

BIOMECHANICAL ANALYSIS OF THE LOWER EXTREMITY DURING MANUAL LIFTING ACTIVITIES

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Abstract

Manual lifting activities involve lots of movement of the body and particularly the lower extremity. This study evaluated the biomechanical analysis of the human lower limb segments during manual lifting activities. The motion of the human lower limb in different cases is analysed, which provides a theoretical basis for motion dynamics. The lower limb segments are model as dynamic linkages with kinematics equations developed using inverse dynamics. Kinematic analysis of the human lower limb was done using the De Leva's ratio and the Dempster's Model. The hip, knee and foot segments were measured from the proximal end. Four (4) different positions were considered during manual lifting activities and the limbs on single and double supports. Kinematic analysis of the lower limb on double supports and single support indicated that the torques are highest at the hip joints at and lowest at the knee joint in flexion movement. The torques are 735.6 Nm and 13.69 Nm respectively. The angular accelerations are 3.28 rad/s, 6.21 rad/s, 7.46 rad/s for 58.65 kg, 77.82 kg and 93.18 kg respectively. This study concluded that more stresses are experienced when the lower limbs are not on double supports, that is, the two limbs on the ground or on the platform of support affirming that double-limb support helps to reduce the risk of tripping, falling and possible injuries to the body frame. It also helps in the total balance of the body frame. Similarly, for single supports, the leading leg performs negative work to redirect the center of mass velocity, while simultaneously, the trailing leg performs positive work to replace the lost energy. The trailing leg helps to balance the leading leg, hence, reducing the mechanical work done by the lower limb altogether.

Keywords: Biomechanical Analysis; Extension; Flexion; Link Segment Model; Lower Extremity

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Introduction

Human movement methods require the rotation of a body part around an axis that passes through the center of a joint; such movements are called angular movements (Tözeren, 2000). Increased injury risk was associated with work postures in restricted and awkward workplaces (Punnett and Wegman, 2004). Restricted and awkward postures arise when a worker's body size is out of proportion to the demands of their job. Stresses are primarily encountered in underground coal mines, warehousing, shipping, mining, maintenance etc. Anytime there is a high external load combined with inadequate movement patterns that results in a high internal stress on the spinal system, there is an increased chance of discomfort and injury. The trunk bends or twists due to an inefficient gait. It bends when lifting and reaching objects from low to high surfaces. Insufficient workspace is the main cause of the trunk's twisting. Severe trunk twisting and bending is associated with increased physiological and biomechanical costs as well as musculoskeletal problems. The connection between back and abdominal muscles in lifting activities has been established (Motomura et.al., 2021). Therefore, finding a solution to low back pain is important.

Biomechanics is the study of motion and its causes in living things which employs the application of the principles and technology of physics in the study of the living systems. (Fontanella and Carniel, 2023). The physical characteristics of biological materials, biological signals and their measurements, biomechanical modeling and simulation, and their applications are all included in this multidisciplinary subject. The musculoskeletal system is a series of simple machines. This aspect is essential when producing artificial limbs (Jadhav and Ram, 2017). Kinematics and kinetics are the two subfields of biomechanics. Kinematics is the study of motion. It begins with describing the system's geometry and its beginning conditions, known values for the location, speed, and acceleration of distinct points in the system. Geometrically, it determines any part of the system's position, velocity and acceleration. Kinetics deals with the relationship between motion and its causes, like forces and torque. Kinematic analysis techniques are considered promising for obtaining more precise and specific objective data to comprehend the impaired upper extremity motion of stroke patients when performing a movement. (Kim et al., 2013). The most frequent angular motions are flexion, extension, adduction, and abduction. A neutral posture occurs when a worker

needs minimum effort for standing or sitting, though all joints are aligned, and there is slight physical stress on bones, muscles, nerves, or tendons (Lowe, 2004). Grassi et al. (2020) identified no significant differences between flexion-extension movement. The extension refers to a movement that increases the angle between two body parts. Extension at the elbow is increasing the angle between the ulna and the humerus. Extension of the knee straightens the lower limb (Freivalds, 2011). Deficits in trunk extensor and flexor endurance and imbalances between trunk muscle groups may have short and long-term negative consequences on the low back (Gomes-Neto et al., 2017). Saito et al. (2022) identified that the knee flexion angle is significantly higher in the trunk-flexion position than in the other trunk positions. The knee angle is also significantly lower in the trunk-neutral and trunk-flexion positions than in the trunk-extension, trunk-right-lateral-flexion, and trunk-left-lateral flexion positions. Saito et al. 2022). Jadhav and Ram (2017) employed the Denavit and Hartenberg method (DH method) for the human upper limb's kinematical analysis and static torque calculation. All body segments are subjected to gravitational force. The joint tension or compression is equal to the body segment's weight when the body segment's centre of gravity is vertically aligned with a joint. A collection of linked segment models of the human body was introduced by Chaffin (2005) and can be used to calculate the forces and mechanical moments applied to the system while it is being used for work. Keir et al. (2021) explained that forceful exertions are strongly associated with hand/wrist tendon-related disorders.

Biomechanical modelling employs inverse dynamics techniques to compute kinetic and kinematic variables such as moment, ground reaction forces and accelerations (Chowdhury and Kumar, 2013). A suitable musculoskeletal model for studying human motion tasks should be sufficiently complex, comprehensive, three-dimensional (3D) and based on actual anatomy but, at the same time, reasonably efficient (Nikooyan et al., 2010). The dynamic measurement of these variables is challenging and may have errors. When a complete kinematic description and inertia attributes are known, it is possible to estimate ground reaction forces and moment of forces at lower limb joints. When linear and angular acceleration operates on the joints and muscles of the lower limbs, kinetic models characterise the forces and moments of those forces, including internal and external forces.

Methodology

The primary structures of the human locomotive (movement) system are the skeleton, the muscles, and the joints (Hase and Yamazaki, 2002). Combined structures allow the human body to move, withstand physical loading, and recover when the body's abilities have been exhausted (Berlin and Adams 2017). The mass of the body segment is calculated as a percentage of total body weight (Malakoutikhah, *et al.*, 2022).

The lower limb's link segment model consists of the Hip-Knee-Ankle segment model. It is a seven-link model comprising of the two legs, five active joints (hip, knee, and ankle of each limb) as shown in Figure 1. It indicates the lower limb link mechanism. The following assumptions are made:

1. Each link is rigid and has mass.
2. The angular positions, velocities, and accelerations are limited to human normal limits.
3. Each leg movements alternates on a flat and anti-skid surface.
4. The model is on simple support.

