BME 315 Biomechanics
Kinematic analysis of center of mass and center of pressure determination

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I. Introduction

In this lab, we will utilize a force plate to assess the ground force reactions in some motions which we commonly perform. Similar to a scale, a force plate measures the force that is exerted by the ground in opposition to the weight on it. However, a force plate is also able to provide information about the forces exerted parallel to the ground and the location of the force vector. An example of motions with a shear (parallel) ground force component would be walking (Fig. 1). The landing and push-off phases of walking each have a vertical force component as well as a horizontal force component. The horizontal force component is parallel to the ground and brakes or accelerates forward motion of the center of mass. Some examples of other force plate uses can be found at the webpage of the manufacturer of our force plate at Bertec Corporation - Applications.

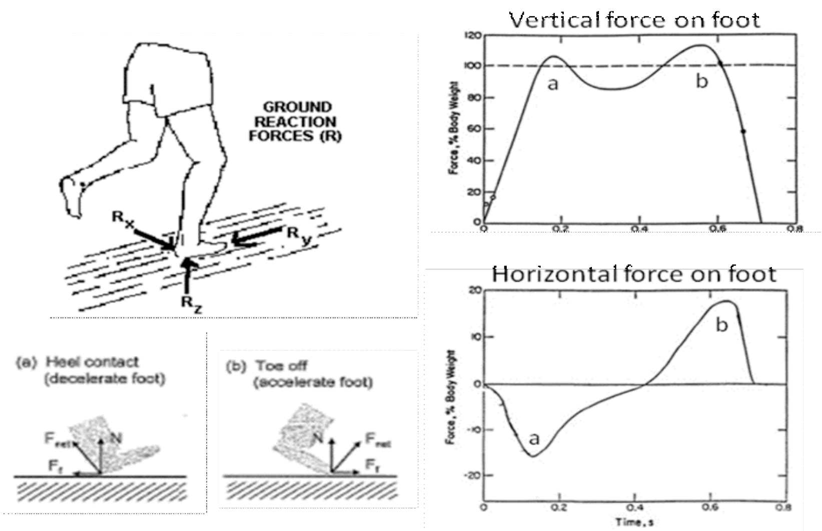

Figure 1: Ground reaction forces on the body can be measured during walking by a force plate.

A force plate is designed to assess the forces in along 3 perpendicular axes and moments about the associated axes. A force plate is a very accurately machined rigid plate that is attached to 4 instrumented pedestals (Fig. 2). A load on the plate deforms each pedestal a different amount, depending on the load direction and location. A piezoelectric or strain gage transducer affixed to each pedestal measures the deformation that occurs. With the known force plate geometry and pedestal locations, the forces and moments acting on the plate can be determined. The manufacturer of the force plate provides calibration parameters that are used to convert the voltages measured by the transducers into force and moment measurements.

II. Objectives

The objectives of this lab are to:

- demonstrate how a force plate can be used to compute the location of the center-of-pressure (COP) under the feet
- perform a balance assessment of a test subject via measurement of COP with eyes open and eyes closed
- learn how to use force plate data to compute the whole body center-of-mass (COM) acceleration, velocity, and height during a standing vertical jump

compare computed jump height to that measured directly with a motion capture system

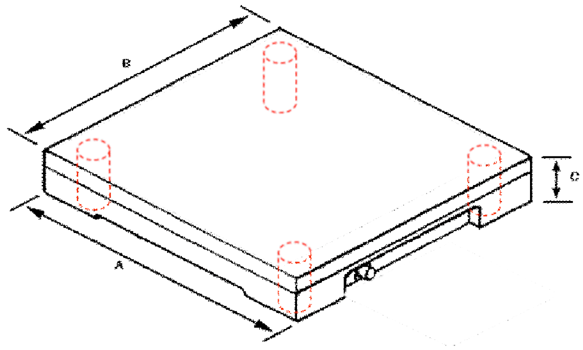
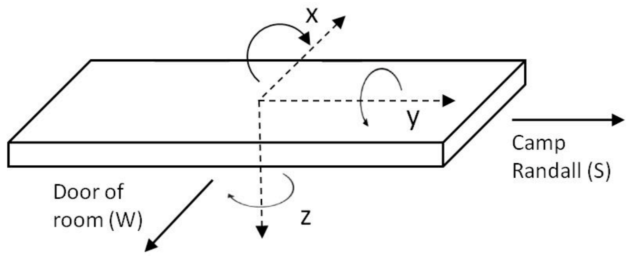

Figure 2 (left): Reaction forces and moments are determined using known force plate geometry, pedestal locations and transducer signals. Figure 3 (right): Force plate coordinate system of the Bertec force plate in ME3034.

