Lab #2 – Introduction to Linear Kinematics and Total Body Center of Mass Model

Kinematics is the geometry of motion.

Purpose:

The objective of this lab is to provide you with a thorough introduction to linear kinematics and the total body center of mass (TBCM) model. Upon completion of this lab you will:
- Understand how to observe a movement, break it into phases, and perform appropriate analyses to answer your particular questions of interest.
- Understand and know how to calculate linear kinematic variables.
- Have the tools to begin your own linear kinematic analyses of upcoming athletic events.
- Understand and know how to calculate TBCM.
- Understand and be able to use the digitizing applet.

Introduction:

I. LINEAR KINEMATICS
   Kinematic analysis focuses on the characteristics of motion from a spatial and temporal perspective, without reference to the forces that cause the motion.

Linear kinematics refers to the kinematic analysis of linear motion. Linear motion occurs when all particles of the moving object follow parallel paths, covering the same distance in the same amount of time. This type of motion occurs very seldom in human movement since angular motion occurs at the joints of the body. For example, walking and running are movements which approximate linear motion at the total body level, but these movements can not be classified as pure linear motion because the individual segments (arms and legs) undergo rotation.

Linear kinematic variables:

Position (x, y, z) : Location of a specific object or point with respect to some reference point

Velocity (v_x, v_y, v_z) : Change in position over a period of time ($v_x = dx/dt$, $v_y = dy/dt$, $v_z = dz/dt$)

Acceleration (a_x, a_y, a_z) : Change in velocity over a period of time ($a_x = dv_x/dt$, $a_y = dv_y/dt$, $a_z = dv_z/dt$)

*Note: velocity and acceleration are averages for that period of time

Figure 1 shows a two-dimensional (2D) example of a ball moving from one position to another over a period of time ($\Delta t = t2 - t1$). The position of the ball at time one (t1) and time two (t2) is (2, 2) and (4, -1), respectively. The time from t1 to t2 is 2 seconds. The average horizontal velocity (v_x) of the ball over the period of time from t1 to t2 can be calculated as follows:

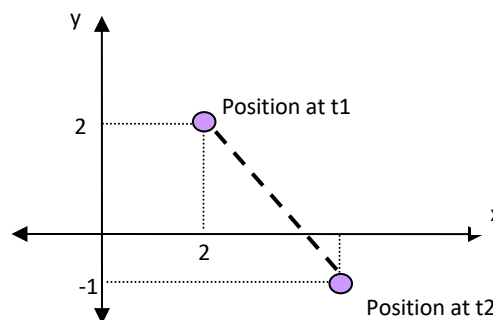$v_x = (x2 - x1) / (t2 - t1)$
$v_x = (4 - 2) / (2-0)$
$v_x = 1$ m/s

Figure 1

Similarly, the average vertical velocity of the ball over the period of time from t1 to t2 can be calculated:

v_y = (y2 - y1) / (t2 - t1)
v_y = (-1 - 2) / (2 - 0)
v_y = -1.5 m/s

The resultant average linear velocity of the ball over the period of time from t1 to t2 can be calculated using the **Pythagorean Theorem; $a^2 + b^2 = c^2$** .

$v_r^2 = v_x^2 + v_y^2$
v_r^2 = $(1)^2 + (-1.5)^2$
v_r^2 = 3.25
v_r = sqrt (3.25)
v_r = 1.8 m/s

Another method to calculate the resultant average linear velocity is to use the Pythagorean Theorem to first solve for the resultant distance from position one to position two (hypotenuse of the triangle). Solving this you find the resultant distance to be 3.6 m. You may then solve for the average linear velocity by dividing the resultant distance traveled by the change in time (2 s), which reveals the same answer as above.

$r^2 = (x_2-x_1)^2 + (y_2-y_1)^2$
r = sqrt $(2^2 + 4^2)$
r = 3.6 m
$v_r = r / (t_2 - t_1)$
v_r = 3.6 / 2
v_r = 1.8 m/s

If we assume the ball started from rest (initial velocity = 0 m/s) and traveled through position two at the calculated resultant velocity, then the ball's resultant average linear acceleration during this phase can be calculated.

