<u>Walk or Waddle?</u>

Caroline Jiang - 78744992
Hayley Shen – 77486001
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INTRODUCTION

Griffin and Kram (2000) found that penguins waddle because it is more energetically efficient than walking. Although humans are obviously different from penguins both anatomically and physiologically, a waddling gait can also be observed in certain types of humans. Instead of walking, as most people do, pregnant women, and excessively overweight individuals tend to waddle. This study investigates the energetic requirements of waddling as compared to walking under two different conditions: overweight, and normal weight. We hypothesize that the total energy cost (work) of waddling is less than the total energy cost of walking for "obese" or pregnant people. The opposite is true for those who are within the "normal" weight range.

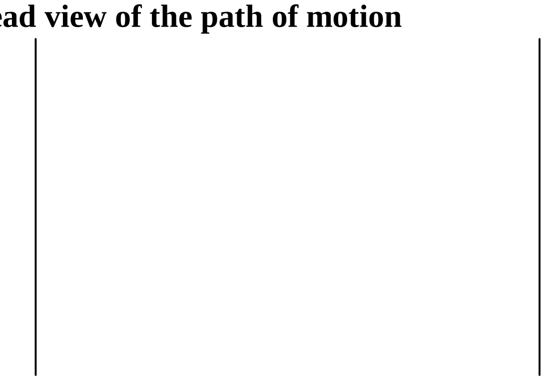
BACKGROUND INFO

This study makes comparisons between two types of gait: walking and waddling. The definitions of walking and waddling may be variable, however, for the purposes of this study, walking and waddling are defined as follows:

Walking: the translation of center of mass through space by lifting and settling down each foot in turn, never having both feet off the ground at once. Locomotion is principally in a straight line, with minimal lateral swaying of the body (Figure 1a).

Waddling: the translation of center of mass through space by means of short steps and a lateral swaying motion. The main motion in waddling is a side-to-side movement, and although net motion is in a forward direction, this is achieved less directly than with walking, in a zigzag-like fashion (Figure 1b). The swaying motion creates a greater shift in the center of gravity than walking and thus, is expected to increase the energy requirement for this activity. Our study challenges this expectation.

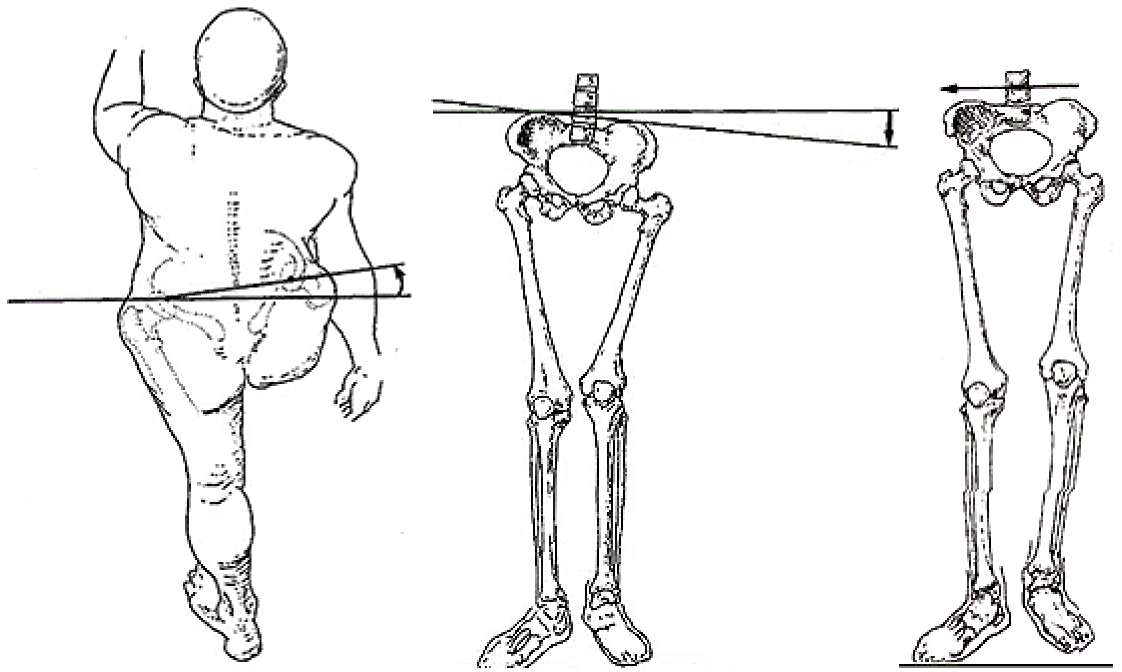
Figure 1. Overhead view of the path of motion