III. Laboratory equipment

The force platform that you will be using is Bertec model FP 4060–10 (manual and product sheet posted at course webpage). The force plate is adhered to the base of a shallow pit in the lab floor, such that the top of the flat, rigid plate is level with the cement floor. The coordinate system of our force plate has the positive y-axis pointing south towards Camp Randall, and the positive z-axis pointing into the floor (Fig. 3).

The strain gages at each corner deform with loading, causing a change in resistance. This change in resistance is measured by the change in voltage over the strain gage. For this reason, the measurements we make are in voltages. These measurements will be converted to forces and moments using the scaling factors (Table 1) as found in the Bertec Product Data Sheet on the course webpage.

Table 1: Force plate calibration parameters.

Quantity	Scaling factor	Units
Fx, Fy	1000	N/V
Fz	2000	N/V
Mx	600	N-m/V
My	400	N-m/V
Mz	300	N-m/V

There is additional equipment that the force plate must interface with in order to provide us with our measurements. The output from the force plate is digitized (see the Bertec Force Plate Manual for further information on this). As the input commonly utilized by measurement systems is analog, the digitized output is converted to analog as well as amplified by the Bertec D/A converter, part number Bertec AM650X. We then use a National Instruments DAQ box (data acquisition box), part number NI USP-6299 to send a 16-bit digital signal to our computing program. The data acquisition program that is used is National Instruments LabVIEW, a computer program that is capable of doing a wide variety of test monitoring activities. This has been simply set up for our testing needs to acquire force plate data at a rate of 1000 Hz. The output is returned to us in a text file with our measurements and a header reminding us what data we have taken and when. The first column (X_value) is time, and the next columns are the voltage measurements of the forces (Fx, Fy, Fz) and moments (Mx, My, Mz) in each of the directions.

The motion capture system that we will be using to measure position is the Visualeyez 3D model VZ-4000 from PhoeniX Techologies Inc. This is an active motion capture system, having three cameras that are located fixed distances apart. Wireless infra-red diodes (LEDs), a battery pack, and an antenna are mounted on the moving body. The markers are strobed (flashing) such that the each infrared-sensitive camera can see the marker in its two-dimensional view. In this laboratory, we will be using the mocap system to track a single marker located at approximately the whole body center of mass.

We will be collecting position data at 100 Hz from the motion capture system using the software VZSoft v2.80. The data we obtain from the LED marker will include the x, y, and z-position data (in mm), where the z-direction is vertical. This data will be exported into a *.trc file, from which you can extract data using Excel or Matlab to determine the jump height.

IV. Theoretical background

COP determination: A point along the line of action of the applied force can be determined using the forces and moments measured by a fixed force plate. For example, assume a vertical force F_z is applied a distance x_{cp} and y_{cp} from the center of the force plate coordinate system (Fig. 4). The force plate would measure the force F_z and the associated M_x and M_y moments generated by the force about the force plate's x and y axes, respectively. Knowing this information, you can then compute the x and y locations of the center of pressure as follows:

$$x_{cp} = \frac{-M_y}{F_z} \qquad\qquad y_{cp} = \frac{M_x}{F_z} \qquad (1)$$

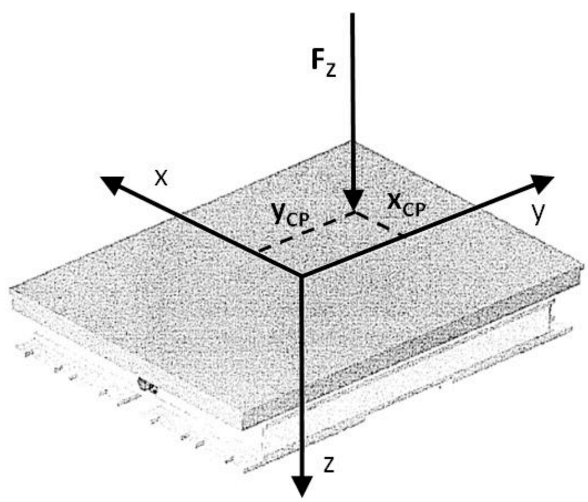

Figure 4: The center of pressure can be determined using measured forces and moments.