$a = (v_2 - v_1) / (t_2 - t_1)$
a = (1.8 - 0) / (2 - 0)
a = 0.9 m/s^2

II. TOTAL BODY CENTER OF MASS (TBCM)
The center of mass (CM) of an object is a theoretical point where all of the object's mass can be considered to be concentrated. If you have a perfect sphere that is composed of a material of uniform density (e.g. a shot put), its center of mass coincides with its geometric center. With objects of non-uniform shapes and non-uniform material densities, the CM does not coincide with their mid-volume point. This is true for the human body. Analyzing movement of a multisegment, multidegree of freedom body like the human musculoskeletal system may be simplified by representing the human body as a particle located at the CM.

From a practical sense, the force of gravity actually pulls on individual body segments and thus gives each segment a weight. Each segment influences the total weight of the body. The positions of the segments in relation to one another, as well as the weights of the segments, are factors in the location of the body's center of mass. Body segment parameters from the literature are used to describe the distribution of mass within and between segments.

Knowledge of the center of mass location of the total body with the body in different configurations is important in movement analysis. In some cases, the center of mass can be located at a point *outside* the body. The segmental weights do not change during movement, however the positions of the segments in relation to others do change. These relative segmental changes, therefore, produce the changes of location of the body's center of gravity.

Segmental Method

The segmental method uses the x-y coordinates from digitized data and the knowledge of the mass distribution and the centers of mass location of each of the body's segments. With this method, you analyze one segment at a time and then calculate the total body center of mass based upon the center of mass locations of all the segments.

Body segment parameters (BSP) are determined based on three methods: 1) measures based on cadaver studies, 2) mathematical modeling, and 3) radioisotope scanning. In this lab we will use BSP provided by DeLeva (*J. Biomechanics*, 1996).

Body Segment Parameters

Men

n = 100	mean Mass: 73.0 kg	mean Age: 23.8yrs	mean Ht: 174.1 cm	
Segment	**CM (% from proximal)**	**Mass (%)**	**Proximal**	**Distal**
Foot	44.15	1.37	Heel	Toe
Shank	44.59	4.33	Knee	Ankle
Thigh	40.95	14.16	Hip	Knee
Hand	36.91	0.61	Wrist	Finger Tip
Forearm	46.08	1.62	Elbow	Wrist
Upper Arm	57.72	2.71	Shoulder	Elbow
Head	50.02	6.94	Vertex	C7
Trunk	51.38	43.46	C7	Hip

Women

n = 100	mean Mass: 61.99 kg	mean Age: 19.0 yrs	mean Ht: 173.5 cm	
Segment	**CM (% from proximal)**	**Mass (%)**	**Proximal**	**Distal**
Foot	40.14	1.29	Heel	Toe
Shank	44.16	4.81	Knee	Ankle
Thigh	36.12	14.78	Hip	Knee
Hand	35.02	0.56	Wrist	Finger Tip
Forearm	45.92	1.38	Elbow	Wrist
Upper Arm	57.54	2.55	Shoulder	Elbow
Head	48.41	6.68	Vertex	C7
Trunk	49.64	42.57	C7	Hip

Table 1: Body segment parameters according to DeLeva.

> **Segment:** Segment name
> **CM (% from proximal):** Location of the segment's center of mass as measured from the proximal joint. Distance is given as a percentage of the length of the segment.
> **Mass (%):** Mass of the segment. Given as a percentage of the subject's total body mass.
> **Proximal:** Segment's proximal bony landmark.
> **Distal:** Segment's distal bony landmark.

Calculating Segment Center of Mass:

Using the information in Table 1, you can find the center of mass location of each segment using the following formula:

x_{cm} = x_p - (length of the segment in x-direction * (CM % from proximal)
   = x_p – ((x_p - x_d)* (CM % from proximal))

y_{cm} = y_p - (length of the segment in y-direction * (CM % from proximal)
   = y_p – ((y_p - y_d)* (CM % from proximal))

where,
   (x_{cm} , $y_{cm)}$ are the coordinates of the center of mass
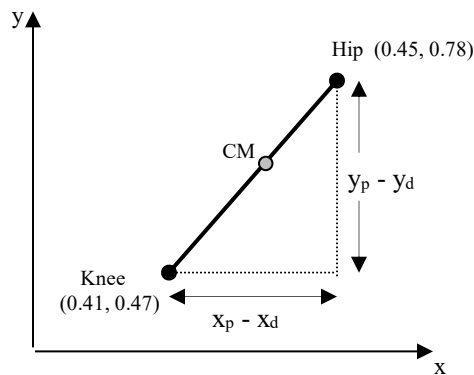   (x_p , $y_{p)}$ are the coordinates of the hip joint
   (x_d , $y_{d)}$ are the coordinates of the knee joint.

