

## Lab #6 - Total Body Kinetics

### **Purpose:**

The purpose of this lab is to fully comprehend, through personal experience, the relationship between the net force acting on the body and the acceleration of the total body center of mass (TBCM). In this lab, we will focus on vertical ground reaction forces and the subsequent linear motion of the TBCM. Upon completion of this lab you will:

- Understand the relationship between force, mass, and acceleration.
- Know how to interpret a force-time curve.
- Be able to draw a free-body diagram and use it to calculate net force.
- Understand and be able to solve projectile motion problems.

### **Introduction:**

In many skilled tasks, the performer needs to perform a series of movements while in contact with the ground and during flight. As we have learned in the previous labs, the mechanical objectives of the phases during foot contact are generally to control and generate the linear and angular momentum necessary for the subsequent flight phase. The final condition of the foot contact phase (velocity at take-off) becomes the input or initial condition of the flight phase. During the flight phase, the path of the total body center of mass (TBCM) follows the laws of projectile motion.

### **I. NET FORCE = MASS \* ACCELERATION**

In addition to Newton's third law of motion referred to as the Law of Action/Reaction, you need to understand Newton's second law of motion referred to as the Law of Acceleration.

$$\text{Newton's Second Law: } \Sigma F = m \cdot a$$

where:  $\Sigma F$  = sum of the external forces  
 $m$  = mass  
 $a$  = acceleration

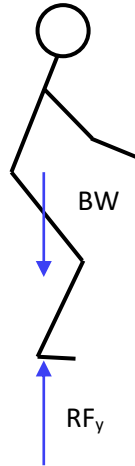
This mathematical formula expresses the relationship between the external forces applied to an object and the linear acceleration that the forces produce. It must be noted that the "a" in the above equation is the acceleration of the TBCM. In addition, the acceleration must be in the direction of the net external force, F. Newton's second law of motion, in conjunction with his third law (which states that for every action there is an equal and opposite reaction), provides the mathematical basis for what happens when someone performs a movement on a force platform.

$$\begin{aligned}\Sigma F &= ma \\ \text{substitute in } \Sigma F &= R_y + (-BW) \\ R_y + (-BW) &= ma \\ R_y &= BW + ma\end{aligned}$$

where: BW = body weight of person  
 $R_y$  = vertical ground reaction force

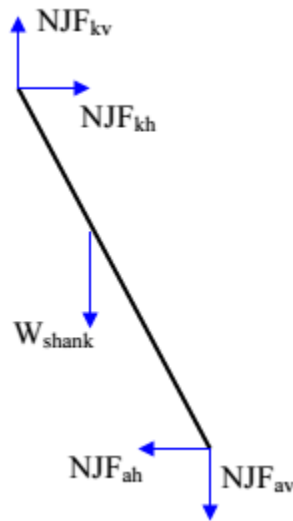
For the case in which a person is in a stationary (static) position, the two forces (BW and  $R_y$ ) must be equal in magnitude and opposite in direction ( $\Sigma F_y = R_y - BW = m \cdot a = 0$ ). If the person starts to move up (positive acceleration of the TBCM), then  $\Sigma F = ma > 0$  and the magnitude of the ground reaction force will be greater than the magnitude of the body weight. With initiation of downwards movement (negative acceleration of the TBCM),  $\Sigma F = ma < 0$  and the magnitude of the ground reaction force will be less than the magnitude of the body weight.

If we take the entire body of a person as the system, our free body diagram (FBD) of a person standing on a force platform may look something like:



Because our system is the body and does not include the ground, we have to include a ground reaction force to remind us that the body is interacting with the ground.

In the same way, we could encounter a situation where we are only interested in the shank segment (lower leg). In this case, just like the ground, we would need to insert forces to remind us that the shank actually interacts with the thigh and the foot. So, in this case, our FBD would look like:



Now, because the shank is not in contact with the ground, we do not call it a GRF, but instead, it is a **net joint force** (NJF). The force is a 3D force and can be drawn in any direction, but must act through the joint. Joint reaction forces will be the topic of the next lab.

