift from walking to running and back again at one’s own discretion, but people normally do not make a conscious effort to do so. As they walk faster and faster, they begin to jog (a slow run), and they do it without thinking about it.

In human motor behavior these points of large change in movement form are often referred to as transition phases. The conditions or variables that cause the transition are called order parameters. In human motor acts, movement speed is a common order parameter. During walking, the body self-organizes a smooth gait. Arms and legs work in unison, and the rhythmic bouncing of internal organs is in line with the movement of the body and breathing. As people walk faster and faster, only a few things change to help them walk faster, but they are still walking. However, at a critical speed, they transition from a walk to a run, and running is fundamentally different from walking.

Methods

Equipment

- Electronic treadmill with speed control
- Running shoes and exercise clothes
- Open space (50+ feet) to walk

Procedures

1. *Stand-to-Walk Transition.* Have the subject start from a standing position with arms down at the sides and begin a super-slow walk for about 10 feet and then gradually speed up to a normal walking pace within about 20 feet. Instruct the subject to not restrain the arms but to allow them to swing free. The slow walk should have a step length similar to that of normal walking and the subject should not shuffle along. During the super-slow walk, note the movements of the arms and how this differs from arm movement during normal-speed walking.

2. *Walk-to-Run and Run-to-Walk Transitions.* This next part of the experiment utilizes an electronically controlled treadmill. You will record the treadmill speed at which the subject transitions from a walk to a run and from a run to a walk.
a. Allow the subject to control the treadmill to get it working at his or her comfortable pace. Have the subject walk on the treadmill at a comfortable pace for about 20 seconds. Record this speed. When the subject is ready, cover the treadmill speedometer so that the subject cannot see it. Do not engage the subject in conversation other than to give instructions as necessary. Explain to the subject that the speed will keep increasing up to the time at which the subject will need to run and then will eventually drop back down again until the subject changes back to a walk. Increase the speed about 1 mph every 10 seconds. Record the treadmill speed at the walk-to-run (W-R) transition. Continue to increase the treadmill speed about 2 mph further and have the subject run for 10 to 15 seconds.

b. After the subject has been running at a comfortable pace for 10 to 15 seconds, begin slowing the treadmill down at the same rate as before and note when the subject begins to walk. Record the treadmill speed at the run-to-walk (R-W) transition in the data table.

<table>
<thead>
<tr>
<th>Walk-to-Run Transition Data Table</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Normal Walking Speed (mph)</td>
</tr>
<tr>
<td>Walk-to-Run Transition Speed (mph)</td>
</tr>
<tr>
<td>Run-to-Walk Transition Speed (mph)</td>
</tr>
<tr>
<td>Subject 1</td>
</tr>
<tr>
<td>Subject 2</td>
</tr>
<tr>
<td>Subject 3</td>
</tr>
<tr>
<td>Subject 4</td>
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<tr>
<td>Subject 5</td>
</tr>
</tbody>
</table>

Questions

1. During the super-slow walk, how did the subject’s arms move in comparison to a normal walk? Explain what is happening to cause the transition in arm movement; that is, determine the order parameter (it is not speed per se).
2. You might expect that the W-R and R-W transition speeds would be the same. Were they? If not, describe the differences and speculate why these differences exist. Read through the following article for help with this answer:
3. How does running differ from walking?
Experiment 5.3  Bimanual control and coordinative structures

Purpose and Background

The purpose of these mini-experiments is to investigate how limbs work together naturally as synergies called coordinative structures.

Controlling two limbs simultaneously is referred to as bilateral control; it is called bimanual control when referring specifically to the arms or hands. Researchers have found that many bilateral arm and leg movements work as synergies. In the previous experiments, you saw that the body has inherent mechanical properties that give rise to certain movement patterns. Among the most noticeable of these movement patterns are how the limbs, especially the arms, work together. The arms are literally linked by the nervous system; because of that, they work in synergy with one another in a system called a coordinative structure. Coordinative structures are synergies of specific muscles and joints that act together to produce specific functional movements of the arms. Coordinative structures generally have both mechanical and neural linkages and may be developed through training or experience or may be innate. They have a number of benefits, such as reducing the degrees of freedom of movement. But there is a trade-off, because sometimes you need to break this linkage to get independent movements.

One feature of a coordinative structure is called assimilation. Assimilation is what happens when two limbs try to work independently but cannot. The limbs begin to do the same thing. One limb may be assimilated into doing what the other limb is doing, or the movements of both limbs may be modified as the limbs assimilate one another into a modified movement. Overcoming the coordinative structure of bimanual control is especially difficult, but it is necessary to produce the independent arm action that is necessary for many activities, such as playing an instrument. It requires a lot of practice.

