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The Effects of Body Mass Index BMI on Human Gait Analysis

Sadiq J. Abass, Jaffar N. Jaffar, Muthanna M. Ghazi

Department of Biomedical Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq.
Department of Pathology, College of Medicine, Baghdad University, Baghdad, Iraq.
Department of Biomedical Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq.
Corresponding Author:Sadiq J. Abass

--ABSTRACT--

Due to the increasing obesity rate, it is crucial to investigate repetitive loading consequences at the lower extremity. The aim of this study was to identify possible relationship between body mass index and gait parameters.60 male adults with good health were recruited for this study. Two-dimensional gait system of a synchronized 60 Hz camera with an AMTI force platform were used for measuring gait kinematics and kinetics while walking at a self-selectedspeed. Compared to normal weight participants, overweight and obese subjects showed decreased stride length and reduced walking speed with inverse weak significant correlation with body mass index. Allthe participants walked with similar joint angular displacements regardless of their weight status. The ground reaction forces with the exception of the maximum lateral force, were all increased as body mass index increased. The joint moments and powers at the hip, knee and ankle joints were shown to have significant correlation with body mass index with the exception of maximum hip flexor moments and the maximum negative hip and knee powers. These results suggest that obese subjects, and to a lesser extent overweight subjects, have a higher risk for musculoskeletal disease formation because of the high moments and powers at their joints resulted from the increased ground reaction forces.

Keywords: *Body mass index, Gait analysis, Kinematic, Kinetic, Obesity.*

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I. Introduction

Obesity can be defined as the condition in which excessive or abnormal body fat had accumulated in the adipose tissue. It is recognized as a serious health problem in many countries and its incidence is rapidly increasing at an alarming rate classifying it as global epidemic disease. Generally, a person of a body mass index (BMI) higher than 30 $kg/m^2$is considered as an obese. Globally, there were greater than 300 million adult obese individuals and greater than 115 million individuals suffering from problems related to obesity [1]. These problems include hypertension, diabetes, heart diseases, respiratory diseases, cancers, and musculoskeletal disorders, particularly at the lower extremities such as osteoarthritis, which are the most common [2].

Relative to the extensive knowledge of many aspects of obesity conditions, there is a few information regarding to the functional restrictions imposed by overweight and obesity on human gait. Human gait is a biomechanical process that involves a complex interaction between inertial and muscular forces which results in smooth progression of the body throughout space while minimizing energy expenditure. It is an essential locomotor task which involves a complex interrelationship of neuromuscular, genetic and environmental factors.

Persistent obesity implications on the musculoskeletal and locomotor systems are poorly understood. Most of the studies concerning locomotor tasks have been done predominantly on normal weight subjects and obese subjects, particularly those without any physical disabilities resulted from obesity, and these studies focused on spatiotemporal characteristics of gait, plantar pressures of the feet, obesity influence on muscular strength, and the possible relationships between postural control and obesity [3].Walking gait main determinant is energy consumption optimization which is responsible for the fine tuning of characteristics of gait [4], however, in the locomotory movements control, there is a margin of a flexibility that allows the adaptation of internally generated neuromuscular patterns to mechanical constrains such as body weight, external mechanical load and supportive surfaces [5].

Because of the overloading on the musculoskeletal structures, obesity has a well-known association with orthopedic problems. Several Studies have shown differences in plantar pressure [6], foot structures [7], and foot mechanics in obese individuals compared with normal weight individuals [8]. Other studies have revealed a strong link between body mass index and osteoarthritis [9][10]. Collectively, these studies showed that obese individuals are more likely to suffer from musculoskeletal pain and disorders. Scientific observations also showed beneficial effects of a moderate loss of weight on knee pain and mobility and on the occurrences of joint surgeries associated with osteoarthritis [11].Regardless, few studies investigated the potential modifications in gait associated with obesity. Some studies in obese adult subjects have reported changes in spatiotemporal parameters such as cadence, walking speed, stride length, and the stance and swing phases duration. Differences in kinematic parameters also have been reported which included higher magnitude of dorsiflexion and lesser in plantar flexion magnitude in ankle motion for the obese individuals when compared with the normal weight counterparts [12].