In summary, at the total body level:

$a < 0$	$a = 0$	$a > 0$
$\Sigma F = BW + R_y < 0$	$\Sigma F = 0$	$\Sigma F = BW + R_y > 0$
$ R_y  <  BW $	$ R_y  =  BW $	$ R_y  >  BW $

## II. PROJECTILE MOTION

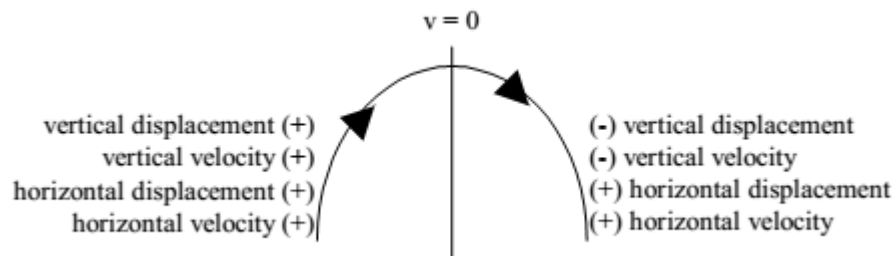
Once a person or projectile is in the air, only two external forces act upon it: gravity and air resistance. The latter force is very important in such sports as ski jumping and skydiving because the velocity is large and the flight time is relatively long. It is also of special significance in the javelin and discus events because of the aerodynamic characteristics of these implements. However, in many activities involving projectile motion, air resistance plays an insignificant role. Because of this fact and the desire to simplify the following laboratory experiment, the force due to air resistance will be considered negligible, that is, it is equal to zero.

What formulas do we use to represent projectile motion?

Vertical	Horizontal
$s_f = s_i + v_i \Delta t + 1/2 a t^2$	$s_f = s_i + v_i \Delta t$
$v_f = v_i + a \Delta t$	$v_f = v_i$
$(v_f)^2 = v_i^2 + 2a(x_f - x_i)$	$v_f^2 = v_i^2$
$a = g = -9.81 \text{ m/s}^2$	$a = 0 \text{ m/s}^2$

where:  $v_f$  = final velocity in (m/s)  
 $v_i$  = initial velocity in (m/s)  
 $a$  = acceleration in (m/s<sup>2</sup>)  
 $t$  = time (s)  
 $s_f$  = final displacement (m)  
 $s_i$  = initial displacement (m)

In general, if a ball is thrown into the air, we can figure out any variables if given enough information.



When the ball is in the air, gravity is the only vertical force acting on the ball. So, the vertical acceleration of the ball is  $-9.81 \text{ m/s}^2$ .

When the ball is in the air, there are no horizontal forces acting on the ball. So, the horizontal acceleration of the ball is  $0 \text{ m/s}^2$ .

**Example:** A ball is thrown from 2.5 m above the ground at 1.05 radians from the right horizontal. The resultant initial velocity is 6.5 m/s.

- a. How long does it take for the ball to reach the highest point on its path?

$$1.05 \text{ rad} * 180^\circ / \pi \text{ rad} = 60.2^\circ$$

$$v_r = 6.5 \text{ m/s}$$

$$v_y = 6.5 \text{ m/s} * \sin 60.2^\circ = 5.64 \text{ m/s}$$

knowns:  $v_f = 0.0 \text{ m/s}$

$$v_i = 5.64 \text{ m/s}$$

$$a = g = -9.81 \text{ m/s}^2$$

$$v_f = v_i + a * t_{\text{up}}$$

$$v_f - v_i = a * t_{\text{up}}$$

$$t_{\text{up}} = (v_f - v_i) / a$$

$$= (0 - 5.64) / (-9.81) = 0.57 \text{ s}$$

- b. How high from the ground does the ball get vertically?

