MODELING OF LOWER EXTREMITY FOR JOINT TORQUES DETERMINATION BY PERFORMING A LIFTING TASK

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ABSTRACT

Physical lifting tasks commonly involve two types of body postures, namely, squat lifting and stoop lifting. Studies shows improper body posture during lifting task has detrimental effect to human lower-back region over extended period of time. This is because generally, stoop-lifting posture exerts relatively higher moments and compression forces on human back than squat lifting posture. However, this claim was never thoroughly examined and validated from mathematical model approach. This paper proposes a mathematical model to represent the lower extremity of human body during lifting tasks, based on a two-link kinematic open chain in two dimensional spaces. Thus, all moment of torque and their effect to every part of lower extremity of human body can be thoroughly analyzed.

KEYWORDS*: Lifting techniques, Mathematical Model, Kane's method, Equation of motion.*

1.0 INTRODUCTION

Issues on back problem tend to be a major health trouble since the 90s'. This problem contributes to tremendous health care costs, human suffering and lost productivity in company. In Malaysia, however, is still at a building stage about the awareness of back pain. Most of industrial workers consider this as petty matters, especially in developing country. Therefore, the Occupational Safety and Health (OSH) practitioners need more promotions and enhancing awareness. Due to awareness level of back pain, (Baba *et.al.*, 2010) have examined the prevalence of Musculoskeletal Disorders (MSD) among workers in manufacturing industry in Malaysia. They investigated this problem through a Body Parts Symptoms Survey (BPSS) by evaluating the comfort level to all body parts that relate to back problem. Besides, (Ismail *et.al.*, 2009) also conducted a survey questionnaire by utilizing the Ovako Work Assessment System (OWAS) tool in order to access the area discomfort of body. Nevertheless, these surveys are not considered as biomechanics criterion which is a crucial part in demonstrating the assessment of back problem. Research in Malaysia on biomechanical analysis in lifting task is due to lack of interest or awareness on this problem (Granata *et.al*., 2001),(Kuzkaya *et.al*.,1997),(Van and Hoozemans,1999). Thus, biomechanists and ergonomists are recognized the analysis in order to express a significant on the prevention of low back pain.

Most of studies have examined a physical lifting task involving lifting techniques which contribute an effect to human-back while performing unnatural postures. Thereby, a particular lifting technique is most crucial factors that can prevent and reduce the risk of back problem. Typically, physical lifting task consist two types of body postures, namely, squat lifting and stoop lifting. The study by (Emolle *et. al.)* mainly considers these techniques to access the back problem by designing a suitable protocol. In past studies have revealed a biomechanical model of trunk which an enable to minimize potentially injuries on low back. Most commonly, development of biomechanical and mathematical model retained physical's law calculations in order to estimate desired results. The difference between them are inherent while mathematical model are required a complex derivation on calculation. The study of lifting task has become an important aspect of investigate low back problem while researchers conceive a biomechanical and mathematical approaches. It is imperative ideas that able to represent human lifting movement based on kinetic and kinematic data.

The structure of this paper is organized as follows: Section 2 describes the related works on lifting technique and also model development representing a motion of lifting. The equation of motion for body movement is demonstrated in section 3. In section 4, results of experiment on lifting task is presented and discussed. Finally, the main findings of this research work are concluded in section 5.

2.0 RELATED WORKS

2.1 Biomechanical Analysis of Lifting

Lifting has received considerable rese*arch attention when concerning to the human back problem (Kuzkaya* et.al.,1997). In lifting motion, researchers used a variety of patterns of motion. These patterns are classified on the basis postures of lifting which are back lifts or stoop lifts, and squat lifts. Stoop lifts are described as hips flexed and knee straight whereas squat lifts are defined as when knees flexed and back vertical. Most researches have pointed out that peoples or workers often use stoop lifting have more stressful to the spine compared to squat lifting. In these cases, they examined the effect of two different lifting techniques on lower back. The results showed the squat lift produced less of torque on hip joint than stoop lift. Overall studies from

(Emolle *et. al*.) demonstrated a greater risk of lower back pain resulting from the stoop lift. Therefore, some authors suggested that the back should on the right position while lifting the heavy load for preventing the back pain. The right position of back should be straight and vertical or it is called the squat lifting.