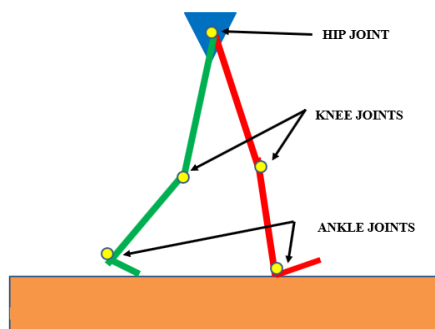


Figure 1. Lower limb link segment model

The lower limbs joints analyzed are the:

1. Hip joint
2. Two knee joints, and
3. Two ankle joints

There are five (5) active joints in the lower extremity considering the two legs as expressed in the Lower Limb Link Segment Model.

Determination of kinematic parameters

The sagittal plane was used for the analyses. The hip joint flexion/extension angle is the angle formed by the long axis of the thigh and the bottom extension of the Y-axis, both of which are projected in the sagittal plane. The knee joint angle is the angle formed by the long axis of the thigh and the long axis of the shank. The angle formed by the long axis of the foot and the shank is known as the ankle joint angle. Biomechanics of the lifters' lower limb segment while lifting the loads involve the generation of internal forces about the joints of the lower limbs, resulting in the external motions of the lower limb segments. The internal forces can be determined from the kinematics and kinetic parameters of the segment motion. The center of mass was determined using the De Leva's ratio in Table 1, anthropometric data and Equation 1. De Leva segmentation methods have been developed to statistically estimate the mass and position of the center of mass of the considered segments (Adolphe *et al.*, 2017).

Anthropometric data from Sanyaolu *et al.* (2023) were employed in the analysis. Anthropometric measurements for the human body are advisably taken on the right side of the body (Norton, 2018). These parameters represent the linear vertical dimensions of the human body when the subject is in a standing position. The equipment used were a weighing scale and stadiometer. The procedure for the anthropometric measurements was as follows:

1. The subjects stood against a wall without a foot wear, feet parallel and back touching the wall.
2. The total body mass was measured on the weighing scale.
3. A mark was made on the wall with the help of the ruler touching the top of the head horizontally.

Table 1. De Leva's Ratio

Body Part	Center of mass	% Length of the total height
Head	59.8	58.9
Neck	59.8	58.9
Trunk	44.9	41.5
Upper Arm	57.7	57.5
Forearm	45.7	45.6
Hand	79.0	74.7
Thigh	41.0	36.1
Shank	44.6	44.2
Foot	44.2	40.1

Source: Adolphe *et al.*, (2017).

4. Measurements of the required body segments were made with the help of the ruler on the stadiometer

Center of Mass,

$$CM = \frac{m_1 x_1 + m_2 x_2 + \dots + m_n x_n}{m} \quad (1)$$

Where $m_1, m_2 \dots m_n$ are the segment masses and while m is the average of the masses while x_1, x_2 and x_n are the segment's dimensions.

Position analysis of the thigh, shank and the foot segments

Using inverse dynamics for the lower limb segment model shown in Figure 2. This is defined by the position of the lower limb's movement during manual activities. The position loop equations in the x and y direction are;

$$f_x(\theta_1, \theta_2, \theta_3) = l_f \cos \theta_3 + l_s \cos \theta_1 + l_t \cos \theta_2 = 0 \quad (2)$$

$$f_y(\theta_1, \theta_2, \theta_3) = l_f \sin \theta_3 + l_s \sin \theta_1 + l_t \sin \theta_2 = 0 \quad (3)$$

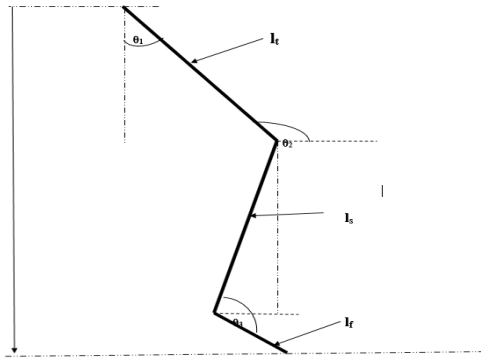


Figure 2. Kinematics of the link segment model free body diagram

The hip angles θ_1 were varied as $0^\circ, 5^\circ, 10^\circ, 15^\circ, 20^\circ, 25^\circ$ and 30° using the natural possible angles of the hip rotation. The knee angles θ_2 are also varied as $0^\circ, 10^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ$ and 60° using the natural possible angles of the hip rotation.

Velocity analysis of the thigh, shank and the feet segment

The differentiation of the position loop equations 2 and 3 gives the velocity loop equations. The resulting linear equations are;

$$\frac{df_x}{dt} = \frac{d}{dt} (l_f \cos \theta_3) + \frac{d}{dt} (l_s \cos \theta_1) + \frac{d}{dt} (l_t \cos \theta_2) \quad (4)$$

$$\frac{df_y}{dt} = \frac{d}{dt} (l_f \sin \theta_3) + \frac{d}{dt} (l_s \sin \theta_1) + \frac{d}{dt} (l_t \sin \theta_2) \quad (5)$$

$$\frac{df_x}{dt} = l_f \frac{\sin \theta_3}{t} + l_s \frac{\sin \theta_1}{t} + l_t \frac{\sin \theta_2}{t} \quad (6)$$

$$\frac{df_y}{dt} = l_f \frac{\cos \theta_3}{t} + l_s \frac{\sin \theta_3}{t} + l_t \frac{\sin \theta_2}{t} \quad (7)$$

Equations 6 and 7 were used to evaluate the velocities of the lower limb.

Acceleration analysis of the thigh, shank and the feet segments

The acceleration loop equations are determined by differentiating the velocity loop equations 6 and 7 equations.

The resulting system of equations are;

$$\frac{d^2 f_x}{dt^2} = \frac{d}{dt} (l_f \frac{\sin \theta_3}{t}) + \frac{d}{dt} (l_s \frac{\sin \theta_3}{t}) + \frac{d}{dt} (l_t \frac{\sin \theta_2}{t}) \quad (8)$$

$$\frac{d^2 f_y}{dt^2} = \frac{d}{dt} (l_f \frac{\cos \theta_3}{t}) + \frac{d}{dt} (l_s \frac{\cos \theta_3}{t}) + \frac{d}{dt} (l_t \frac{\cos \theta_2}{t}) \quad (9)$$

$$\frac{d^2 f_x}{dt^2} = -l_f \left(\frac{t \cos \theta_3 + \sin \theta_3 t^2}{t^2} \right) - l_s \left(\frac{t \cos \theta_3 + \sin \theta_3 t^2}{t^2} \right) - l_t \left(\frac{t \cos \theta_3 + \sin \theta_3 t^2}{t^2} \right) \quad (10)$$

$$\frac{d^2 f_y}{dt^2} = -l_f \left(\frac{-t \sin \theta_3 + \cos \theta_3 t^2}{t^2} \right) + l_s \left(\frac{-t \sin \theta_3 + \cos \theta_3 t^2}{t^2} \right) - l_t \left(\frac{-t \sin \theta_3 + \cos \theta_3 t^2}{t^2} \right) \quad (11)$$

Equations 10 and 11 were used to evaluate the acceleration of the lower limb.