Other researchers reported that obese adult subjects walked with a more erect posture with a substantially more plantar flexion at the ankle joint and less knee and hip joints flexion. They also showed that normal weight and obese individuals possessed similar knee joint moments and powers, whereas in the ankle joint, plantar flexor moment and the related power were increased significantly in the obese group [13].As such, it was hypothesized that joint moments and powers at the hip, knee and ankle joints increase as body mass index continue to increase until reaching a specific critical magnitude of obesity, as estimated with body mass index, above which obese individuals make behavioral adaptations in their walking gait biomechanics. These behavioral adaptations were thought to enable obese subjects to modulate their hip and knee moments and powers to values exhibited by normal weight subjects despite the excessive body mass they have while simultaneously increasing the moments and powers at their ankle joint [14].

Long lasting mechanical loads (due to excess body weight) are usually countered by different compensatory and adaptive strategies in gait biomechanics. Behaviors that are displayed in the walking gait might give a quantification of the differences in the gait between obese, overweight and normal weight subjects. The aims of this research were to investigate the potential effects of overweight and obesity and their impact on gait characteristics of the lower extremities, identify possible relationship between body mass index and the kinetic and kinematic of gait and to document the dynamic aspect of the overweight and obese individuals. These aims are accomplished through the comparison of kinematic, kinetic and spatiotemporal (general) parameters in normal weight, overweight and obese individuals.

II. Methodology

2.1 Spatiotemporal Parameters

Distance and temporal factors associated with the gait analysis represent the general gait parameters also known as the spatiotemporal parameters which include cadence (stride frequency), stride length, walking speed, stance and swing phases' periods. Calculations of the general gait parameters from the recorded video of the subject's walking trail are executed by measuring the distance between two points representing the initial contact of one foot of the subject. Some extra space was given before the first point and after the second one so as to ensure that the subject is walking at a constant self-selected speed and to get rid of acceleration and deceleration that take place during walking. After that, the period of time for passing over the distance between the two points was measured. Both of the distance and the time period mentioned earlier were measured using Kenova application. Then, the number of steps taken in that period was counted. Finally, the equations below are used for the calculation of the general gait parameters as follow [15]:

Cadence (steps/min) = steps counted x (60/time (s)) … (1)

Stride length (m) = distance (m) x (2/steps counted) … (2)

Speed (m/s) = distance (m) / time (s) … (3)

Stride frequency (Hz) = cadence (steps/min) / (2x60) … (4)

2.2 Kinematic Data

The measurements of joint position, which is used for computing the joint angular displacement (joints relative angles), are obtained from the two dimensions motion analysis system. The joint positions are converted into joint absolute angles using the tangent function as shown in Figure 2-1. The general equations for measuring the absolute angle is [15]:

$$\theta_{i\,j} = \text{tan-1}\left(\frac{Y_j - Y_i}{X_j - X_i}\right) \quad \ldots(5)$$

The relative angles were determined as followed [49]:

Ankle angle (θ_a) = θ_{54} - θ_{43} – 90 … (6)

Knee angle (θ_k) = θ_{32} - θ_{43} … (7)

Hip angle (θ_h) = θ_{32}- θ_{21} … (8)

The angular acceleration vector ($\vec{\alpha}$), the angular velocity vector ($\vec{\omega}$) and the linear acceleration vector ($\overrightarrow{\alpha_x}$,$\overrightarrow{\alpha_y}$) at center of mass of the lower limb segments (thigh, shank and foot) are needed for the inverse dynamic calculations. For acquiring these quantities, numerical differentiation using five point central difference formulae is used[16]:

$$\dot{y}_k = \frac{-y_{k+2} + 8\,y_{k+1} - 8\,y_{k-1} + y_{k-2}}{12/f_s} \quad \ldots (9)$$

$$\ddot{y}_k = \frac{-y_{k+2} + 16\,y_{k+1} - 30\,y_k + 16\,y_{k-1} - y_{k-2}}{12/{f_s}^{12}} \quad \ldots (10)$$

Where:
k = a point index.
f_s = the sampling frequency.
$\dot{y}$ = the first derivative of the filtered gait data.
$\ddot{y}_k$ = the second derivative of the filtered gait data.

The center of mass location (X_{cg}, Y_{cg}) of each segment is estimated from the (x,y) marker coordinates (joints positions data) from the equations [15]:

$$X_{cg} = X_{proximal} + R_{proximal}\left(X_{distal} - X_{proximal}\right) \quad \ldots(11)$$

$$Y_{cg} = Y_{proximal} + R_{proximal}\left(Y_{distal} - Y_{proximal}\right) \quad \ldots(12)$$

Where:
$R_{proximal}$ = the customary location of COM from the segment proximal end.