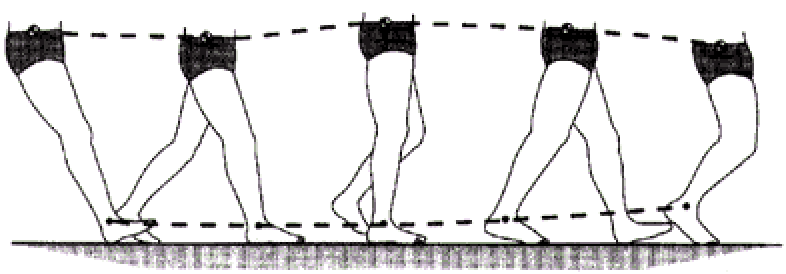
(a) walking (b) waddling

According to Ayappa (1997), six distinct motions of the body regulate the way a person walks; these motions are called the six determinants of gait. The six determinants are: pelvic rotation; pelvic tilt; knee flexion at mid-stance; foot and ankle motion; knee motion; and lateral pelvic displacement (Figure 2a-e). Variations in these motions together affect energy expenditure and the mechanical efficiency of walking. Generally, these motions function to minimize the movement of the center of gravity.

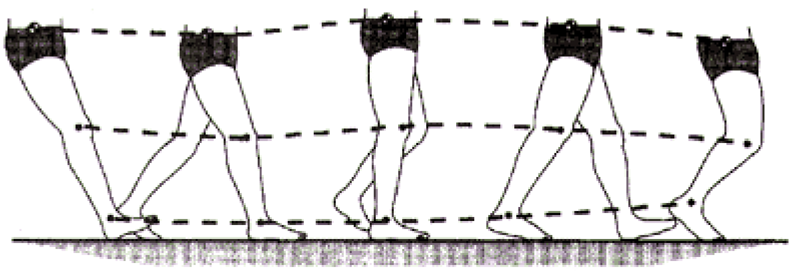
Figure 2. Determinants of gait.



(a) pelvic rotation (b) pelvic tilt (c) lateral displacement



(d) foot and ankle motion



(e) knee motion

The center of gravity, or center of mass can be defined as the point in the body through which a single downward force equal to the weight of the body may be considered to act. Donaldson (1979) suggests that the center of mass in humans is located between 55 to 57 percent of the total standing height from the ground. Thus, in most people, the center of mass in humans should lie in the region of the hips. We used this assumption in our calculations for method I (*see below*), using the total weight of the body applied by the center of gravity, rather than using the weight of only a part of the body (such as the weight of the pelvic girdle).

The Body Mass Index (BMI) is a measure of body fat based on height and weight that applies to both adult men and women. To calculate BMI, divide weight over the square of height. The value obtained from this calculation is then categorized into a numerical scale. A BMI less than 18.5 means one is underweight. The normal weight range is between 18.5-24.9. A BMI value from 25 to 29.9 is considered to be overweight, and a BMI value greater than or equal to 30 is classified as obese. For this study, a female of normal weight is observed. Her weight is then manipulated to become such that is classified as obese, and observations are again taken for comparison.

METHODS

To compare walking and waddling, two different methods are applied and the results are subsequently compared. The first method is a component analysis, which involves calculating energy expenditure for individual determinants of gait. The second method is a theoretical analysis where calculations are based on an inverted pendulum model.

I. Component Analysis:

Two conditions were set up for the analysis. We studied one female subject who was within the "normal" BMI range. The subject was instructed to first walk, and then waddle in the manner previously described. After appropriate analysis, the six motions defined as the six determinants of gait were recorded on video and paused on a television screen so that distances could be measured. Before the measurements were taken, the subject was allowed to walk and waddle for a brief period so that she could get accustomed to the motion. It was noted that fours walking steps were roughly equivalent to ten waddle steps, both spanning a distance of 1 meter.

Under a second experimental condition, the subject was asked to carry additional weights around her midsection. It was calculated that an additional 25 kg of weights would alter the BMI value for our experimental subject so that she fell into the obese category. The weights were put in a backpack carried in a backward fashion so that the pack was actually positioned in front of the body, similar to that of what a pregnant woman may experience. Waist straps on the backpacks were also used so that the weight was more evenly distributed around the subject's centre of mass. While carrying this additional weight, the subject was again instructed to first walk and then waddle. As soon as she was comfortable performing the motions, and the steps were relatively consistent, the activity was recorded on video, and measurements were taken from a television screen.