Determination of segment's forces and moments

For the moments of force at the three major joints, Newton-Euler free-body dynamic equilibrium equations taking into account the linear and angular motions were employed. The ground response components applied at the foot/ground contact as well as the gravitational and inertia forces applied at each body segment's center of mass were the external forces taken into consideration. For body segments to be in dynamic equilibrium, it is essential to satisfy the translational and rotational equations. The free-body diagram of the segment's models showing the positioning of the forces and moments is presented in Figures 3(a-d).

$$\sum F_y = m a_y \quad (12)$$

$$\sum F_x = m a_x \quad (13)$$

$$\sum M = I \alpha \quad (14)$$

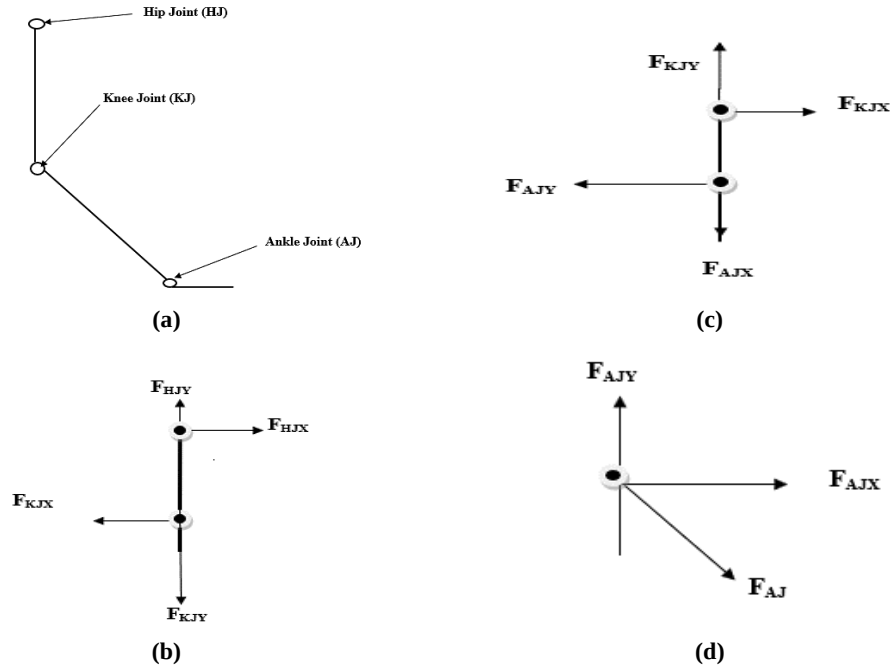


Figure 3. (a) Hip-knee-ankle joints link model; (b) Free body diagram of the forces of the thigh segment (hip joint); (c) Free body diagram of the forces of the thigh segment (knee joint) and (d) Free body diagram of the forces at the ankle joint

Where;

1. F_{HJY} represent force acting in the y-axis at the hip joint
2. F_{HJX} represents force acting in the x-axis at the hip joint
3. F_{KJY} represents force acting in the y-axis at the knee joint
4. F_{KJX} represents force acting in the x-axis at the knee joint
5. F_{AJX} represents force acting in the x-axis at the ankle joint
6. F_{AJY} represents force acting in the y-axis at the knee joint

Where x = distance to the center of mass as measured from the proximal end

For body segments to be in dynamic equilibrium, it is essential to satisfy the translational and rotational equations. The location of the center of mass and the moment about the center of mass from the proximal end is calculated using Dempster's Model as presented in Table 2. The Free Body Diagram of the Forces and Moments at the (Hip-Knee- Ankle Joint Segments) is presented in Figure 4.

where I = Moment of inertia of the segment considered

$$l = (I/m)^{0.5} \quad (15)$$

where l = length of each segment

$$\text{Hence, } I = ml^2 \quad (16)$$

The relationship between the moment of inertia at the center of mass at any axis of rotation along the segment length (l) is expressed by the parallel axis theorem.

$$I = \frac{m}{2} (x - l)^2 + \frac{m}{2} (x + l)^2 \quad (17)$$

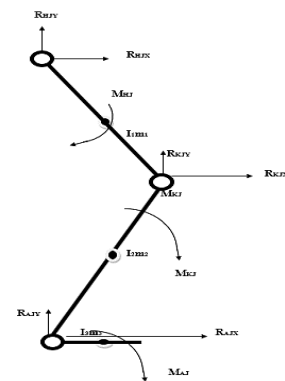


Figure 4. Free body diagram of the forces and moments at the (Hip-knee-ankle joint segments)

Table 2. Body Segment Parameters (Dempster's Model)

Body Segment	Percentage of total body weight (%)	Location of Center of Mass (% of limb segment length from the proximal end)	Moment of inertia about the center of mass (kgm ²)
Head and Neck	7.9	4.3	0.029
Upper Extremity	4.9	51.2	0.335
Arm	2.7	43.6	0.040
Forearm and Hand	2.2	67.7	0.058
Forearm	1.6	43.0	0.018
Hand	0.6	50.6	0.002
Lower Extremity	15.7	43.4	1.785
Thigh	9.6	43.3	0.298
Leg and Foot	5.9	43.3	0.339
Leg	4.5	43.4	0.143
Foot	1.4	43.8	0.007

Where;

1. R_{HJX} represents the reaction forces in the x-axis at the hip joint
2. R_{HJY} represents the reaction forces in the y axis at the hip joint
3. M_{HJ} represents the moment at the hip joint axis
4. R_{KJX} represents the reaction forces in the x-axis at the knee joint
5. R_{KJY} represents the reaction forces in the y axis at the knee joint
6. M_{KJ} represents the moment at the knee joint axis
7. R_{AJX} represents the reaction forces in the x-axis at the ankle joint
8. R_{AJY} represents the reaction forces in the y axis at the ankle joint
9. M_{AJ} represents the moment at the ankle joint axis
10. m_1 , m_2 and m_3 represent the segment masses
11. I_1 , I_2 and I_3 represent each segment's moment of inertia respectively about each center of mass.