2.3 KINETIC DATA

The ground reaction forces with their center of pressure are obtained from the AMTI force platform. The force plate outputs are processed for bias removal using basic signal averaging for smoothing the signals utilizing MATLAB software. Inverse dynamic calculations are utilized for the estimation of the hip, knee and ankle joint moments. The calculations are started from the ankle joint, continuing up to the hip joint as can be seen in Figure 2-2.The ankle joint forces and moment are [15]:

$$F_{A_x} = m_f \,.\, a_{f_x} - F_{g_x} \quad \ldots (13)$$

$$F_{A_y} = m_f \,.\, a_{f_y} - F_{g_y} + m_f \,.\, \vec{g} \quad \ldots (14)$$

$$F_{ankle} = [F_{A_x}, F_{A_y}]$$

$$M_A = I_f \,.\, \alpha_f - \left[\overrightarrow{r_{ankle}} \times \overrightarrow{F_{ankle}}\right] - \left[\overrightarrow{r_{ground}} \times \overrightarrow{F_{ground}}\right] \quad \ldots (15)$$

Where:
$r_{ground} = [COP_{cg}, 0]$ of the foot segment.
$r_{ankle} = [X_{cg}, Y_{cg}]$ of the foot segment.
The net force and moment at the ankle proximal end causes reaction force and moment at the leg distal end in accordance with Newton’s third law. As such, the knee forces and moment:

$$F_{K_x} = m_s \,.\, a_{s_x} + F_{A_x} \quad \ldots (16)$$

$$F_{K_y} = m_s \,.\, a_{s_y} + F_{A_y} + m_s \,.\, \vec{g} \quad \ldots (17)$$

$$F_{knee} = [F_{K_x}, F_{K_y}]$$

$$M_K = I_s \,.\, \alpha_s + M_A - \left[\overrightarrow{r_{knee}} \times \overrightarrow{F_{knee}}\right] - \left[\overrightarrow{r_{ankle}} \times \overrightarrow{-F_{ankle}}\right] \quad \ldots (18)$$

Where:
$r_{knee} = [X_{cg}, Y_{cg}]$ of the shank segment.
The net force and moment at the knee proximal end also produces reaction force and moment at the thigh distal end. The hip forces and moment are:

$$F_{H_x} = m_t \,.\, a_{t_x} + F_{K_x} \quad \ldots (19)$$

$$F_{H_y} = m_t \,.\, a_{t_y} + F_{K_y} + m_t \,.\, \vec{g} \quad \ldots (20)$$

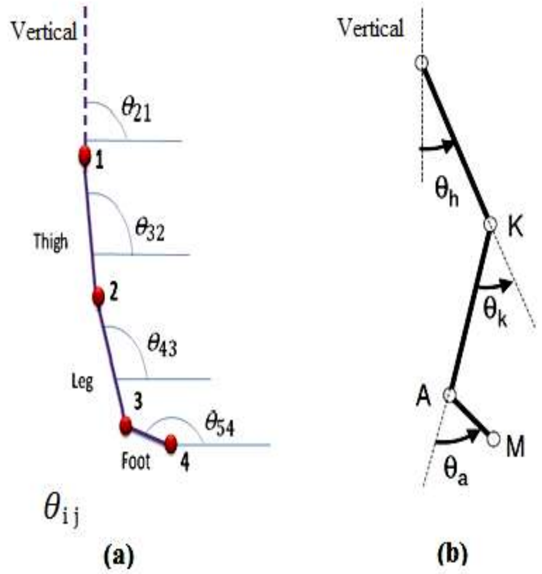
$$F_{Hip} = [F_{H_x}, F_{H_y}]$$

$$M_H = I_t \,.\, \alpha_t + M_K - \left[\overrightarrow{r_{Hip}} \times \overrightarrow{F_{Hip}}\right] - \left[\overrightarrow{r_{knee}} \times \overrightarrow{-F_{knee}}\right] \quad \ldots (21)$$

Where:
$r_{Hip} = [X_{cg}, Y_{cg}]$ of the thigh segment.
The mechanical power at each joint is estimated as follows:

$$P_j = M_j \,.\, \omega_j \quad \ldots (22)$$

Where:
M_j = the net muscle moment measured in N.m.
ω_j = the joint angular velocity measured in rad⁄s.