By calculating the work [J] required to perform the above actions, we can add up the values for each motion to determine the energy requirement for walking and waddling respectively. In the following equation, the subscripts pr, pt, fa, and lp resepectively correspond to pelvic rotation, pelvic tilt, foot and ankle motion, and lateral pelvic motion:

$$\mathbf{W_{total} = W_{pr} + W_{pt} + W_{fa} + W_{lp}}$$

Knee motion and knee flexion were not included in the total amount of work because the bending of the knee is also neglected in the simplified pendulum model; the second method used in this study.

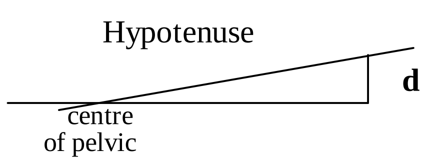
1. Force [N] = mass [kg] x gravity [m/s^2]
2. Work [J] = force [N] x distance [m].

For Equation 1, the mass used was the mass of the subject. This calculated force was then substituted into Equation 2. For Equation 2, the distance was the distance of motion measured in pelvic tilt, pelvic rotation, and lateral pelvic rotation.

Although the total work is a sum of components, which involved only segments of body, the whole body mass, not just the upper body mass, is used in calculating the partial work. This is based under the assumption that movement of the whole body is involved although we are examining only a part of the motion. As mentioned above, the center of mass is the point, usually found in the pelvic region, at which the weight of the entire body is applied.

The distances for work associated with the pelvis is obtained as the length of the opposite side of a right angled triangle (Figure 4). The right-angled triangle is constructed with one line drawn from the center of the pelvis as the adjacent line of a right angle triangle. The hypotenuse is drawn from the center of pelvis to the peak point of each cycle of pelvic movement. The distance is an average value from four peak points for walking and ten peak points for waddling.

Figure 4. Distance of pelvic work calculation



The work required for foot and ankle motion was measured by using Equation 3.

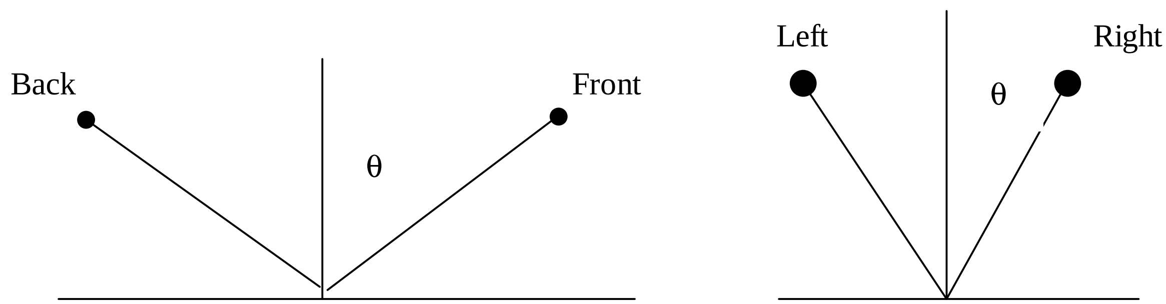
3. **Tension/Force [N] =** $\mathbf{\dfrac{mass\ [kg] \times gravity\ [m/s^2] \times distance_1\ [m]}{distance_2\ [m]}}$

The distance (d_1) for ankle and foot motion was an average obtained from the height of heel lift. Distance (d_2) is the length of foot area that force is exerted on.

II. Inverted Pendulum Model:

The human legs are assumed to be cone-shaped when using the inverted pendulum model (Figure 5). The force, also known as the torque, of the pendulum is given by the equation $\tau = mg\sin\theta$. θ is the angle between the line of center of mass and a line going through the end point of the swing. For walking, θ is assumed to be 40^o for every half of a step, with θ moving in an anterior posterior orientation. For wadding, θ is assumed to be 20^o for every half step, and this motion is taken as a lateral side to side motion.