The distance from the joints to the center of mass is considered to be fixed as well as the lengths of the segment.

Adapting equations 12, 13 and 14 into Figure 4, the forces and moments in the x and y-axis can be deduced.

$$\sum F_y = ma_y = F_{HJY} + F_{KJY} + F_{AJY} \quad (18)$$

$$\sum F_x = ma_x = F_{HJX} + F_{KJX} + F_{AJX} \quad (19)$$

$$\sum M = M_{HJ} + M_{KJ} + M_{AJ} = I\alpha \quad (20)$$

Results and Discussions

Considering the right lower limb on double support, single support with the hip joint in flexion, single support with hip joint extension and single support with hip and knee joint flexion. For values of m_1 , m_2 and m_3 at 5.72 kg, 2.10 kg and 0.98 kg respectively and l_1 , l_2 and l_3 as 0.273 m, 0.332 m and 0.191 m respectively. For m_1 , m_2 and m_3 values of 6.60 kg, 3.10 kg and 1.70 kg, the values of l_1 , l_2 and l_3 are 0.312 m, 0.342 m and 0.205 m respectively. Similarly, for m_1 , m_2 and m_3 as 7.30 kg, 3.37 kg and 1.83 kg respectively. l_1 , l_2 and l_3 are 0.40 m, 0.357 m and 0.205 m respectively. For the average value, m_1 , m_2 and m_3 are 6.10 kg, 2.7 kg and 1.40 kg respectively. l_1 , l_2 and l_3 are 0.33 m, 0.338 m and 0.198 m respectively. The ground reaction forces, F_X and F_Y being forces corresponding to weights 58.65 kg, 77.82 kg and 93.18 kg respectively.

Case I: Double support (right lower limb)

Considering the right lower limb on double support, that is, the two feet resting on the floor or on the platform, the torque at the hip and knee joints being T_1 and T_2 , the mass of the thigh, shank and foot are m_1 , m_2 and m_3 respectively while l_1 , l_2 and l_3 are the lengths of the thigh, shank and the foot. The masses of the segments are calculated using Dempster's Model in Table 2.

During the double support phase, the hip and the knee joints are in the flexion state (bending movement around the joint) and the hip and knee joint angles are positive. The hip angle is less than the knee joint angle as shown in Figure 5.

Taking moments about the hip joint,

$$T_1 + m_1 g[(l_1/2) \sin \theta_1] + m_2 g[(l_2/2) \sin(\theta_1 - \theta_2) + l_1 \sin \theta_1] + m_3 g[l_2 \sin(\theta_1 - \theta_2) + l_1 \sin \theta_1] = -F_x[l_2 \cos(\theta_1 - \theta_2) + l_1 \cos \theta_1] + F_y[l_2 \sin(\theta_1 - \theta_2) + l_1 \sin \theta_1] \quad (21)$$

Taking moments about knee joint

$$T_2 + m_1 g[(l_1/2) \sin \theta_1] + m_2 g[(l_2/2) \sin(\theta_1 - \theta_2)] + m_3 g[l_2 \sin(\theta_1 - \theta_2)] = -F_x[l_2 \cos(\theta_1 - \theta_2) + F_y[l_2 \sin(\theta_1 - \theta_2)] \quad (22)$$

The ranges of lengths of the shank and thigh are 0.273 m and 0.332 m for the 58.65 kg respectively. The masses of the shank, thigh and feet are 5.72 kg, 2.10 kg and 0.98 kg respectively for the same body mass. The weights of the subjects represent the ground reaction forces F_x and F_y .

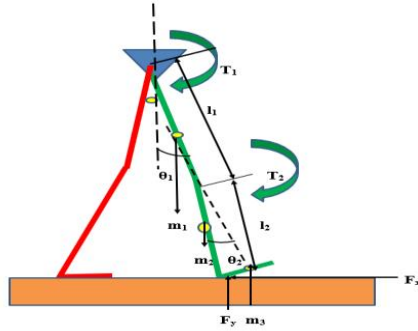


Figure 5. Double support (right lower limb)

The corresponding angles are varied for the hip and knee joints. From equations 21 and 22, T_1 was between -361.1 Nm and -771 Nm while T_2 was between -191.4 Nm and -523.7 Nm. This is an indication that a high torque is not needed when the two limbs are on support during lifting operations. Increasing the angle of twist reduces the values of the torques T_1 and T_2 . The torques also reduces with

increasing body weights and heights of the subjects. Table 3 gives the details of the torques, segment masses and lengths.

Case II: Single support (hip joint flexion)

With single support, the hip joint is in extension (unbending movement around the joint) as shown in Figure 6 and the joint angle is negative. When the hip joint is in the flexion state (bending movement around the joint), the hip joint angle is less than the knee joint angle.

Taking moments about the hip joint;

$$T_1 + m_1 g[(l_1/2) \sin \theta_1] + m_2 g[(l_2/2) \sin(\theta_1 - \theta_2) + l_1 \sin \theta_1] + m_3 g[l_2 \sin(\theta_1 - \theta_2) + l_1 \sin \theta_1] = F_x[l_2 \cos(\theta_1 - \theta_2) + l_1 \cos \theta_1] + F_y[l_2 \sin(\theta_1 - \theta_2) + l_1 \sin \theta_1] \quad (23)$$

Taking moments about the knee joint;

$$T_2 + m_2 g[(l_2/2) \sin(\theta_1 - \theta_2)] + m_3 g[l_2 \sin(\theta_1 - \theta_2)] = F_x[l_2 \cos(\theta_1 - \theta_2) + F_y[l_2 \sin(\theta_1 - \theta_2)] \quad (24)$$

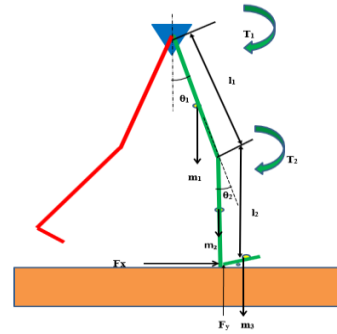


Figure 6. Single support (hip joint flexion)

From equations 23 and 24 for the calculations of the torques T_1 and T_2 . The ranges of lengths of the shank and thigh are 0.273 m and 0.332 m respectively for the 58.65 kg. The masses of the

Table 3. Hip and Knee Joints Torques for Double Support (Right Lower Limb)