knowns:  $y_i = 2.5 \text{ m}$

$$v_i = 5.64 \text{ m/s}$$

$$v_f = 0.0 \text{ m/s}$$

$$t_{\text{up}} = 0.57 \text{ s}$$

$$a = g = -9.81 \text{ m/s}^2$$

$$y_f = y_i + v_i * t_{\text{up}} + \frac{1}{2} * a * t_{\text{up}}^2$$

$$y_f = 2.5 + (5.64 * 0.57) + \frac{1}{2} * (-9.81) * 0.325$$

$$y_f = 7.32 \text{ m}$$

**Factors that Influence Projectiles:**

1. Projection angle (angle of the resultant velocity vector at departure)
2. Projection velocity (horizontal & vertical)
3. Projection height (height at departure)

**Pre Lab:**

You will be analyzing the vertical jump of a former graduate student (body weight = 814 N). Print the graph of the vertical ground reaction force curve from the lab website (Jump GRF).

1. Draw the free body diagram and mass acceleration diagram of the subject during the load phase (stand to squat). Draw one for the first part when  $|GRF| < |BW|$  and one for the second part when  $|GRF| > |BW|$ . Draw the arrows so they represent the magnitude of the forces (i.e. longer arrows for greater forces).
2. Draw the free body diagram and mass acceleration diagram of the subject during the push phase (low to take-off). Draw one for the first part when  $|GRF| > |BW|$  and one for the second part when  $|GRF| < |BW|$ . Draw the arrows so they represent the magnitude of the forces (i.e. longer arrows for greater forces).
3. Describe the impulse momentum relationship. What is its importance?
4. On the Force-Time curve that you downloaded, label body weight, unweighting ( $|GRF| < |BW|$ ), weighting ( $|GRF| > |BW|$ ), flight, and landing.
5. Using the box-counting method, estimate the net vertical impulse generated for the vertical jump up to takeoff. Hint: the subject starts his jump from a quiet standing position at approximately  $t = 1.85\text{s}$ .
6. Estimate the vertical velocity at takeoff using the impulse momentum relationship.
7. Calculate the total time in the air from the velocity calculated in question 5 and the equations of projectile motion.
8. Calculate the maximum height of the jump from the velocity calculated in question 5 and the equations of projectile motion.
9. Calculate the total time in the air from the GRF curve (duration when the vertical GRF is 0 because the subject is not on the plate). Does this value match the one you calculated in question 7?

### **Laboratory Procedure (Data Collection):**

#### **Vertical GRF:**

In this section, the vertical jump will be broken into parts. Each student will perform the listed movements on the force platform while it monitors the vertical ground reaction force ( $R_y$ ) you generate. You will download the vertical force curves for analysis. A 30 Hz video camera will also be used to record a sagittal view of each student's movements on the force plate for future video grabbing and analysis. Flight time during the vertical jump can be calculated from this video if you know the frames of take-off and landing, since you know the frame rate.

Movement 0: Measure the standing reach height and jump height of the squat and countermovement jump.

Movement 1: From a standing position, forcibly swing your arms up.

Movement 2: With your arms overhead, forcibly swing your arms down.

Movement 3: With your hands on your hips, rapidly squat down.

Movement 4: From a squatted position, rapidly return to a standing position.

Movement 5: From a standing position with the hips flexed (i.e. bent over at the waist), rapidly extend your hips to return to an upright position.

Movement 6: From a standing position, perform rapid plantar flexion.

Movement 7: Starting in a squatted position, perform a maximum vertical jump (squat jump).

Measure your maximum jump height on a ruler beside the force plate.

Movement 8: Starting in a standing position, perform a normal countermovement vertical jump. Measure your maximum jump height on the ruler beside the force plate.