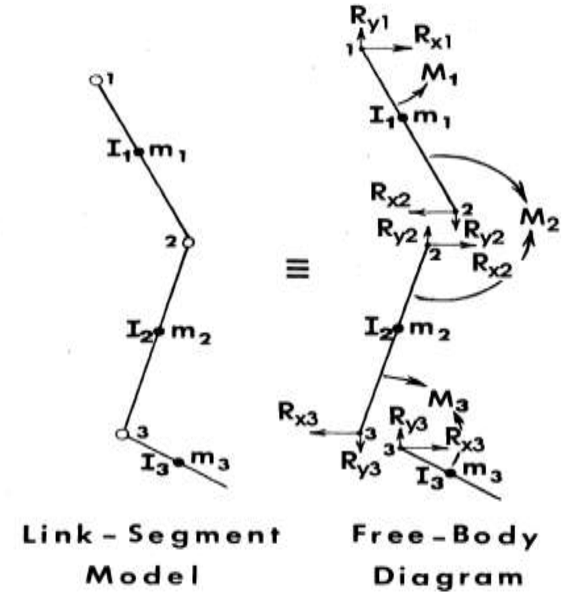


Figure 2-1: (a) Joints' absolute angles **Figure 2-2:** Lower limb model free body diagram [16].
(b) Joints' relative angles [15].

III. Participants Criteria

Twenty normal weight, overweight and obese individuals were recruited for this study. Theparticipating subjects were classified according to their body mass index to three categories as stated bythe world health organization criteria. Body mass index is a value used for quantifying the fatness of the human body and it is estimated bydividing body mass by the square of body height, it is expressed in unit of kg/m^{2}universally. The mean age (years), mass (kg), height (m) and body mass index (kg/m^2) of the participants subjects are illustrated in Table 3 for the normal weight, overweight and obese groups.

The body mass index for normal weight group is between 18.5 and 24.9 kg/m^2, between 25 and 29.9 kg/m^2 for the overweight group and equal to or more than 30 kg/m^2 for the obese group. Only male individuals were chosen to eliminate any possible differences in gait characteristics related to gender.

The participant individuals were administered a basic questionnaire of health history constricted to identify factors which could affect the participant gait. For example, lower limb recent injuries or having any disorder affecting balance and gait. The health history questionnaire also involved subjective questions such as whether the participants subjects have difficulty in walking in certain surfaces and if the subjects had any medications for the last past 48 hours before participating in the walking trials. In order for the subjects to participate in this research, they were required to be seemingly healthy with the exception of possessing high body mass index for the obese group. Participant subjects were excluded if they possessed any past or current neurological, musculoskeletal, neuromuscular, or physiological disabilities, cardiovascular or neurological illness, orthopaedic abnormality, gait problems or pain that might affect or interfere with their walking gait. Individuals who had previous surgeries in their lower limbs were also excluded from participating. Before talking the walking trials, the accepted individuals were informed about the details of the study.

Table 3: subjects' statistical data (mean±SD).

Subject's characteristics	Normal weight group	Overweight group	Obesegroup
Age (years)	24.8 ±4.8	25.3 ±4.5	26.7 ±4.7
Mass (kg)	69.4 ±5.8	85.6 ±7.5	107.7 ± 12.17
Height (m)	1.763 ± 0.046	1.742 ± 0.055	1.747 ± 0.067
BMI (kg/m2)	22.322 ± 1.850	28.164 ± 1.455	35.304 ± 3.566