From the subjective point of view, squat lifting was found more tiring than stoop lifting. On the other hand, squat lifting are most demanding compared to stoop lifting in terms of physiological cost (Kothiyal *et.al*.,1992). (Kuzkaya *et.al*.,1997) explained that squat lifting are required less work, since upper body mass not moved and may result in lower spinal compression forces. Commonly, most researchers advised the squat lifting technique remains as erect as possible on back and flexed the knees (Van and Hoozemans,1999). They have reviewed systematically on comparison between the stoop and squat lifting technique with considering the biomechanical studies. They showed the result which are squat lifting have higher moment and compressive force. Also, they recommend that their biomechanical literatures does not support for the squat lifting technique as a better technique for preventing low back problem in lifting task.

Therefore, a model for representing these issues needs more concentrate with demonstrating variations in lifting styles. Moment of forces and dynamic factors can be evaluated and produced from model development.

2.2 Mathematical Models

In mathematical modeling, analyses of joint torques or moment of forces acting on the body segments are evaluated. For example, Chaffin performed analysis of forces for two body segment under static planar conditions. Researcher used Newtonian mechanic to determine the force action on segment. Besides, a two-link model of arm was developed by Pearson et al. They computed forces and torques which present at elbow and shoulder part.

Researches on biomechanical models have demonstrated by Chaffin and Chaffin and Baker. The developed the model to evaluate stress caused by external load during lifting in sagittal plane. The model also expanded to predict the compressive force sustained by lumbar spine. This model approach has been adopted a simple model of lifts with concerning ankle angle trajectory and motion of knees [4]. A three segment model of human body have been used from (Kothiyal *et.al*.,1992),(Chaffin *et.al*.,1991). They used a dynamic equation of motion using Newton-Euler dynamic algorithm to evaluate reactive moment of the body. Chaffin developed a seven-link, two-dimensional static model to calculate joint force and moment during lifting. This model was expanded with Freivalds et al in order to estimate the sagittal plane kinematic which consider both forces (external and internal) loading when considering the compression force on spine.

Modeling approaches can determine by physical models. Physical model is constructed physically to investigate related quantities. The model may serve to check the result of mathematical modeling (Kothiyal *et.al.*,1992). For instance, K.P. Granati and S.E.Wilson are designed a three-dimensional inverted double pendulum or called three dimensional, two segment model to determine spinal stability of trunk posture (Granata *et.al*.,2001). Little research is investigated the compression force and other kinematic value of body using Kane's method during lifting task. Several researchers have been developed the arm models via Kane's method during badminton activity (Fadiah and Azmin, 2009).The study are used inverse dynamic approach to calculate the torques at each joint. The results showed that elbow joint produce a higher value of torque during performing an activity. It proved that the equation of motion can be used in order to estimate the unknown value (torque) using kinematic data. Otherwise, (Sharifah Alwiah *et.al.,* 2011) also designed a mathematical model via Kane's equation to solve trunk motion with load carriage. They utilized two-link planar of rigid bodies in two-dimensional space for presenting trunk and head inclination angles.

3.0 MATERIAL AND METHODS

3.1 Research Method

A subject without joint and muscular pathology is selected among UniMAP student for performing a lifting task. The subject characteristics are measured before perform the task, which are 1.59 m in height and 52 kg in weight. There were two trials involved and each trial consists of 300 frames starting standing position until lifting a load. The recording system is utilizes five Oqus cameras with 70 Hz to collect the motion data. The cameras captured a reference structure with seven reflective markers in space of laboratory. A Qualysis software is used to analyze all trials and acquire the kinematic data as an input for mathematical model developed.

3.2 Mathematical Model for Whole Body (Sagittal Plane)

In this study, a mathematical model is developed in two-dimensional space to illustrate the inclination angles of whole body during lifting postures. Figure 1 shows a skeletal model of the lower extremity of a human body in sagittal (side) plane. The model is used Kane's dynamics equation of motion with created from two degree of freedom (DoF) (Yamaguchi, 2001). This model is showed in two-link planar kinematic chain.

Figure 1 illustrated two-link kinematic open chain for the lower extremity in sagittal plane while lifting posture. Rigid bodies A and B, and the ground reference frame N are connected together within frictionless pins at points A_0, B_0, and C_0, and .Vector component directions are perpendicular for each of two rigid body reference frames. $\tilde{a}_1$ remains parallel to $A_0 B_0$ as body A rotates by angle q_1 and etc.