T^1 (Nm)	T^2 (Nm)	θ_1 (°)	θ_2 (°)	F_y (N)	F_x (N)	l_1 (m)	l_2 (m)	m_1 (kg)	m_2 (kg)	m_3 (kg)
-346.1	-191.4	0	0	575.36	575.36	0.273	0.332	5.72	2.10	0.98
-461.9	-261.1	0	0	763.41	764.41	0.312	0.342	6.60	3.10	1.70
-533.1	-312.9	0	0	915.00	915.00	0.357	0.400	7.30	3.37	1.83
-351.5	-203.7	5	10	575.36	575.36	0.273	0.332	5.72	2.10	0.98
-500.6	-289.4	5	10	763.41	764.41	0.312	0.342	6.60	3.10	1.70
-623.3	-344.5	5	10	915.00	915.00	0.357	0.400	7.30	3.37	1.83
-364.7	-248.3	10	20	575.36	575.36	0.273	0.332	5.72	2.10	0.98
-693.4	-422.9	15	30	915.00	915.00	0.357	0.400	7.30	3.37	1.83
-543.4	-311.5	20	40	575.36	575.36	0.273	0.332	5.72	2.10	0.98
-628.7	-399.7	20	40	763.41	764.41	0.312	0.342	6.60	3.10	1.70
-742.7	-458.9	20	40	915.00	915.00	0.357	0.400	7.30	3.37	1.83
-575.1	-383.7	30	60	575.36	575.36	0.273	0.332	5.72	2.10	0.98
-652.5	-459.9	30	60	763.41	764.41	0.312	0.342	6.60	3.10	1.70
-771.2	-523.7	30	60	915.00	915.00	0.357	0.400	7.30	3.37	1.83

shank, thigh and feet are 5.72 kg, 2.10 kg and 0.98 kg respectively for the same body mass. The same is repeated for the 77.92 kg and 93.27 kg body mass respectively. The weights of the subjects represent the ground reaction forces F_X and F_Y . For the hip joint flexion on single support, one of the legs is active on the floor or the ground support, hence, the ground reaction forces F_X and F_Y acts on the active leg denoted in green colour. The corresponding angles are varied for the hip and knee joints. T_1 was between 347.8 Nm and 735.6 Nm while T_2 was between 191.3 Nm and 223.21 Nm. The increasing positive values of the torques with increasing varying angles of the hip and ankle angles indicates that more twist is involved at the hip joint than the knee joints. Hence, the hip joints are more susceptible to injuries based on the amount of weight being exerted on the hip joint as against the knee joint. The negative torques also implies that more energy is absorbed during this phase and possible eccentric muscle action close to the joints. Table 4 gives the details of the torques, segment masses and lengths.

Case III: Single support (hip joint extension)

In the case of the hip joint extension, the hip joint angle is less than the knee joint angle as shown in Figure 7.

Taking moments about the hip joint;

$$T_1 + m_1 g [(l_1/2) \sin \theta_1] + m_2 g [(l_2/2) \sin(\theta_1 - \theta_2) + l_1 \sin \theta_1] + m_3 g [l_2 \sin(\theta_1 - \theta_2) + l_1 \sin \theta_1] = F_X [l_2 \cos(\theta_1 - \theta_2) + l_1 \cos \theta_1] + F_Y [l_2 \sin(\theta_1 - \theta_2) + l_1 \sin \theta_1] \quad (25)$$

Taking moments about the hip joint;

$$T_2 + m_2 g [(l_2/2) \sin(\theta_1 - \theta_2)] + m_3 g [l_2 \sin(\theta_1 - \theta_2)] = F_X [l_2 \cos(\theta_1 - \theta_2) + F_Y [l_2 \sin(\theta_1 - \theta_2)] \quad (26)$$

From equations 25 and 26 for the calculations of the torques T_1 and T_2 , the ranges of lengths of the shank and thigh are 0.273 m and 0.332 m for the 58.65 kg, the masses of the shank, thigh and feet are 5.72 kg, 2.10 kg and 0.98 kg for the same body mass

respectively. The same is repeated for the 77.92 kg and 93.27 kg body mass respectively. The torques T_1 for 58.65 kg body mass ranges from 130.3 Nm and 301.2 Nm while T_2 is calculated as 81.8 Nm and 275.7 Nm. The torques T_1 for 77.92 kg body mass ranges from 268.9 Nm and 478.7 Nm while T_2 is calculated as 277.3 Nm and 483.6 Nm. The torques T_1 for 93.27 kg body mass ranges between 329.7 Nm and 501.6 Nm while T_2 is calculated ranges from 305.6 Nm to 499.7 Nm. The weights of the subjects represent the ground reaction forces F_X and F_Y . For the hip joint extension on single support, one of the legs is active on the floor or the ground support, hence, the ground reaction forces F_X and F_Y acts on the active leg denoted in green colour. The centers of mass acts as indicated in Table 3.5 and measured from the proximal end. The corresponding angles are varied for the hip and knee joints. T_1 was between 347.8 Nm and 735.6 Nm while T_2 was between 191.3 Nm and 223.21 Nm. The increasing positive values of the torques with increasing varying angles of the hip and ankle angles indicates that more twist is involved at the hip joint than the knee joints. Hence, the hip joints are more susceptible to injuries based on the amount of weight being exerted on the hip joint as against the knee joint. The positive torques also implies that more energy is generated during this phase and possible concentric muscle action is possible close to the joints. Table 5 gives the details of the torques, segment masses and lengths.

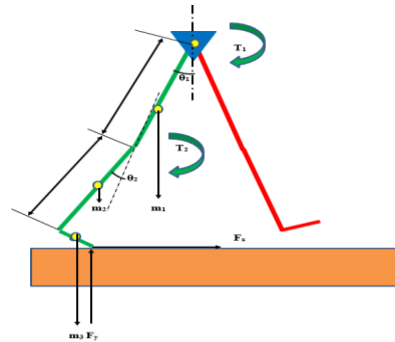


Figure 7. Single support (hip joint extension)

Table 4. Hip and Knee Joint Torques Single Support (Hip Joint Flexion)

T^1 (Nm)	T^2 (Nm)	θ_1 (°)	θ_2 (°)	F_Y (N)	F_X (N)	l_1 (m)	l_2 (m)	m_1 (kg)	m_2 (kg)	m_3 (kg)
348.7	191.3	0	0	575.36	575.36	0.273	0.332	5.72	2.10	0.98
499.2	253.45	0	0	763.41	764.41	0.312	0.342	6.60	3.10	1.70
692.7	303.78	0	0	915.00	915.00	0.357	0.400	7.30	3.37	1.83
374.5	173.61	5	10	575.36	575.36	0.273	0.332	5.72	2.10	0.98
588.6	160.2	20	40	763.41	764.41	0.312	0.342	6.60	3.10	1.70
692.1	223.45	20	40	915.00	915.00	0.357	0.400	7.30	3.37	1.83
490.4	101.75	25	50	575.36	575.36	0.273	0.332	5.72	2.10	0.98
623.0	130.36	25	50	763.41	764.41	0.312	0.342	6.60	3.10	1.70
711.4	182.85	25	50	915.00	915.00	0.357	0.400	7.30	3.37	1.83
503.5	127.63	30	60	575.36	575.36	0.273	0.332	5.72	2.10	0.98
654.7	183.77	30	60	763.41	764.41	0.312	0.342	6.60	3.10	1.70