IV. Experimental Work

After being screened for exclusion and inclusion criteria, body mass, height and body mass index were measured for the participant subjectsand they underwent gait analysis procedure. They walked bare footed at a self-selected speed on a 6 m wooden level walkway with AMTI force platform instrumented in it. In order to make the walking trial as normal as possible, each subject was allowed to practice and take as many as walking trials as the subject needed before the actual trials. This is done so as the subject will not be targeting the force platform resulting in abnormal ground reaction forces or walking with unusual patterns due to being present in atypical environment which is the gait laboratory. Walking trials in which the subject's right foot did not make a full contact with the force platformor the left foot made a contacted with forceplatform were discarded. Any walking trials in which the subjects made noticeable alteration to their walking gait were also discarded. While the subjects undergone the walking trials, their kinematic and kinetic gait parameters for the right lower extremity were estimated utilizing the available two dimensional gait analysis system which consisted of motion capture system and the AMTI force platform. The motion capture system consisted of 60 Hz camera placed perpendicular to the plane of the movement (sagittal plane) and used for recording the movement of seven skin surface passive markers positioned at anatomical references at the subjects lower limbs including the right great trochanter, the medial epicondyle and the lateral epicondyle, the lateral and medial malleoli and the head of the fifth metatarsal bone. Elastic stockinet was placed at the subject's knee in order to minimize the movement of marker. The marker movements were digitized into joint position data using Skillspectorsoftware as can be seen in Figure 4, which also shows a subject performing the walking trials and the marker positions.

The ground reaction forces and their center of pressure were measured using the force platform at 50 Hz. Synchronization of the kinematic and kinetic data were achievedusing resample function in MATLAB program for thereduction of the kinematic data to 50 Hz. For each walking trial, the gait analysisproduced spatiotemporal gaitparameters, kinematics and kinetics data of gait. The spatiotemporal parameters included stride length, walking speed, cadence, stance and swing time periods. The kinematics data included joint angular displacements while the kinetic data consisted of joint moments and joint powers at the hip joint, knee joint and ankle joints and the ground reaction forces. The spatiotemporal parameters were calculated form the measured walking distance, time period and the counted footsteps.Joint angular displacements were calculated using the tan function on joint positions acquired from the motion capture system. Relative joint angles were calculated using the difference of theangle between two adjacent segments. The GRFs were acquired from the force platform while net joints moments were estimatedusing the inverse dynamic calculations with the lower limb location of mass centers, segmentsof masses and moments of inertia being based on the data of De Leva[17].The obtained joint moments then used to compute the amount of mechanical power at the hip joint, knee joint and ankle joint by multiplying these joint moments by the corresponding angular velocities of the joints.Filtering and processing ofdata was completed using MATLAB program. Second order low pass digital Butterworth filter was used for filtering the data with cut-off frequency calculated for each subject by multiplying the stride frequency of the subject by six.Analyses of data were conducted using SPSS - v24 (Statistical Packages for Social Sciences - version 24). The meanvalues and the standard deviation valuesin this study were computed for the kinetic, kinematic,spatiotemporal and anthropometric measures. The relationships between body mass index with respect to maximum ground reaction forces, maximum hip,knee, and ankle joint angular displacements, moments and powers were analyzed using Pearson correlation and regression analyses. Significance was tested at probability (p) value ≤ 0.05.

Figure 4: Marker's positions being digitized during a subject walking trials.

V. Results and Discussion

The results consist of the general gait parameters (stride length, walking speed, cadence, stance and swing phases) and the kinematic and kinetic data of gait during a single gait cycle which includes the ground reaction forces on the foot, the angles, moments and powers at the hip, knee and ankle joints. Figures 5-1 to 5-6 show the hip joint's moments and powers for the three weight categories.

The data analysis showed that there were no significant correlations with body mass index and kinematics of the joints. Furthermore, Individuals from every weight category groups walked with a very similar joint angular displacement with mean maximum hip flexion angle of (25.14±3.581°), mean maximum knee flexion angle of (63.22±5.505°), and mean maximum dorsiflexion angle of(12.97 ± 3.727°). The cadence, stance and swing phase durations also showed no significant correlation with body mass index and individuals from the weight categories walked with similar mean values of cadence (103 ±7.526 step/min), stance phase (62.95 ±2.048 % gait cycle) and swing phase (37.05 ± 2.048 % gait cycle). However, the stride length and walking speed showed significant correlation with body mass index ($r = -0.362$, $p < 0.05$ for the walking speed and $r = -0.266$, $p < 0.01$ for the stride length) and they decrease as body mass index increases. All of the ground reaction forces presented a strong significant correlation with the body mass index (with p value less than 0.05) with exception of the maximum lateral force which is the most variable. Powers and moments at the hip joint, knee joint and ankle joint showed direct significant correlation with body mass index with the exception of maximum negative powers at the hip joint and knee joint and maximum hip flexor moment. The significant correlations between body mass index and the stride length and walking speed with body mass index are shown in Figures 5-7 and 5-8 while the ground reaction force components significant correlations with body mass index are shown in Figures5-9 to 5-12.