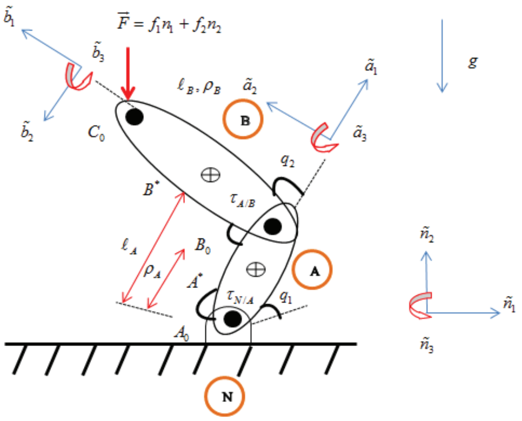


FIGURE 1
Two link kinematic open chain representing the lower extremity of human body in sagittal plane while lifting the load

The respective bodies of mass centroids (A^* and B^*) are located at distances ρ_A and ρ_B from their proximal ends. A torque, $\tau_{N/A}$, is exerted by N on A and another torque. An external influence at endpoint of linkage C_0 is exerting by force, $\vec{F} = f_1n_1 + f_2n_2$. From Figure 1, the symbols used in this model are:

● = Joints

⊕ =center of mass

Ⓐ =segment A (Ankle-Knee)

Ⓑ =segment B (Knee-Hip)

A^*, B^* = center of mass of segments A and B respectively

$\tilde{n}_1, \tilde{n}_2, \tilde{n}_3, \tilde{a}_1, \tilde{a}_2, \tilde{a}_3, \tilde{b}_1, \tilde{b}_2, \tilde{b}_3$ = mutually orthogonal unit

ρ_A, ρ_B = distances of center of mass from their proximal ends

ℓ_A, ℓ_B = length of segments

$\tau_{N/A}, \tau_{A/B}$ = Torques of each joints

$\vec{F} = f_1n_1 + f_2n_2$ = endpoint force of arbitrary direction and magnitude

Derivation expressions for the angular velocity and angular acceleration are the first step to describe each rigid body comprising the system by utilizing Kane's method. The angular quantities allow the velocities and accelerations within the system to be computed along with geometrical information. All of descriptions related to determine the motions, there are called kinematical equations.

The dot products of vectors are computed in different reference frames via direction cosine table using Kane's methods. Therefore, the angular velocities and angular accelerations of bodies A and B with respect to reference frame N can be determined,

General equations for angular velocities:

$$ {}^{N}\vec{\omega}^{B} \equiv \dot{q}\tilde{k} \qquad [1] \qquad [1]$$

Where, partial angular velocities ${}^{A}\vec{\omega}^{B}$, (i=1,2,3,…,n),as defined for the rotation of a rigid body B in an inertial reference frame N. $\dot{q}$ is called the angular velocity of B in N . $\tilde{k}$ is a unit vector parallel to the instantaneous rotation axis of B in N.

In this case, the angular velocities of bodies A and B with respect to reference frame N are obtained to be,

$$ {}^{N}\vec{\omega}^{A} = \dot{q}_1\tilde{a}_3 \qquad [2]$$

$$ {}^{N}\vec{\omega}^{B} = (\dot{q}_1 + \dot{q}_2)\tilde{b}_3 \qquad [3]$$

General equations for angular accelerations:

$$ {}^{N}\vec{a}^{B} \equiv \ddot{q}\tilde{k} \qquad [4]$$

Where, partial angular accelerations ${}^{A}\vec{a}^{B}$, (i=1,2,3,…,n),as defined for the rotation of a rigid body B in an inertial reference frame N . $\tilde{k}$ is called the angular accelerations of B in N . $\ddot{q}$ is a unit vector parallel to the instantaneous rotation axis of B in N.

$$ {}^{N}\vec{a}^{A} = \ddot{q}_1\tilde{a}_3 \qquad [5]$$

$$ {}^{N}\vec{a}^{B} = (\ddot{q}_1 + \ddot{q}_2)\tilde{b}_3 \qquad [6]$$

The velocities of all points with force acting through body and accelerations of mass centers are known for establishing the kinematical equation. The velocity of point A_0 in reference frame N is indicated as ${}^N\vec{v}^{A_0}$, which shows zero as a result since that point is located of a point pinned rigidly to reference frame N. The velocities of points A^*, B_0, B^* and C_0 are determine to be,

$$ {}^N\vec{v}^{A^*} = \rho_A \dot{q}_1 \tilde{a}_2 \quad [7] $$

$$ {}^N\vec{v}^{B_0} = \ell_A \dot{q}_1 \tilde{a}_2 \quad [8] $$

$$ {}^N\vec{v}^{B^*} = \ell_A \dot{q}_1 \tilde{a}_2 + \rho_B (\dot{q}_1 + \dot{q}_2) \tilde{b}_2 \; {}^N\vec{v}^{C_0} = \ell_A \dot{q}_1 \tilde{a}_2 + \ell_B (\dot{q}_1 + \dot{q}_2) \tilde{b}_2 \quad [9] $$