Table 5. Hip and Knee Joint Torques Single Support (Hip Joint Extension)

T ¹ (Nm)	T ² (Nm)	θ ₁ (°)	θ ₂ (°)	F _Y (N)	F _X (N)	l ₁ (m)	l ₂ (m)	m ₁ (kg)	m ₂ (kg)	m ₃ (kg)
130.3	81.8	0	0	575.36	575.36	0.273	0.332	5.72	2.10	0.98
268.9	277.3	0	0	763.41	764.41	0.312	0.342	6.60	3.10	1.70
329.7	305.6	0	0	915.00	915.00	0.357	0.400	7.30	3.37	1.83
206.7	135.8	10	20	575.36	575.36	0.273	0.332	5.72	2.10	0.98
344.1	349.4	10	20	763.41	764.41	0.312	0.342	6.60	3.10	1.70
403.5	382.7	10	20	915.00	915.00	0.357	0.400	7.30	3.37	1.83
272.3	205.7	20	40	575.36	575.36	0.273	0.332	5.72	2.10	0.98
414.5	442.6	20	40	763.41	764.41	0.312	0.342	6.60	3.10	1.70
457.6	467.7	20	40	915.00	915.00	0.357	0.400	7.30	3.37	1.83
301.2	275.7	30	60	575.36	575.36	0.273	0.332	5.72	2.10	0.98
478.7	483.6	30	60	763.41	764.41	0.312	0.342	6.60	3.10	1.70
501.6	499.7	30	60	915.00	915.00	0.357	0.400	7.30	3.37	1.83

Table 6. Hip and Knee Joint Torques Single Support (Hip and Joint Flexion)

T ¹ (Nm)	T ² (Nm)	θ ₁ (°)	θ ₂ (°)	F _Y (N)	F _X (N)	l ₁ (m)	l ₂ (m)	m ₁ (kg)	m ₂ (kg)	m ₃ (kg)
0	0	0	0	575.36	575.36	0.273	0.332	5.72	2.10	0.98
0	0	0	0	763.41	764.41	0.312	0.342	6.60	3.10	1.70
0	0	0	0	915.00	915.00	0.357	0.400	7.30	3.37	1.83
1.79	0.81	5	10	575.36	575.36	0.273	0.332	5.72	2.10	0.98
4.91	2.69	5	10	763.41	764.41	0.312	0.342	6.60	3.10	1.70
5.92	3.55	5	10	915.00	915.00	0.357	0.400	7.30	3.37	1.83
11.17	2.72	20	40	575.36	575.36	0.273	0.332	5.72	2.10	0.98
16.01	9.01	20	40	763.41	764.41	0.312	0.342	6.60	3.10	1.70
23.41	11.86	20	40	915.00	915.00	0.357	0.400	7.30	3.37	1.83
14.45	2.90	30	60	575.36	575.36	0.273	0.332	5.72	2.10	0.98
25.22	10.40	30	60	763.41	764.41	0.312	0.342	6.60	3.10	1.70
34.35	13.69	30	60	915.00	915.00	0.357	0.400	7.30	3.37	1.83

Case IV: Single support (hip and knee joint flexion)

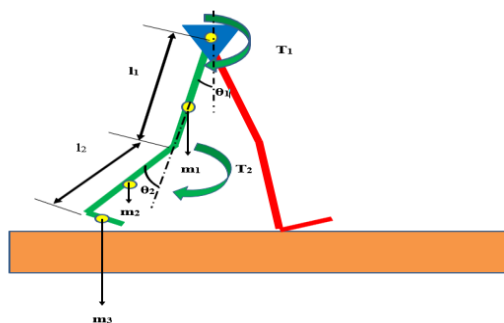
In case of both the hip joint and the knee joint in flexion as shown in Figure 8.

Taking moments about the hip joint;

$$T_1 = m_1 g [(l_1/2) \sin \theta_1] + m_2 g [(l_2/2) \sin (\theta_1 + \theta_2) + l_1 \sin \theta_1] + m_3 g [l_2 \sin (\theta_1 + \theta_2) + l_1 \sin \theta_1] \quad (27)$$

Taking moments about the knee joint;

$$T_2 = m_2 g [(l_2/2) \sin (\theta_1 + \theta_2) + m_3 g [l_2 \sin (\theta_1 + \theta_2)] \quad (28)$$

**Figure 8. Single support (hip and knee joint flexion)**

From equations 27 and 28 for the calculations of the torques T_1 and T_2 , the ranges of lengths of the shank and thigh are 0.273 m and 0.332 m for the

58.65 kg, the masses of the shank, thigh and feet are 5.72 kg, 2.10 kg and 0.98 kg for the same body mass respectively. The same calculation is repeated for the 77.92 kg and 93.27 kg body mass respectively. The torques T_1 for 58.65 kg body mass ranges from 0 Nm to 14.45 Nm while T_2 is calculated to be between 0 Nm and 2.90 Nm. The torques T_1 for 77.92 kg body mass ranges from 0 Nm to 25.22 Nm while T_2 is calculated to be between 0 Nm and 10.40 Nm. The torques T_1 for 93.27 kg body mass ranges from 0 Nm and 34.35 Nm while T_2 is calculated as 0 Nm and 13.69 Nm. The ground reaction forces F_X and F_Y for the hip and knee joint flexion on single support is zero. Table 6 gives the details of the torques, segment masses and lengths. The increasing positive values of the torques with increasing varying angles of the hip and ankle angles indicates that more twist is involved at the hip joint than the knee joints. The positive torques also implies that more energy is generated during this phase and possible concentric muscle action is possible close to the joints.