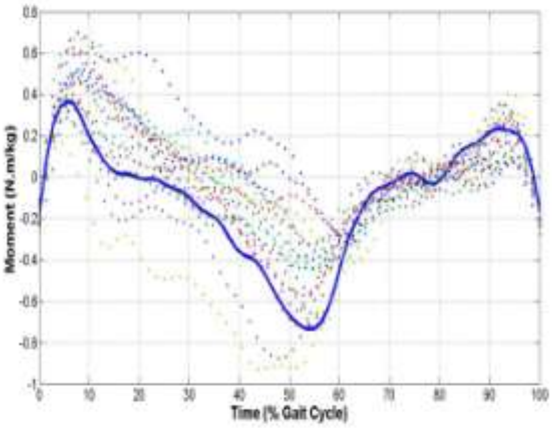


Figure 5-1: Hip joint moments of the sagittal plane during a gait cycle for normal weight subjects.

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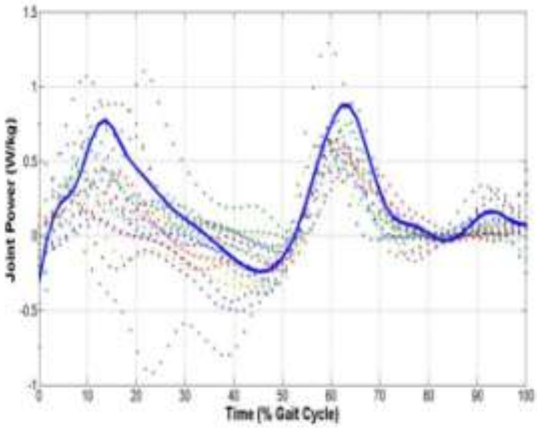

Figure 5-2: Hip jointpowers of thesagittal plane during a gait cycle for normal weight subjects.

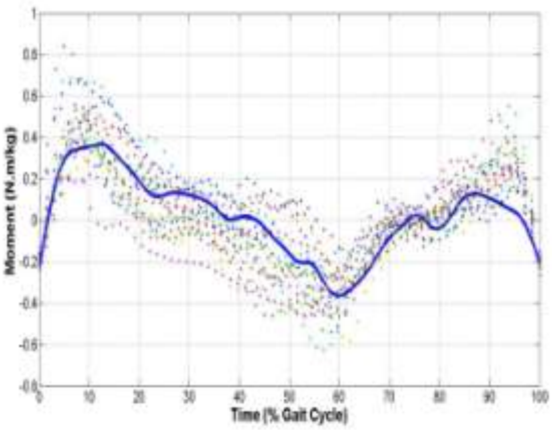

Figure 5-3: Hip joint moments of the sagittal plane during a gait cycle for overweight subjects.

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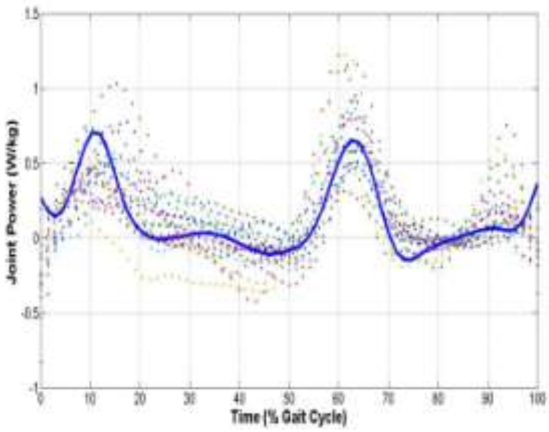

Figure 5-4: Hip jointpowers of thesagittal plane during a gait cycle for overweight subjects.

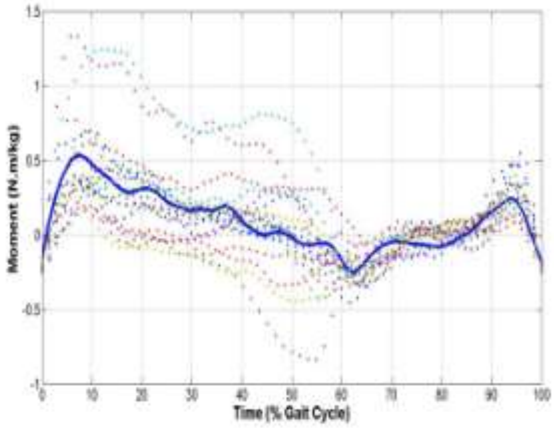

Figure 5-5: Hip joint moments of the sagittal plane during a gait cycle for obese subjects.