Figure 5. Inverted Pendulum model of gait

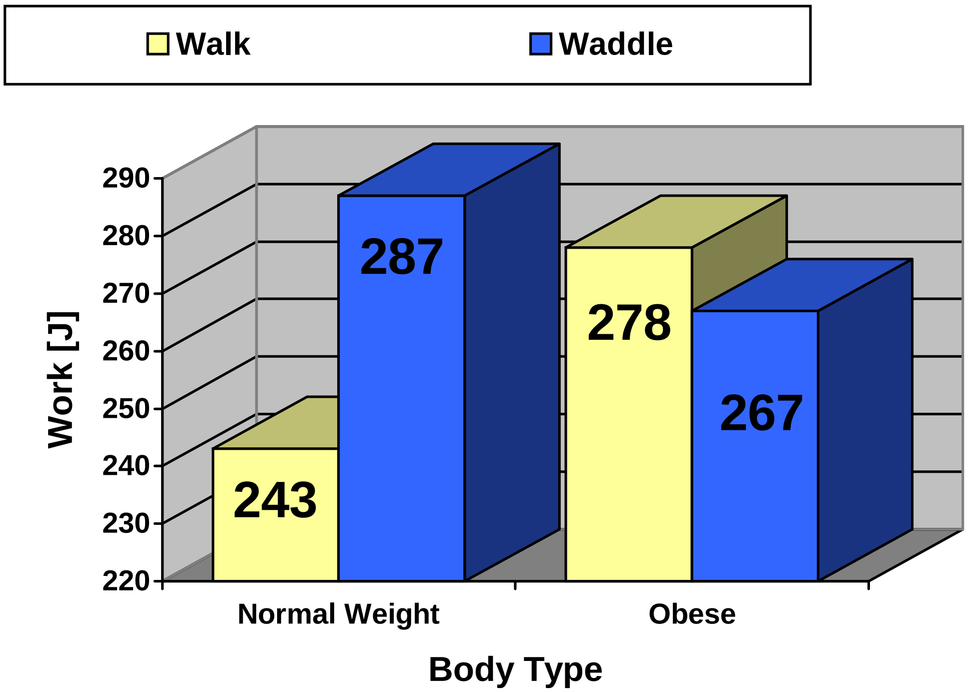


a) walking b) waddling

RESULTS

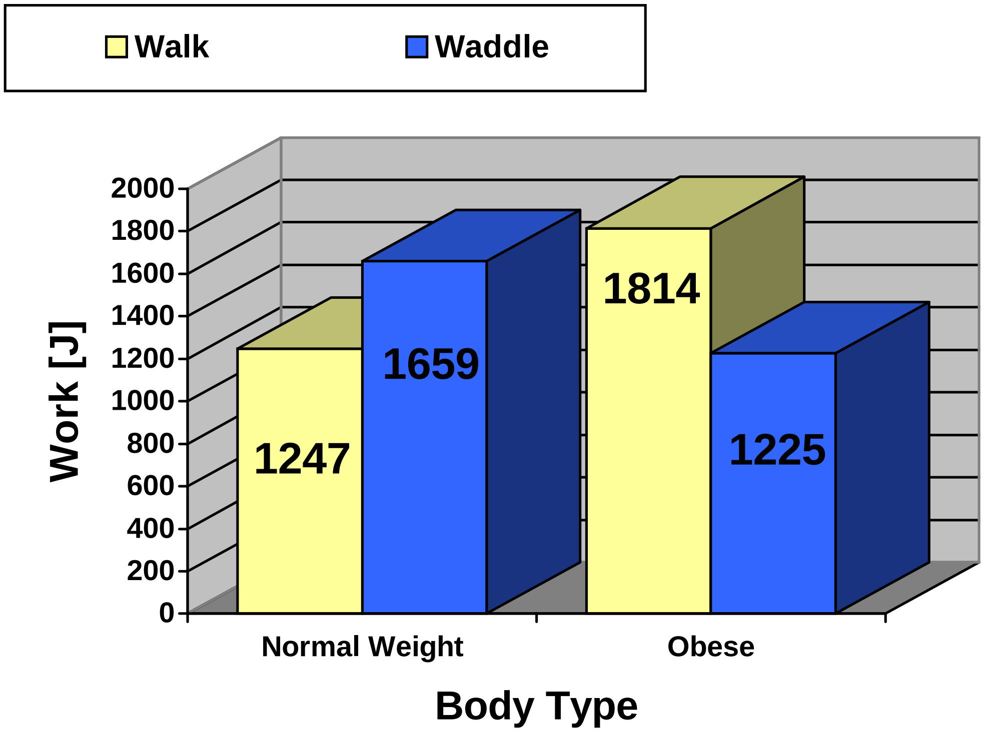
Calculations according to the component analysis for our female subject shows that the greatest total work required is for a normal weight individual waddling (287 joules). The second highest work required is for the obese walking condition (267 joules). Third is the energy requirement for the obese walking condition (278 joules), and the lowest work requirement was found for the normal weight walking condition (243 joules).