Hence, the hip joints are more susceptible to injuries based on the amount of weight being exerted on the hip joint as against the knee joint. However, it is noted that the torques for the hip and knee flexion on single support is lower than all the other cases considered. This indicates that less musculoskeletal injuries may occur as a result of twist to the hip and knee joints as against the other cases. This is the best positioning when the twisting

effect of lifting and carrying of loads is involved. The positive torques also implies that more energy is generated during this phase and possible concentric muscle action is possible close to the joints

Accordingly, there are more stresses placed on the lower limbs when they are not on multiple supports, that is, when both limbs are on the ground or a support platform. The other hanging limb will therefore be under increased tension. Double-limb support will reduce the chance of tripping and falling. It will also support the body's overall equilibrium. A single limb is supported on the floor or a platform in a similar manner for a limb on single support. The trailing leg generates positive work to make up for the energy lost while the leading leg, which is this one, conducts negative effort to reroute the center of mass velocity. By aiding in the leading leg's balancing, the trailing leg lessens the overall mechanical effort required by the lower limb.

Positional and velocity analysis

The movement of the hip, knee and ankle is either flexion or extension. Net forces and moments cannot be measured directly as they represent the net effects which produce forces and moment of forces of each joint, hence, the estimation of the position and velocity of hip joint, knee joint and ankle joint were applied to different segments and positions. The ankle joint, the knee joint and the hip joint of the lower extremity were sectioned into three segments (thigh, shank and foot) to determine the interactions between them.

Using De Leva's ratio to find the center of mass of the various segments of the subjects.

1. Mass of shank, $m_1 = 0.2236$ of the total mass of the subject
2. Mass of the thigh, $m_2 = 0.0878$ of the total mass of the subject
3. Mass of the foot, $m_3 = 0.0366$ of the total mass of the subject
4. Length of the shank, $l_1 = 0.26$ of the total height of the subject
5. Length of the thigh, $l_2 = 0.24$ of the total height of the subject
6. Length of the foot, $l_3 = 0.12$ of the total height of the subject
7. Location of the center of the mass for the shank, l_{c1} is 0.433 from the start of the link
8. Location of the center of the mass for the thigh, l_{c2} is 0.433 from the start of the link
9. Location of the center of the mass for the feet, l_{c3} is 0.429 from the start of the link

Figure 9 indicates the plot for the positional analysis of the lower limb in the x-axis. The values of the position reduce to from the segment angles

30° and 38° to 0 then it drops to negative and then back to 0. The curve is sinusoidal curve indicating sequential movement in either flexion or extension movements until the angle reaches 180°. Extending the angles may results in overstretching the segments beyond natural tendencies, hence it is not advisable. The positional analysis in the y-axis also indicates the same trajectory as the x-axis as shown in Figure 10. This implies that the movement in both directions (x and y axis) are synchronized. Any alteration in the sinusoidal curve for the positional analysis may result in injuries, musculoskeletal disorders. In the same vein, this may cause increased torsion in the parallel position of the lower limb segments.

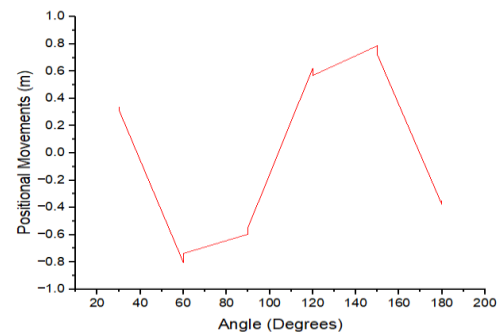


Figure 9. Positional analysis of the lower limb (X-axis)

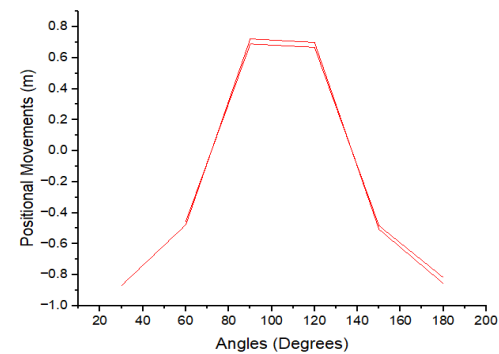


Figure 10. Positional analysis of the lower limb (Y-axis)

Figures 11 and 12 are the plots for the velocity analysis of the lower limb segments in the x and y axis on the sagittal plane. The curves show a downward curve which indicates a gradual decrease in the velocity of the segments as the segmental angles are increased until it reaches about 100° when the increase resumes till it reaches the optimum velocity. This movement is in the x-axis of the lower limb. In the same vein, y-axis curve shows a curve indicating the decrease, increase and decrease in the velocity.

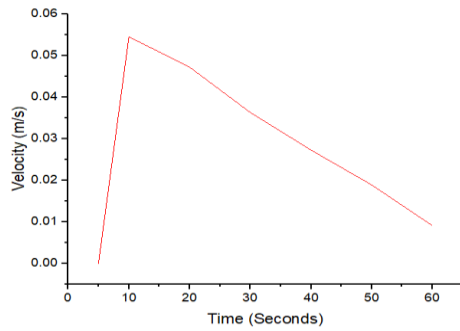


Figure 11. Velocity analysis of the lower limb (Y-axis)

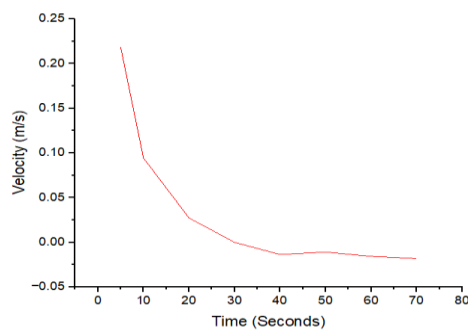


Figure 12. Velocity analysis of the lower limb (Y-axis)

Analysis of moments

Using the Newton-Euler equation, the effects of force and moments on the human body's lower leg were evaluated. The total net impact of the forces acting on the various lower limb joint structures to produce movement is represented by the computed net forces and moment of forces. Each step a person takes when moving is attributed to a lower limb joint. The conventional inverse dynamics analysis was used to compute the internal moments of the ankle, knee, and hip joints. The length and body mass of each segment were used to evaluate its inertia properties. It is noted that both the segment lengths and the subjects' total mass affect the masses of the segments. Therefore, the moments of inertia are functions of the lengths and

mass of the subjects and they are important for stability and balancing of the whole-body structure. These values were taken from the proximal end of the joints. It indicates that, moments of the segments are functions of the lengths and mass of the segments. A shorter segment length will produce a high moment. However, variability in terms of the length can also affect its value. Thus, the moment values decrease from the ankle to hip joint.

The angles are varied with 30° intervals for the various segments, that is 90°, 120° and 150° for the flexion and extension movements of the thigh segments based on the maximum and the minimum allowable angles of the segments to their corresponding joints. Similarly, the angles are varied with 30° intervals for the shank segment, that is 90°, 120° and 150° for the flexion and extension movements of the shank segments based on the maximum and the minimum allowable angles of the segments to the joint. Similarly, the angles are varied with 30° intervals for the various segments, that is 0°, 30°, 60°, 90°, 120°, 150° and 180°, for the flexion and extension movements of the feet segments based on the maximum and the minimum allowable angles of the segments to their corresponding joints.