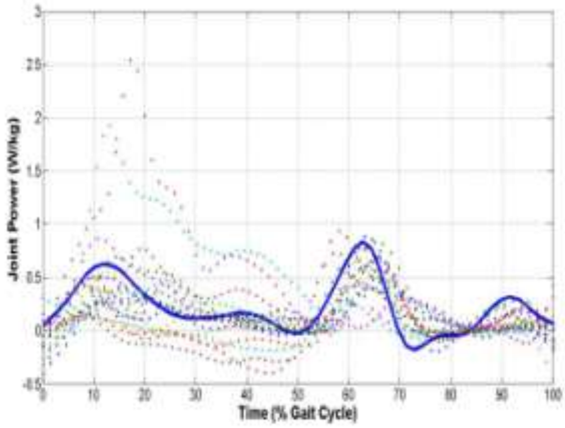

Figure 5-6: Hip joint powers of the sagittal plane during a gait cycle for obese subjects.

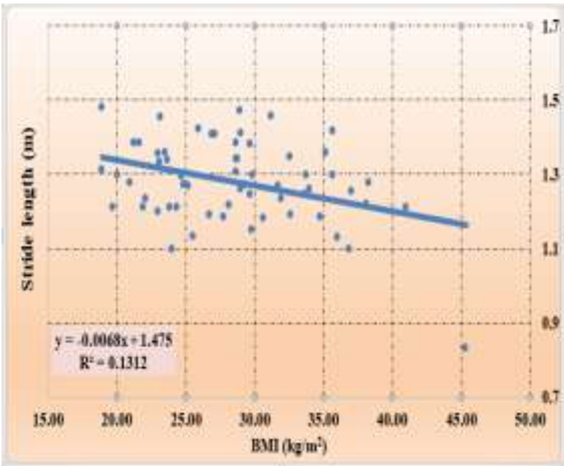

Figure 5-7: Scatter diagram showing significant correlation between BMI and stride length, $r = -0.362$, $p < 0.01$.

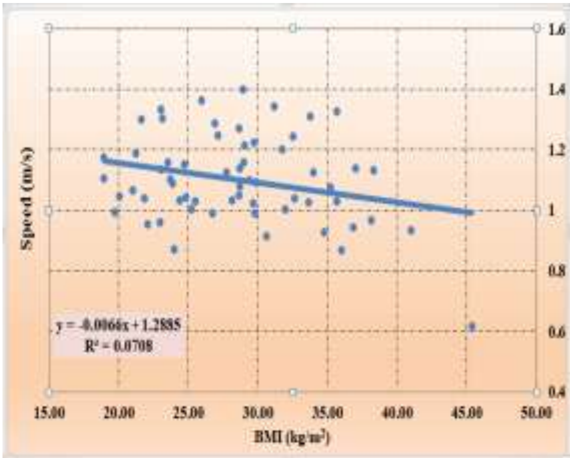

Figure 5-8: Scatter diagram showing significant correlation between BMI and walking speed, $r = -0.266$, $p < 0.05$.

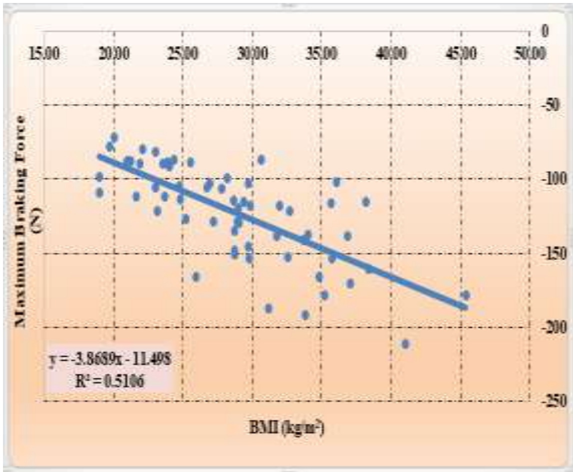

Figure 5-9: Scatter diagram showing significant correlation between BMI and maximum braking force, $r = -0.715$, $p < 0.01$.