Example: Calculate the center of mass of the right thigh using DeLeva's BSP given the following:
   right hip: (0.45,0.78)m
   right knee: (0.41,0.47)m

First, draw a picture:

Next, according to Table 1, the center of mass of the thigh is located at 40.95% of the length of the thigh measured from the proximal end along the longitudinal axis of the segment. Then, the location of the right thigh CM can be calculated as follows:

x_{cm} = x_p - (length of the segment in x-direction * (CM % from proximal)
   = x_p - ((x_p - x_d)* 0.4095)
   = 0.45 - ((0.45 - 0.41)* 0.4095)
   = 0.4336m

y_{cm} = y_p - (length of the segment in y-direction * (CM % from proximal)
   = y_p - ((y_p - y_d)* 0.4095)
   = 0.78 - ((0.78 - 0.47)* 0.4095)
   = 0.6531m

Therefore, the CM of the segment is (0.4336, 0.6531)m in the reference frame.

NOTE: THE LOCATION OF THE CM MUST BE BETWEEN THE VALUES FOR THE PROXIMAL AND DISTAL ENDS OF THE SEGMENT.

Calculating Segment Mass (m)

Using the information in Table 1, you can calculate the mass of each segment using the following formula:

$$m_{segment} = (Mass \%) * M$$, where M=total body mass

> **Example**: For a male subject, calculate the mass of his right thigh using DeLeva's BSP given a total body mass of 73 kg.

> m_{thigh} = (Mass % of thigh) * M
> = (0.1416) * 73
> = 10.34 kg

Calculating Total Body Center of Mass (TBCM):

The segment mass and CM coordinates for each segment are used to determine the TBCM location. Essentially, the TBCM location is a weighted average of the individual segment CM locations. In algebraic terms, the TBCM is calculated as follows:

$$x_{tbcm} = (\Sigma m_i x_{cmi}) / M \quad (for\ i=1\ to\ n)$$

$$y_{tbcm} = (\Sigma m_i y_{cmi}) / M \quad (for\ i=1\ to\ n)$$

> where,
> x_{tbcm} is the horizontal location of the total body center of mass
> y_{tbcm} is the vertical location of the total body center of mass
> m_{cmi} is the mass of the i-th segment
> x_{cmi} is the horizontal location of the i-th segment center of mass
> M is the total body mass
> n is the number of segments

The formula tells you that, for each segment, you need to multiply the location of the segment CM by the mass of the segment and divide by the total body mass. Then sum the results for all segments to get the TBCM.

(Note: There is a shortcut for performing the TBCM calculation. If you remember that the segment mass is really the total body mass times the mass %, and plug that into the formula, you will see that the total body mass, M, cancels out. Therefore, the subject's total body mass does not affect the TBCM calculations.)
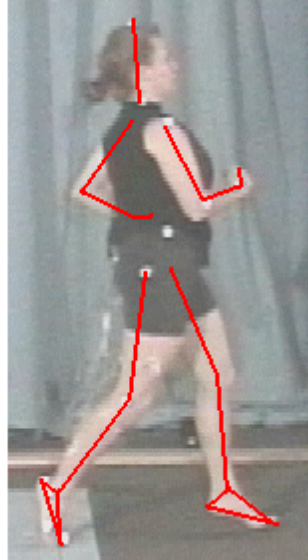
First Central Difference Method:

The TBCM velocity is calculated using the change in distance divided by the change in time ($v_x=dx/dt$). With discrete data, the calculated velocity is an average velocity between two time steps and it corresponds to the velocity at the time exactly halfway between the two times. So, this means that if you calculate the velocity from t_1 to t_2, your result will be the velocity for $t_{1.5}$, which does not correspond to an actual data point. Instead, you can use the first central difference method which skips time steps; i.e. you calculate the velocity from t_1 to t_3, and your result is the velocity at t_2. The general formal is:

$$v_i = (x_{i+1} - x_{i-1})/(t_{i+1} - t_{i-1})$$

For example, the velocity at t_5 would be calculated as follows: $v_5 = (x_6 - x_4)/(t_6 - t_4)$. This method should also be used for calculating acceleration from velocity.