When standing upright, your whole body center of mass is continuously moving. In response, you adjust the COP underneath your feet in a way that keeps the center of mass within the feet, i.e. the base of support (Fig. 5). Hence, a plot of the COP motion, termed a stabilogram, can be used to assess one's standing balance. In this lab, we will compare the stabilogram observed during standing with eyes open and eyes closed to assess the affect of vision on standing balance.

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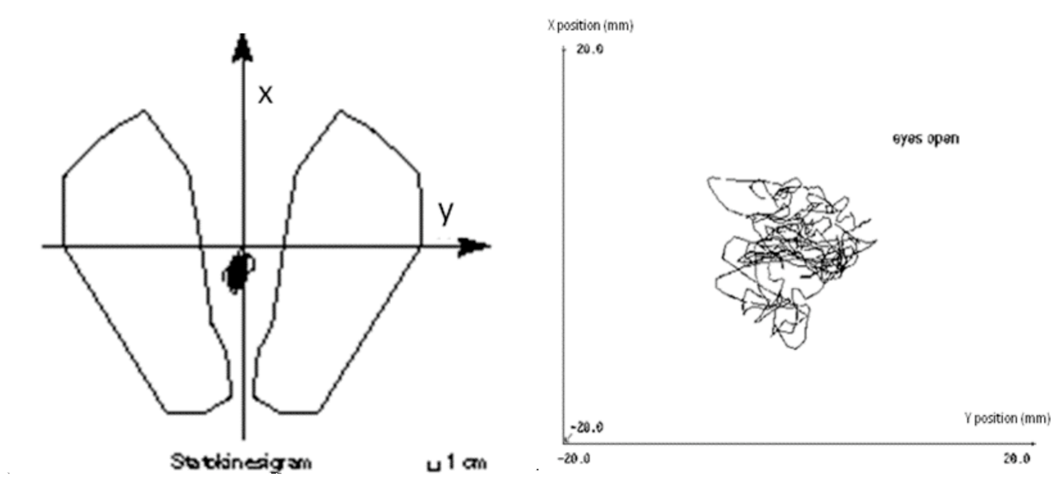

Figure 5: A stabilogram shows the x- and y-coordinates of the COP over a period of time.

Kinematics of jumping: Newton's 2nd Law relates the vector sum of the net forces acting on the body to the center-of-mass acceleration, denoted as $\vec{a}$ or $\frac{d\vec{v}}{dt}$:

$$\sum \vec{F} = m\vec{a} = m\frac{d\vec{v}}{dt} \qquad (2)$$

where *m* is the mass of the body. Considering just the vertical component of this vector equation, the forces acting on the body in the z-direction are the ground reaction force $F_z(t)$ and the force due to the mass of the body, *mg*. This can be related to the vertical acceleration $\frac{dv_z}{dt}$:

$$\sum F_z = m\frac{dv_z}{dt} = F_z(t) - mg \qquad (3)$$

Solving Eq. (3) for $\frac{dv_z}{dt}$ and integrating results in an expression for the velocity of the whole body center of mass as a function of time:

$$v_z(t) = \frac{1}{m}\int (F_z(t) - mg)\ dt \qquad (4)$$

Recall from dynamics that an impulse is a force which is applied over a period of time and causes a change in the momentum of a body. The vertical impulse imparted to the whole body center of mass during a vertical jump can be computed by integrating the measured vertical ground reaction force up until the point of take-off, when the force goes to zero:

$$I_z = \int_{t_1}^{t_2} F_z(t)\,dt = m\int_{t_1}^{t_2} v_z(t)\,dt \qquad (5)$$

Similarly, the center of mass velocity at take-off, v_{to}, is then given by:

$$v_{to} = \frac{1}{m}\int_{t_1}^{t_2} (F_z(t) - mg)\ dt \qquad (6)$$

where t_1 is a time point before the jump (when standing stationary on the force plate), and t_2 is the take-off time. Center of mass jump height is purely a function of take-off velocity after take-off. Hence during a vertical jump, the total impulse that is imparted to the body will determine the jump height that can be achieved (Fig. 6).