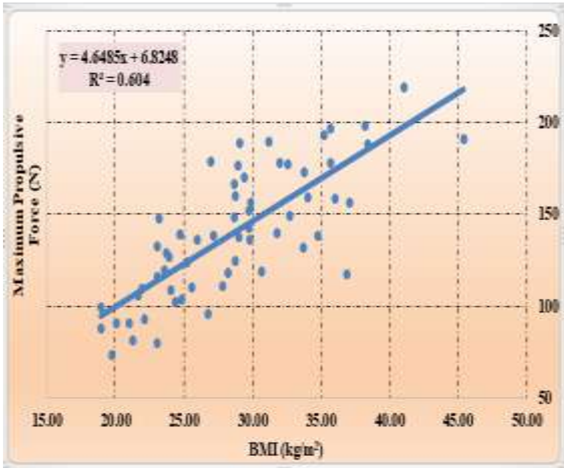

Figure 5-10: Scatter diagram showing significant correlation between BMI and maximum propulsive force, $r = 0.777$, $p < 0.01$.

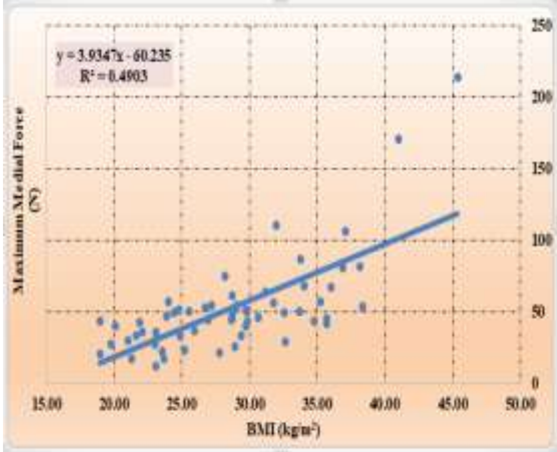

Figure 5-11: Scatter diagram showing significant correlation between BMI and maximum medial force, r = 0.700, p < 0.01.

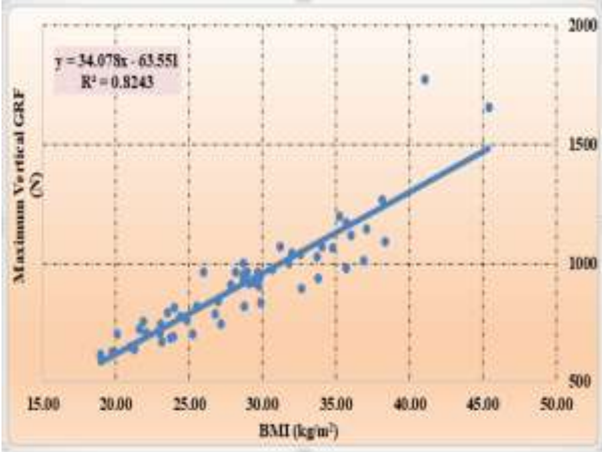

Figure 5-12: Scatter diagram showing significant correlation between BMI and first maximum vertical GRF, r = 0.908, p < 0.01

VI. Conclusion

The stride length and walking speed were found to have significant correlation (inverse weak correlation) with body mass index. The decrement in stride length and walking speed might be a sign of balancing problems associated with excess weight.No significant correlations were found between body mass index and the joints' angular displacement and allparticipant individuals walked with similar sagittal plane kinematics. Strong significant correlation was found between body mass index and the ground reaction forces with exception of the maximum lateral forcewhich is the most variable depending on foot placement. These ground reaction forces are directly proportional to the body mass and increased as direct response to body massindex increments leading to very high joint moments and powers.Significant correlations were also found between body mass index and joints' powers and moments with exception of maximum hip flexor moment, maximum negative hip and knee powers which had higher values in the obese subjects. These high joint moments and powers may increase the risk of developing musculoskeletal diseases at the obese subjects' joints due to walking with similar joint kinematics as the normal weight subjects.The body mass index mean valuewas 35.304kg/m^2 in this research, indicating that obese subject had a linear adaptation to body mass index in this range.

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