Pre Lab:

1. Listed below are the (x, y) coordinate data of body landmarks at both ipsilateral foot-strike (IFS) and ipsilateral toe-off (ITO). Using the coordinate data and the body segment parameters in Table 1, calculate the location of the runner's TBCM at each of the two events. **USE EXCEL**

	IFS		ITO	
	X	**Y**	**X**	**Y**
RTOE	1.89	0.31	1.91	0.31
RHEEL	1.67	0.31	1.82	0.48
RANKLE	1.72	0.34	1.88	0.45
RKNEE	1.71	0.65	2.07	0.71
RHIP	1.56	1.02	2.13	1.09
LTOE	1.04	0.65	2.51	0.37
LHEEL	1.15	0.80	2.33	0.41
LANKLE	1.17	0.74	2.37	0.45
LKNEE	1.53	0.70	2.33	0.78
LHIP	1.52	1.02	2.18	1.11
RSHOULDER	1.52	1.47	2.20	1.53
RELBOW	1.39	1.27	2.30	1.30
RWRIST	1.57	1.18	2.41	1.34
RFINGER	1.69	1.12	2.40	1.39
LSHOULDER	1.57	1.48	2.11	1.52
LELBOW	1.66	1.28	1.95	1.31
LWRIST	1.76	1.27	2.16	1.26
LFINGER	1.81	1.31	2.24	1.24
C7	1.52	1.54	2.13	1.59
VERTEX	1.54	1.76	2.09	1.82

2. In a table, compare the hip as an estimate of TBCM with TBCM calculations using segmental method.
3. Discuss the pros and cons of using each method. Which method provides greater accuracy in determining the location of the TBCM? Explain.
4. Where is the center of mass of the person relative to the base of support for both conditions (in front of, within, or behind)? Discuss how you think the location of the TBCM with respect to the base of support may affect the mechanical demands of a movement.

Laboratory Procedure:

When modeling the human body, we consider it to be a system of rigid links connected by pin joints. In gait analysis, as illustrated in the Pre Lab, you would choose a model of the body that has two arms and two legs. In the case of a movement that is symmetrical (right and left sides of the body do the same thing), you can choose a model of the body that has one arm (with a mass equivalent to two arms) and one leg (with a mass equivalent to two legs). Templates for both models are available on the website.

Back timer = translation backwards without rotation
Back = translation backwards with backward rotation
Reverse = translation forwards with backward rotation

- Use the digitizing applet to model the human body as a system of rigid links connected by pin joints following the directions provided below.
    1. Open Matlab. Download "dltdv5.m" and be sure that the folder it is in is the current operating folder on Matlab. Click "Run" when it is open in Editor.
    2. Choose "Initialize" and select meter.mp4. Select "Display in Color"
        a. Digitize the left side of the meter stick between the white lines.
        b. Digitize the right side of the meter stick between the white lines.
        c. Save your data as "DLTdv5_data_meter"
    3. Choose "Initialize" again and select the video of your dive of choice (Back, Back Timer, Reverse). Select "Display in Color".
        When digitizing, note and **record** the frames during which the body is at its highest point, up on toes, arms up (High), and the lowest point when the hip and knees are fully flexed (Low). Also look for when both the knees and hips start to extend (Joint Extension) and the time of plate departure (Depart). The phase between High and Low events will be called the Loading phase. The phase between the Low and Joint Extension events will be referred to as the Tip phase. The phase between the Joint Extension and Depart events will be referred to as the Push phase. Please make a table with the events and corresponding frame numbers.
        a. Digitize one point at a time, in order of body digitizing template given on excel sheet. (i.e. heel marker through all frames, then toe, etc.)
        b. Click "save data" and label "DLTdv5_data_(DIVE OF CHOICE)".
        c. Tips
            - Left click to digitize point
            - Right click to remove point
            - Click "add a point" to create a new point (i.e. point1 point2)
            - Make sure to write down which point is which joint/position
            - Press 'f' to move forward 1 frame
            - Press 'b' to move back 1 frame
            - Press "+" to zoom in. Picture will zoom in where cursor is
            - Press "-" to zoom out
            - Press "r" to restore to original image zoom
        d. Once complete, save all data and copy and paste into correct location of TBCM template **(Male, Half Body)**. Do not include headers.
        e. Ignore second tab, "Aspect Ratio", and go to "Scale Factor": input difference of xCM points of meter stick in image length (pixels) (i.e. =412-240). Real length (m) = 1.
        f. Save the Excel file.
            - Make a back-up copy of your data and save this to your drive. Do NOT touch this file! It is for backup only.
        g. In sheet 4, 'Scaled Coordinates', you will find coordinate data (x,y) of each digitized point.
        h. In sheet 5, 'Right Foot', you will find the calculation of the right foot center of mass and the result of the CM calculation of the right foot in the columns K(x) and L(y).
        i. Calculation of other body segments will be shown in the subsequent sheets.
        j. In the sheet named 'TBCM', x and y coordinates of the TBCM are in columns AD and AE.