Figure 3 - Component Analysis: W_{total} required for walking / waddling



Calculations according to method II, the inverted pendulum model showed that the obese walking condition required the most energy (1814 joules). Next was the normal weight waddling condition which required 1659 joules. The third highest requirement was the normal weight walking condition (1247 joules) and finally the least energy costly condition was the obese waddling condition, calculated to be 1225 joules.

Figure 4 - Inverted Pendulum Model: Work Required to Walk and Waddle



Sample Calculations

I. W = F x d F = mg m = 55kg $g = 9.8 m/s^2$

$F = 55kg \times 9.8\ m/s^2 = 539N$ Wpr = 539 x 0.01m = 5.39J

Wtotal = Wpr + Wpt + Wfa + Wlp + Wkm + Wkf

Wkm & W kf are neglected as knee is assumed straight

Wtotal = 243 J

II. Work [J] = $\tau = mg\sin\Theta$ h= 0.9m $\Theta = 40^o$

$W = 55kg \times 9.8\ m/s^2 \times 0.90m \times \sin 40^o = 311.8J$

4 steps needed for 1m of distance when 0.25m per step

311.8J x 4 = 1247J

DISCUSSION

The trend in our walking results (243 joules for normal weight, and 278 joules for obese weight) from component analysis is in accordance with the results from inverted pendulum model (1247 joules for normal weight, and 1814 joules for obese weight). For both methods of analysis, the walking subject in the normal condition performs less work than the person in the obese condition. These values were expected, since when mass is increased, so does the expected work accomplished.

The values obtained for our waddling results in both component analysis (287 joules for normal weight, and 267 joules for obese weight) and in the inverted pendulum analysis (1659 joules for normal weight, and 1225 joules for obese weight) also support the hypothesis. Less energy is required to waddle when a person is obese as compared to normal weight. This follows our theory that obese people waddle because it is energetically favourable whereas people of normal weight do not because it is not advantageous to do so.

Though the difference in waddling energy between the obese and normal condition in the component analysis is not significantly large (20 joules), the result is still noteworthy because they are only the values are calculated from the sum of slight variations in movements of parts of body.

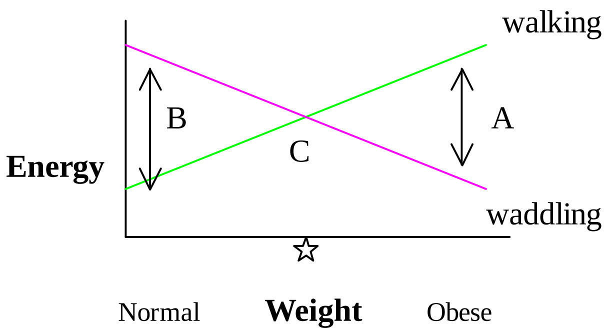
Although our results support our hypothesis, this data is somewhat remarkable. Much like the penguin study conducted by Griffin and Kram (2000), it is unexpected that waddling would be energetically favorable over walking. Theoretically, waddling is a motion which involves exaggerated displacement of the center of gravity and thus should require more energy. The six motions making up the determinants of gait are meant to minimize the shifting of the center of mass. Perhaps we oversimplified our analysis by omitting the knee motion from our calculations. However, this omission made so that comparisons to the simplified inverted pendulum model would be more parallel (the pendulum model assumes that there is no knee motion, and the leg is a straight cone or rod).

According to the pendulum model analysis, our findings make sense. The lateral motion of the pendulum seen with waddling is only 20 degrees compared to the anterior-posterior motion of the pendulum for walking which is modeled at 40 degrees.