In this set of experiments, you will look at the strong linkage of coordinative structure and the difficulty in breaking this linkage.

Methods

Equipment

- Chair
- Tabletop
- Pad or book to support forearms

Procedures

Each person can do these experiments on his or her own.

In the first experiment, you will examine wrist radial and ulnar deviation movements (abduction/adduction) in the horizontal plane. Movements will be made in phase (both hands performing ulnar deviation or radial deviation simultaneously) and out of phase (one hand doing
radial deviation while the other does ulnar deviation). There are no data to collect, but be sure to observe closely so that you can answer the questions.

1. Sit at a table and place your forearms on a padded support surface or book on the table. Your hands and wrists should extend over the support in a palms-down (pronated) position. See the figure below.

2. Begin moving both hands back and forth in radial and ulnar deviation so that the fingers point in the opposite directions as you move. Although the hands point in the different directions, the movement is in phase because the joint action is the same in each wrist. Begin the movements at about one movement per second, and take a few moments to get into a rhythm. Concentrate on only wrist movements; avoid elbow and shoulder accessory movements.

3. Speed up the movement, making it as fast as you can while you simply observe your level of coordination.

4. Take a few moments to rest before beginning out-of-phase movements. Next, move both hands back and forth in radial and ulnar deviation so that the fingers point in the same direction. Although the hands point in the same direction, the movement is out of phase because the joint action is opposite in each wrist. Begin the movements at about one movement per second, and take a few moments to get into a rhythm.

5. Steadily speed the movements up to a point of maximal speed. Things may get uncoordinated during this time, so you might need to restart.

6. At some point, you might be unable to continue the movement. At this time, what do you notice about your hands? Are they now pointing in opposite directions? If so, your wrist movements have spontaneously transitioned from out-of-phase to in-phase movements. Repeat several times and observe carefully.

In the next set of movements you will examine whole-arm bilateral movements. Movements will be made in phase (both arms flexing or extending at the same time), 180 degrees out of phase (one arm flexing while the other is extending at the same rhythm), phase-shifted (out of phase but both arms going at different speeds), and direction-shifted (arms moving in different planes of motion). You may evaluate these movements as you do them yourself, but it will be helpful to observe others. Again, there are no numerical data to collect, but be sure to observe closely so that you can answer the questions.
1. Have the subject start all movements by standing and swinging the dominant arm in the sagittal plane at a comfortable, natural pace. The nondominant arm remains at the side. For these tasks, it is useful to have the experimenter observe the subject’s movements because some potential actions are subtle and may go unnoticed by the subject.

2. When the subject is in a comfortable rhythm with the dominant arm, have the subject start to swing both arms in phase (both extend, both flex, etc.). Record what happens to the arms and the overall disposition of the subject when the subject goes from the unilateral arm swing to a bilateral arm swing. Specifically, observe when the nondominant arm began to swing (when dominant arm was straight down, or end of extension, or end of flexion, etc.). Also observe the subject for hesitancy, contemplation, smoothness of movement, and postural adjustments. Write down these observations before proceeding with the next tasks.

3. With the dominant arm swinging comfortably in the sagittal plane, the subject begins swinging the nondominant arm 180° out of phase (e.g., right arm flexes while left arm extends).

4. With the dominant arm swinging comfortably in the sagittal plane, the subject begins to swing the nondominant arm at an entirely different speed or cadence.

5. With the dominant arm swinging comfortably in the sagittal plane, the subject begins abduction-adduction movement of the nondominant arm.

In the next series of movements you will examine the synergies between arms and legs, that is, interlimb coordination of agonist and antagonist muscles of arms and legs.

1. Sit comfortably in a chair with enough room in front of you to extend your legs. Extend your right leg out and make circular movements of the whole leg in a clockwise direction. (The hip circumducts so that the foot traces out circles.)

2. While in a stable rhythm with the leg circles, extend your right arm forward and above horizontal about 20 degrees (see the figure below). Point your index finger. Hold this position for a few seconds to allow your leg circles to stabilize. Using your index finger as an imaginary pen, trace out a large number 6 in the air with your whole arm. Observe what happens to the leg action.
3. Repeat the experiment above, but now circle your leg in a counterclockwise direction. Observe the leg action.

4. Repeat the two movements above, but this time, use your left leg instead of your right leg. Continue to draw the number 6 with your right arm. Observe the actions.

Questions

1. Summarize your observations for these mini-experiments. How are the movements on the same side of the body (e.g., right arm, right leg) linked and how are movements on opposite sides of the body (e.g., right arm, left leg) linked?

2. Explain why you think these arm coordinative structures and arm-leg synergies exist. In your answer highlight their benefits.