The acceleration of mass location A^* and B^* are,

$$ {}^N\tilde{a}^{A^*} = -\rho_A \dot{q}_1^{\,2} \tilde{a}_1 + \rho_A \ddot{q}_1 \tilde{a}_2 \quad [10] $$

$$ {}^N\tilde{a}^{B^*} = -\ell_A \dot{q}_1^{\,2} \tilde{a}_1 + \ell_A \ddot{q}_1 \tilde{a}_2 - \rho_B (\dot{q}_1 + \dot{q}_2)^2 \tilde{b}_1 + \rho_B (\ddot{q}_1 + \ddot{q}_2) \tilde{b}_2 \quad [11] $$

The kinematical equations are completed when all velocities of all points and accelerations of mass centers are known.

3.3 Kane's Method

In Kane's approach, partial angular velocities and partial velocity vectors can be determined straightly from angular velocity and velocity of point expressions. The use of partial angular velocities is to define rotation of bodies in responses to applied torques. Generally, the partial velocities vectors able to obtain at points where forces act, while partial angular velocities can be obtained fir rigid bodies on which torques or moment act. Therefore, these velocities can be factored into the following form,

$$ {}^N\vec{\omega}^A = (\tilde{a}_3) u_1 + (\vec{0}) u_2 \quad [12] $$

Where, the quantities $u_i \equiv \dot{q}_i, (i = 1, 2)$, u_1 is the first generalized speed of the system and u_2 is defined as the second generalized speed.

The generalized active and inertia forces are then formulated for each segment bodies. Vector dot product between partial velocities of points and forces acting on those points should be added together for creating the generalized active forces. Furthermore, dot products between partial angular velocities and torque are summed together with the previous results. The generalized inertial forces are computed after calculating the generalized active forces. The dot products between the partial velocities of the mass center and the inertial forces are composed, as well as the dot products between the partial angular velocities and inertial torques. Equations below represent the summarization of the generalized active forces and the generalized inertial forces as follows,

$$F_1 + F_1^* = 0; F_1 = -F_1^* \quad [13]$$

$$F_2 + F_2^* = 0; F_2 = -F_2^* \quad [14]$$

Where F_1 and F_2 are generalized active forces and F_1^* and F_2^* are generalized inertia forces.

These dynamic equations can be represented in matrices form,

$$M\ddot{\vec{Q}} = \vec{G} + \vec{E} + \vec{T} \quad [15]$$

Where

M :: mass matrix
$\ddot{\vec{Q}}$: angular acceleration vectors
$\vec{G}$: vector of moments from gravitional forces
$\vec{E}$: vector of moments from external forces
$\vec{T}$ :: vector of applied torques

Eventually, matrices form in (Sharifah Alwiah *et.al.*,2011) similar to this model but have certain modified because of more links planar are used. Therefore, those matrices can be able to utilize manually calculations for investigating the motion of trunk during lifting and also determine the joint forces and moments acting on the body.

4.0 RESULT AND DISCUSSION

4.1 Description of Lifting Motility

The motion of the subject during lifting a load is shown in Figure 2. The numbered points represent movement of subject which marked in accordance with respective moving: standing position (1), lowering condition (2-4), squatting (5) and lifting a load (6-9). These movements are standardized while collecting a motion data.

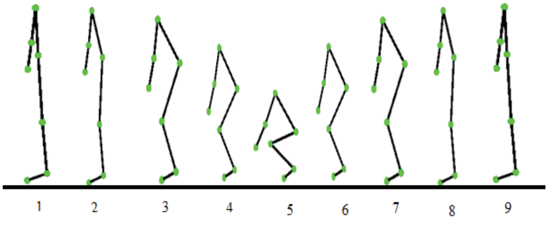
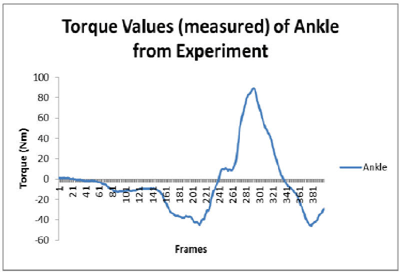


FIGURE 2
The sequential movement of subject during lifting a load which representing in sagittal (side) plane. The spatial position of the each joints are shown by small grey closed circles.