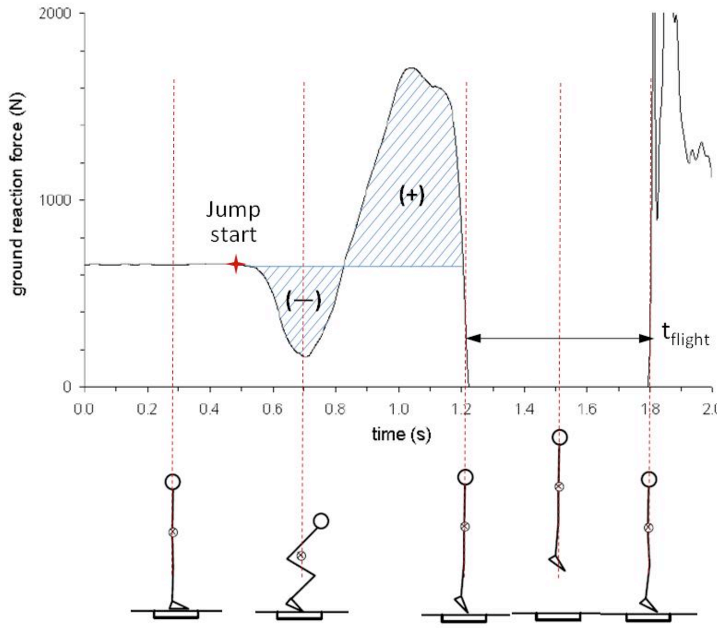

Figure 6: Vertical ground reaction force (Fz) measured by the force plate during a standing vertical jump. Take-off velocity is dependent on the net impulse imparted on the whole body center of mass during the push-off phase. Shown are the phases during which the vertical force is less than (-) and greater (+) then body weight.

Jump height calculations: The jump height of an individual can be determined via energy methods or time-of-flight calculations. We will calculate the jump height using both of these methods and compare the results. Both of these methods require analysis of the measurements made by the force plate during the jump.

Energy Method: The vertical take-off velocity can be used to solve for jump height. To do this, we can equate the kinetic energy of the whole body center of mass at take-off to the potential energy of the whole body center of mass at peak jump height.

$$KE_{to} + PE_{to} = KE_{ph} + PE_{ph} \quad (7)$$

$$KE_{to} = PE_{ph}$$

This assumes the center of mass potential energy, PE_{to}, is zero (assuming the initial center-of-mass to be at a zero height) at take-off, and the kinetic energy, KE_{ph}, goes to zero when the vertical velocity drops to zero at peak jump height. Substituting $KE_{to} = \frac{1}{2}m{v_{to}}^2$ and $PE_{ph} = mgh_{EM}$ results in an expression for the jump height:

$$h_{EM} = \frac{v_{to}^2}{2g} \quad (8)$$

where m is mass, and h_{EM} designates the height as calculated by energy methods.

Time-of-flight method: Jump height can also be determined using the airborne time, t_{flight}. To do this, we first begin with the relation between velocity and acceleration (which in our case is gravity, g):

$$a = g = \frac{\Delta v}{\Delta t} = \frac{v_f - v_o}{t_f - t_o} \qquad (9)$$

where v_o and v_f are the initial and final velocities, and t_o and t_f are the initial and final time. We can either proceed by evaluating this at the mid-point (max height) or landing point of the jump. To evaluate Eq. 9 at the mid-point of the jump, we set $t_f = \frac{1}{2} t_{flight}$, and we assume that the vertical velocity $v_f = 0$. To evaluate Eq. 9 at the landing point of the jump, we can assume that the final velocity is equal and opposite to the initial velocity, i.e. $v_f = -v_o$ and $t_f - t_o = t_{flight}$. Both manners of evaluating this will result in the relation:

$$v_o = -\frac{g t_{flight}}{2} \qquad (10)$$

We then can evaluate the maximum jump height by evaluating the kinematic equation of position,

$$h_{tof} = h_o + v_o t + \frac{1}{2} a t^2 \qquad (11)$$

with $t = \frac{t_{flight}}{2}$, $a = g$, and $h_o = 0$ at the mid-point of the jump (with h_{tof} indicating the height determined by the time of flight method). This results in the expression

$$h_{tof} = -\frac{g t_{flight}^2}{8} \qquad (12)$$

V. Data acquisition

1. Verify the data acquisition system details listed above.
2. Zero the force plate using the button on the Bertec D/A converter/amplifier box.
3. **COP determination**