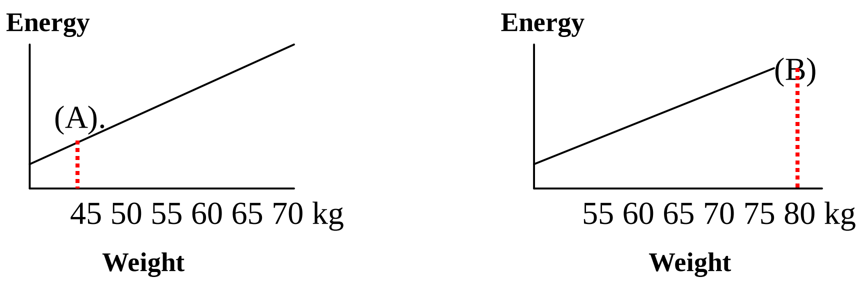
Despite the similar trends that support our hypothesis, there is also a discrepancy found between the two analyses. Our results in both methods show that it is energetically cheaper to walk/waddle under the obese condition compared to the normal weight condition. Logically, one would expect an obese person to require more energy than a thinner person to perform any given activity. Our findings in the data could be due to experimental error in measurements in the component analysis. Perhaps some factors were neglected such as distribution of weight around the body as a whole. We assumed that the increase in mass represented by the subject carrying a heavy pack would be a fair representation of weight gain. However, adipose tissue is usually more evenly distributed around the entire body although much if it rests in the abdominal area. As well, using a backpack may have further distorted our findings by causing slight shoulder discomfort, thus altering balance and gait in our experimental subject.

As seem in Figure 5, when a line is drawn for walking energy versus weight, a linear increase is seen whereas a linear decrease is seen drawn for waddling energy versus weight. It was suggested that there could be a point where two lines cross, which could mean a weight (☆), that is okay to either walk or waddle.

Figure 5. Energy versus weight



Thus, we took the walking energy of obese minus the waddling energy of obese and got line A. We took the waddling energy of normal minus the walking energy of normal and got Line B. The values of two lines were divided by half to obtain the medium energy requirement, point C. By averaging out A and B we obtain the more precise point C where two lines intersect, and thus the corresponding weight. But this is not a plausible weight for same energy requirement of both waddling and walking because the energy values of a single step for each walking and waddling were multiplied by the total number of steps required to reach a distance of one meter. Walking energy per step was multiplied by four whereas waddling energy per step was multiplied by ten. Supposed that point C was divided by ten, point (A) for walking to gain per step energy and divided by four to gain per step energy for waddling, point (B), the weight value that contributes those specific energy do not overlap (Figure 6).



The two lines are actually parallel thus it is impossible to find a weight that waddling and walking needs same energy when the height is the same.

CONCLUSIONS

Our hypothesis that waddling requires less energy than walking for a person with obese BMI is supported by the results of this study. Our results also show that walking requires less energy than waddling for a person with normal BMI.

Our study used highly simplified models to analyze components of walking which is a fairly complex procedure involving numerous bones and muscles of the body. Since our findings are preliminary, further studies can be conducted in a more detailed fashion. Perhaps future studies could put more focus on knee movements, which are also important to stabilizing the center of gravity. Future studies can also analyze the effect of distribution of mass on the body and how that affects the way a person walks. Finally, we only had one test subject who was a female. More test subjects would provide more data and reduce statistical uncertainty. There may also be variations between male and female subjects.

The significance of this study lies on the basis that it is a starting point in the study of a question that has not yet been thoroughly investigated. The implications of this study will remind people that if they feel that they tend to waddle instead of walk, they will realize that they are probably unhealthy and overweight (except in the case of pregnant women). This study may also have implications lying within the development and marketing of health-oriented equipment. For example, if we develop a better understanding of waddling and the energetic costs, perhaps this can lead to the development of shoes that provide extra support for waddling, or clothing that is more movement friendly and comfortable for this type of gait.

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APPENDIX

I. Component Analysis

Fnormal = mg = 55kg x 9.8m/s^2 = 539 N

Fobese = 80kg x 9.8m/s^2 = 784 N

Energy [J] = work = Force x distance

Component		**Normal**		**Obese**	
		Walking	**Waddling**	**Walking**	**Waddling**
Pelvic rotation	**Distanc (m)**	0.01	0.04	0.03	0.02
	Energy (J)	5.39	21.56	23.52	15.68
Pelvic tilt	**Distanc(m)**	0.01	0.02	0.005	0.03
	Energy(J)	5.39	10.78	3.92	23.52
Foot & Angle motion	**Distanc(m)**	0.07	0.06	0.05	0.04
	Energy(J)	226.38	194.04	235.2	188.16
Lateral pelvic displacement	**Distanc(m)**	0.01	0.03	0.02	0.05
	Energy(J)	5.39	16.17	15.68	39.2

II. Inverted Pendulum Model

Work = mghsin θ

	Normal		**Obese**	
	Walking	**Waddling**	**Walking**	**Waddling**
Mass [N]	539		784	
Height = 0.9m				
sin θ	40	20	40	20
Work [J] per step	311.8	165.9	453.5	122.53
Work [J]over 1m	1247.32	1659	1814.2	1225.3