- Repeat this process for other two diving trials and use the data to complete the post lab analysis. Only do this for subject 1. Pair up with someone so that they digitize one of the remaining dives and you digitize the other.
    1. On one graph, plot the TBCM horizontal position vs. time for each dive.
        - Line up the graphs at a common event for easier analysis.
            i. Find the 'Depart' frame for each dive.
            ii. Make that time = 0.0 s.
            iii. For previous frames, the time will be negative. For subsequent frames, the time will be positive. Remember, each frame is 1/30 s. Use this information to create a formula for time before departure and a different formula for time after.
        - For each dive, label the following events on your graph: high, low, joint extension, departure.
        - For each dive, label the following phases on your graph: load, tip, push, flight.
        - Make sure your graphs have a title, axes labels, and a legend.

    2. On one graph, plot the **TBCM vertical position vs. time** for each dive.
        - Again, line up your graphs at the common event, 'Depart'.
        - For each dive, label the following events on your graph: high, low, joint extension, departure.
        - For each dive, label the following phases on your graph: load, tip, push, flight.

        Note: If your graphs do not have a smooth appearance, you may have to redigitize one frame. Locate which data point is "out of line" and find out which frame on the digitizing applet that corresponds to. Highlight the data in your first sheet of the excel template that you will be overwriting. You can redigitize that one frame of data by going to that frame and copy the coordinates from that one frame of data into the correct location on your first sheet of your excel template. This applies to Steps 12-15, as well.

    3. On one graph, plot the **TBCM horizontal velocity vs. time** for each dive (use First Central Difference Method on horizontal position data).
        - Line up the graphs at the common event, 'Depart'.
        - Label the following events: high, low, joint extension, departure.
        - Label the phases: load, tip, push, flight.

    4. On one graph, plot the **TBCM vertical velocity vs. time** for each dive (use First Central Difference Method on vertical position data).
        - Line up the graphs at the common event, 'Depart'.
        - Label the following events: high, low, joint extension, departure.
        - Label the phases: load, tip, push, flight.

    5. On one graph, plot the **TBCM horizontal acceleration vs. time** for each dive(use First Central Difference Method on horizontal velocity data).
        - Line up the graphs at the common event, 'Depart'.
        - Label the following events: high, low, joint extension, departure.
        - Label the phases: load, tip, push, flight.

    6. On one graph, plot the **TBCM vertical acceleration vs. time** for each dive (use First Central Difference Method on vertical velocity data).
        - Line up the graphs at the common event, 'Depart'.
        - Label the following events: high, low, joint extension, departure.
        - Label the phases: load, tip, push, flight.

Data Analysis and Questions:

Also include the necessary sections for a lab report! Remember: If you are asked to calculate anything/make a graph/make a table, they should be included in the report.

1. Display your vertical and horizontal position vs time graphs.

2. Briefly describe what your position vs. time graphs tell you about the similarities and differences among the dives. Use your understanding of the mechanical objectives of each phase in your answer.

3. Display your vertical and horizontal velocity vs time graphs.

4. Briefly describe what your **velocity vs. time graphs** tell you about the similarities and differences among the dives. Use your understanding of the mechanical objectives of each phase in your answer.

5. Display your vertical and horizontal acceleration vs time graphs.

6. Briefly describe what your **acceleration vs. time graphs** tell you about the similarities and differences among the dives. Use your understanding of the mechanical objectives of each phase in your answer. What do you notice about the noise in your graphs as you go from position to velocity to acceleration?

7. In general, what is the relationship between the CM position, velocity, and acceleration? (Discuss slopes and zero-crossings). Examine your vertical TBCM curves in your explanation.

8. For one trial, calculate the shank segment length for each frame. Calculate the average shank length over time and convert it to feet and inches (1 in= 2.54 cm). Does this value make sense? Knowing that the subject's shank did NOT actually change length during the movement, explain at least two possible reasons for the differences in calculated length over time.