   First we will demonstrate how to measure the location of the COP with the force plate. We will do this by applying a force at the locations shown in Figure 5 and filling in Table 2 with the measured force plate output. Use the calibration parameters to convert voltage measurements for F_z, M_x, and M_y into *N* and *N-m*, and then use Eq. 1 to calculate the x- and y-coordinates of the COP.
4. **Postural Balance**

   Stand still on the platform with eyes open (EO) and heels together, near the center of the platform. Collect force plate data for 30 seconds. Repeat this experiment with your feet in the same place but your eyes closed (EC).
5. **Vertical Jump**

   Strap a velcro belt around the subject's waist and place a single LED marker at the approximate height of the center of mass, i.e. in the lumbar spine region. Remove unnecessary clothing (jackets, vests) prior to strapping the belt securely in place, making sure the LED is facing outwards on your back. Unnecessary clothing will increase the amount of noise in our measurements, as it may shift during the movements, or fold over the marker and hide it from view.

   While standing on the force platform facing in the positive x-direction, perform a vertical jump as high as you can using both legs. Stand in a stationary position for a second or two before you jump and collect force plate data through your return landing on the plate.

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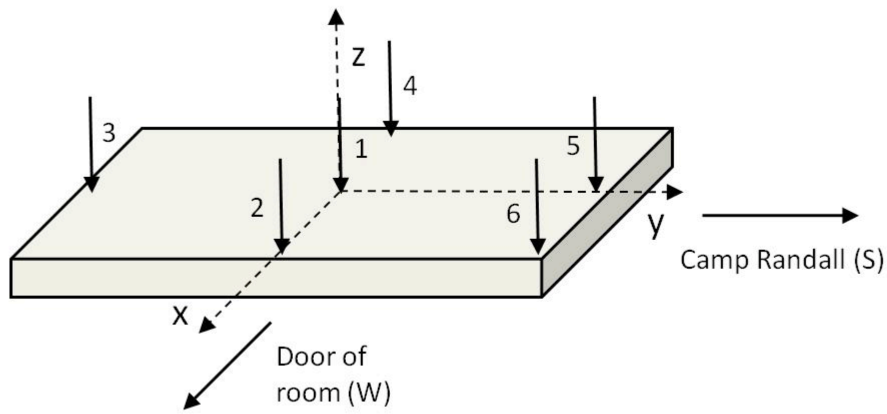

Figure 7: Locations at which the COP will be determined.

Position	F_z output (V)	M_x output (V)	M_y output (V)	F_z (N)	M_x (N-m)	M_y (N-m)	X_{CP} (m)	Y_{CP} (m)
1								
2								
3								
4								
5								
6								

Table 2: Calculation of COP location for stationary loads on the force plate.

VI. Data Analysis

In this lab, we are collecting a significant amount of data as our data acquisition system samples at a frequency of 1000 Hz. It is very difficult to utilize a program like Excel to work with this much data, and is much better to use a more advanced computational program. The program that is recommended is Matlab, which can be found on the CAE computers. As this course does not require a computer programming course as a prerequisite, some Matlab tutorials and the basic computer code you will need is included in the Appendix. This code will perform the basic parts of your assessment, but will not do things like modify the axis of your figures (which you might need to do to show some figures appropriately) or put labels on your figures. The help menu of Matlab is easily searchable to find code that will assist you, and often includes many examples of code usage.

1. Using the balance data, compute the *x*- and *y*-coordinates of your COP. Create a stabilogram plot in which you plot the trajectory of the COP over the duration of your standing trial. Do this for both the eyes open (EO) and eyes closed (EC) conditions.