Tables 7, 8, 9 and 10 describes the relationship between the moments of inertia, acceleration and angular acceleration of the body segments with respect to the weight of the subjects. The weights considered are 58.65 kg, 77.82 kg, 93.18 kg and 74.59 kg respectively. Figure 13 and 14 plots the relation between the segmental masses of the foot and thigh and their angular acceleration. The angular acceleration of the foot and shank increases with increasing weight. This implies that the weight of the segment is a major determinant of the angular acceleration. The values for the angular acceleration for 58.65 kg mass of the foot is 3.28 rads^{-2} , 77.82 kg is 6.21 rads^{-2} , 74.52 kg is 7.46 rads^{-2} , 77.82 kg is 6.21 rads^{-2} and 93.18 kg is 7.46 rads^{-2} .

However, the angular acceleration of the shank segment decreases with increasing weight of the segment as indicated in Figure 15.

Table 7. Moment of Inertia, Acceleration and Angular Acceleration of Segments for a 58.65 kg Weight

Segment	Mass (kg)	Moment of Inertia (kgm^2)	Length (m)	Acceleration (m/s^2) X	Y	Angular Acceleration (rads^{-2})
Foot	0.98	0.08	0.191	-4.13	6.63	3.28
Shank	2.1	0.056	0.332	-3.71	2.62	-2.64
Thigh	5.72	0.123	0.273	6.13	-1.13	6.71

Table 8. Moment of Inertia, Acceleration and Angular Acceleration of Segment for a 77.82 kg Weight

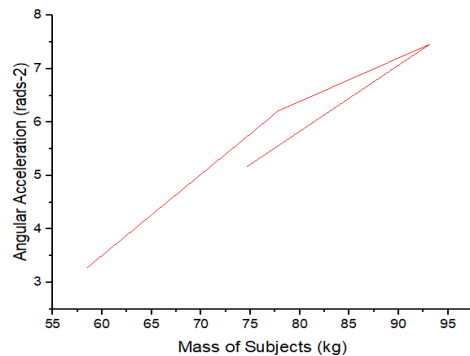
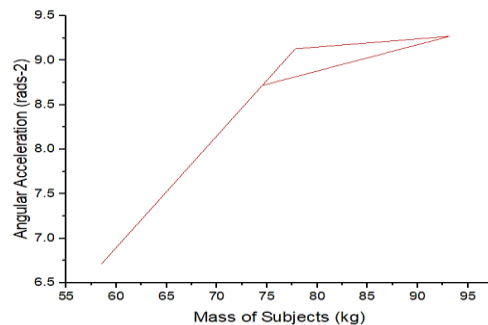
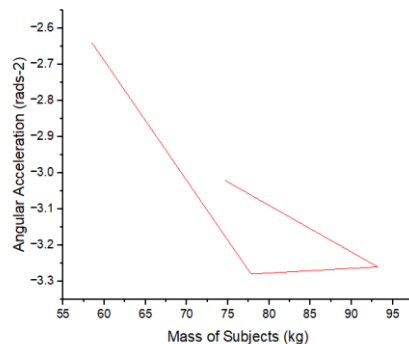
Segment	Mass (kg)	Moment of Inertia (kgm^2)	Length (m)	Acceleration (m/s^2) X	Y	Angular Acceleration (rads^{-2})
Foot	1.7	0.018	0.205	-4.52	7.12	6.21
Shank	3.1	0.071	0.342	-4.33	2.95	-3.28
Thigh	6.6	0.142	0.312	7.75	-1.14	9.13

Table 9. Angular Acceleration of Segments for a 93.18 kg Weight

Segment	Mass (kg)	Moment of Inertia (kgm ²)	Length (m)	Acceleration (m/s ²) X	Y	Angular Acceleration (rads ⁻²)
Foot	1.83	0.023	0.205	-4.81	7.24	7.46
Shank	3.37	0.076	0.357	-4.28	3.05	-3.26
Thigh	7.3	0.152	0.40	7.21	-1.62	9.27

Table 10. Moment of Inertia, Acceleration and Angular Acceleration of Segments for a 74.59 kg Weight

Segment	Mass (kg)	Moment of Inertia (kgm ²)	Length (m)	Acceleration (m/s ²) X	Y	Angular Acceleration (rads ⁻²)
Foot	1.4	0.016	0.198	-4.26	6.67	5.16
Shank	2.7	0.068	0.338	-3.98	2.70	-3.02
Thigh	6.1	0.132	0.33	6.44	-1.17	8.72

**Figure 13. Angular acceleration for the foot segment****Figure 14. Angular acceleration for the thigh segment****Figure 15. Angular acceleration for the shank segment**

Conclusions

A study of the biomechanical analysis of the lower extremity identified that hip and joint torques for double support are the lowest ranging between -771 Nm and -361.1 Nm while single supports (hip joint flexion and extension) are the highest between 348.7 Nm and 735.6 Nm. This postulates that more stresses are experienced when the lower limbs are not on double supports, that is, the two limbs on the ground or on the platform of support. Hence, there will be more stress on the other limb that is hanging. This agrees with an earlier work by Sung (2018) indicating that double-limb support helps to reduce the risk of tripping and falling. It will also help in the total balance of the body frame. Similarly, for the limb on single support, one limb is supported on the floor or the platform. This limb is the leading leg and performs negative work to redirect the center of mass velocity, while simultaneously, the trailing leg performs positive work to replace the lost energy. The trailing leg helps to balance the leading leg, hence, reducing the mechanical work done by the lower limb altogether. Manual operations with the double supports allow even distribution of stresses on the body frame and less stress while the single supports cause more stress on the body frame because of the high torques, hence, manual handling activities should be done on double supports rather than single supports. Consequently, due to these stresses on the body as a result of manual handling activities, it is advised that it should be reduced as much as possible. Risk assessment of manual handling activities should be done prior to the commencement of such activities. A similar work by Arnold *et al.* in 2010 used a model which allows detailed examination of the force and moment generation capacities of the muscles about the ankle, hip and knee. provided a model. Employers and employees should take the necessary precautions to minimize the risk of injury

when manual handling operations are not reasonably practicable to avoid. If the risk of injury persists, they should also take the necessary precautions (such as training) to give employees general indications, accurate information about the weight of the load, and the heaviest side of any load when the center of gravity is not positioned centrally.

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