Data:

Squat Jump:                      Subject's stand & reach height: \_\_\_\_\_  
   Recorded jump height: \_\_\_\_\_  
   Net jump height: \_\_\_\_\_

Countermovement Jump:                      Subject's stand & reach height: \_\_\_\_\_  
   Recorded jump height: \_\_\_\_\_  
   Net jump height: \_\_\_\_\_

### **Data Analysis and Questions:**

1. A shot putter releases the shot at a vertical velocity of 10.19 m/s and a horizontal velocity of 8.55 m/s from a height of 2.20 m.
  - a. Draw a free body diagram of the shot at release.
  - b. Calculate the resultant velocity of the shot at release.
  - c. Determine the angle of takeoff of the shot.
  - d. Calculate the time required for the shot to reach the apex of its flight.
  - e. Calculate the height of the shot at the apex.
  - f. Calculate the displacement of the shot from take-off to apex in the horizontal direction.
  - g. Calculate the total time the shot is in the air.
  - h. Calculate the total horizontal displacement of the shot put in the air.
  
2. If an object projected into the air lands at a lower height than that at which it takes off (such as throwing a ball), what may be said about its:
  - a. time up vs. time down
  - b. horizontal velocity and vertical velocity
  - c. horizontal acceleration during the impact phase when it hits the ground and comes to a stop
  - d. vertical acceleration during the impact phase when it hits the ground and comes to a stop

## Introduction to Biomechanics

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3. A high jumper leaves the ground with a resultant velocity of 4.0 m/s at an angle of 35° from the right horizontal. What was her vertical velocity at takeoff? What was the horizontal and vertical position of her center of gravity at the top of the jump?
4. Explain why the vertical position of the total body center of mass at takeoff may be different than at landing for a long jump.
5. Download the file <GRFmovements.pdf> from the lab website. Using those ground reaction force curves, complete the following chart for the time periods indicated on the GRF record. Movements 1 and 2 have already been done. Movements 1-8 correspond to the movements performed during the lab.

Movement	Change in CM Position	GRF vs. Weight (Net Force)	Acceleration	Change in speed	Direction
1-A	Up	GRF > W	Positive	Increase	Upward
B	Up	GRF < W	Negative	Decrease	Upward
2-A	Down	GRF < W	Negative	Increase	Downward
B	Down	GRF > W	Positive	Decrease	Downward
3-A					
B					
4-A					
B					
5-A					
B					
6-A					
B					
7-A					
8-A					
B					
C					
D					
E					
F					
G					
H					

6. Compare movements 1 and 2 with movements 3 and 4. Clearly, the latter two movements show greater fluctuations in the vertical ground reaction force. Briefly explain why. (Remember  $\Sigma F = ma$ )
7. Label your force vs. time graphs as follows and include the graphs in your post lab.
  - Label the following intervals on each of your vertical jump graphs:
    - a. BW = body weight when the subject is quietly standing
    - b. UW = unweighting (your tracing may not contain this event.)
    - c. W = weighting
  - Label the following events on each of your vertical jump graphs:
    - d. a = peak force before takeoff
    - e. b = takeoff
    - f. c = duration of flight
    - g. d = landing

8. Using the scaling at the bottom of the graph, calculate the flight time for the squat jump and the countermovement jump and compare these values to those recorded from the 30 Hz camera.
9. Draw the free body diagrams and the mass acceleration diagrams of the person during the unweighting phase, the weighting phase, and the flight phase (3 FBD's and 3 MAD's). Based on these drawings, write out the complete impulse-momentum equations (horizontal and vertical).
10. Using the box counting method, calculate the positive, negative, and net vertical impulse generated during the squat jump and countermovement jump. Place these values in a table and include the table in the lab report.
11. Using the impulse-momentum relationship and projectile motion equations, calculate the maximum height for the squat jump and the countermovement jump.
12. Calculate the jump height using the flight time calculated from the movie clips on the website (knowing that the video is recorded at 30Hz). Discuss the differences or similarities in this jump height versus the one you calculated using the impulse-momentum relationship.
13. Discuss the differences in your force-time curves for the vertical jumps with and without countermovement. Discuss the difference in jump height for the two conditions. If there is any difference, explain why?