2. Using your vertical jump data, plot the acceleration, $\frac{dv_z}{dt}$, of the COM from a time point before the jump until the point of landing (see Eq. 3). Clearly label the take-off time, time of peak height, and time of landing on this plot.
3. Perform numerical integration to compute the COM vertical velocity (Eq. 4) from a time point before the jump until the point of landing. Numerical integration can be done in Matlab using the Trapezoidal rule or Simpson's rule. Computational code for this is included in the Appendix. Create a plot of the center of mass velocity and clearly label the take-off time, time of peak height, and time of landing on this plot.

4. Use the motion capture data to determine the measured jump height. You can open the *.trc file with Matlab code included in the Appendix. This file contains the x, y, and z-position data (in mm) of the LED that is mounted to your body, where the z-direction is the vertical (jump) axis. Assume the position while standing stationary before the start of the jump to be the initial (zero) height and determine the jump height relative to this point.
5. Predict the jump height using the energy (Eq. 8) and time-of-flight (Eq. 12) methods. NOTE: Take-off velocity can be determined from the definite integral (Eq. 6) with Matlab using the function 'trapz.' Take-off velocity can also be determined by assessing the plot of velocity (Data Analysis #3) at the take-off time. Time-of-flight can be determined by assessing your plot of acceleration or velocity.

6. Determine the measured jump height, take-off velocity, and predicted jump height (by both the energy and time-of-flight methods) for all of the individuals in your lab section. Make a table showing this data.

   NOTE: You do not need to include plots of the acceleration and velocity for all of these individuals in your lab report. However, you might find it helpful to make these plots to determine the take-off velocity and time-of-flight needed for your calculations.

7. Plot the predicted jump height (by both the energy and time-of-flight methods) and the measured jump height versus the take-off velocity.

8. From the measured jump height, determine the individual with the largest and smallest jump height. Normalize the measured F_z force plate data by the weight of the individual (F_z when standing). Plot the normalized F_z data for both of these individuals on the same plot, aligning them such that the start of the jump motion (shown in Fig. 6) coincides.

VII. Questions

1. How does the center of pressure motion differ between the eyes open and eyes closed conditions? Does the COP location vary more in the anterior – posterior (x-axis) or left – right (y-axis) direction? Suggest some possible reasons for your observations.
2. If you wanted to measure balance using COP, what are some ways you could think of to quantify the stabilogram plots? The study performed by Raymakers, et al [1] evaluates

several different methods of quantifying COP variation which you may find useful. You may calculate the variation with Matlab or include a different plot (x or y position versus time) to show this.

3. Compare the different calculations for jump height. Was one of these calculations consistently higher? What are the possible errors in your calculations or measurements? Which value do you think is more accurate? The study performed by Moir [2] evaluates different methods calculating jump height which you may find useful.
4. Comparing the plots of the normalized vertical force for the individuals with the smallest and largest jump heights, what do you observe about the total impulse (Fig. 6) that led to the jump heights?

VIII. Laboratory report

The basic format of your laboratory report should follow the handouts Rubric_Labs.pdf and Grading_labs.pdf available on the course webpage. Some specific guidelines and suggestions for this report are detailed below.

- Procedure: In addition to the typical details about the experiment (what we did), this section should include information concerning the experimental setup, a diagram showing the coordinate system of the force plate, and a table with the force plate scaling factor information.
- Results and Discussion: This section of your report should include discussion of each of the questions from section VII. You should explain important findings of each of your analyses: i.e. the COP determination, vertical jump height measurement, and vertical jump height predictions. Consider what you observed while doing the experiments, what your figures showed, the assumptions you made in making calculations, and potential sources of error.
- Appendix: The derivations of the equations that were used to calculate jump height should be included here. You should show each step of the derivation and state your assumptions. Your figures and tables may either be included in the Appendix or the text of the paper depending on the requirements of your TA, however they must consistently be in one or the other. Each of the included figures must be referred to within the lab report.

IX. References

1. Raymakers, J.A., et al. "The assessment of body sway and the choice of the stability parameter(s)," *Gait and Posture* 21 (2005): 48 – 58.
2. Moir, G.L. "Three Different Methods of Calculating Vertical Jump Height from Force Platform Data in Men and Women," *Meas. in Phys. Ed. and Exer. Sci.* 12 (2008): 207 – 218.