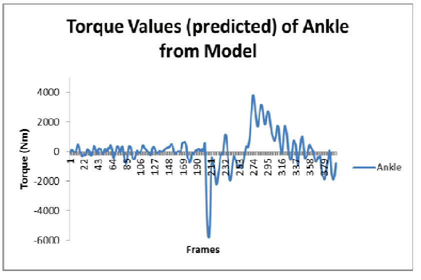
The model development in section 3 is used for determining the value of torque, or moment of force for each joint (ankle and knee) on human body. Another torque of joints, however, will be investigated in different model. Generally, the model developed is utilized the kinematic and anthropometry data (Winter, 2005) obtained from a university student while performing a lifting task. In order to elaborate the rotational movement, three significant points are identified, which represent a point in the phases while a subject performing a lifting movement. All these crucial points are called an event. The first event identified is the standing posture, which occurs in the subject in beginning stage of lifting motion. Then, subject moved slightly anterior relative to body for picking a load during squat lifting technique. During squat lifting, knee is greater flexion and also has a decrease hip flexion. This event is called trunk flexion when subject in lowering condition. Finally, subject is in a follow through phase and her body move upward while lifting a load to initial condition (standing posture).

4.2 Comparison of Experimental (measured) with Model (predicted) results

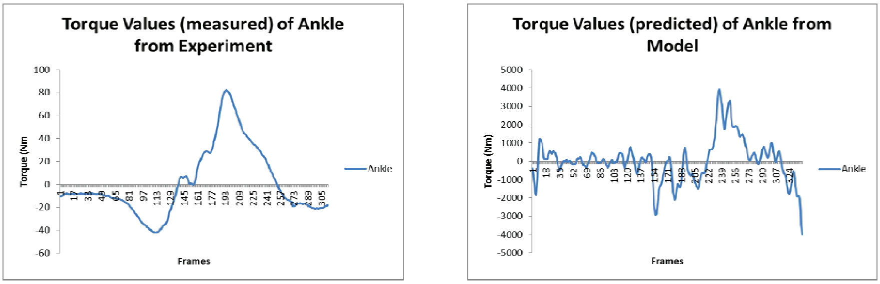
Evaluation the quality of model gives indication about the validity of modeling and experimental results. The validity and quality are identified with served a comparison between modeling and experimental results. Figure 3 depicts the conventions of joint torque at ankle joint from two subjects. These figures able to demonstrate a verification of uselessness model developed with having a comparison between torques values from experiment (Figure 3a and 3c) and model (Figure 3b and 3d).



(a)



(b)



(c) (d)

FIGURE 3

The conventions of joint torque at ankle joint from 2 subjects. Subject 1 are represented a pattern of joint torque (ankle) in (a) from experiment and (b) from model. Similarly, subject 2 are represented

For the convenience of discussion, joint torques calculated by using inverse dynamic with applied Kane's method and called predicted torque, while torques from the experiment results named as a measured torques. As can be seen, torque values or patterns of ankle exclusively showed either from experiment or model results. It is relevant while accomplished a comparison by choosing one items for examine the similarities or differences. Apparently, Figure 3(a) and 3(b) are exhibited an exactly a similar graph patterns of torque values of ankle. Likewise in Figure 3(c) and 3(d). Based on graph below, the values of joint torques are unconsidered because of limitations that influenced the result. One of the limitations is different anthropometric characteristics between subjects. The variances of these characteristics are revealed from Dempster et al since able to summarize and express an average of human anthropometric characteristics. Discrepancies of anthropometric data between human are inherent with having a different of race, sex, age, body mass and others factors. Generalizations of the results are computed for shortcoming these variances. Anthropometric data from (Winter,2005) are utilized for decisive the joint torques.

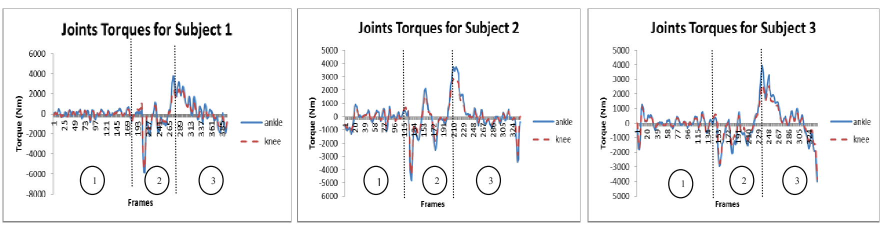
4.3 Joint Torques Prediction using Model

The results of this study indicate that mathematical model using inverse dynamic approach is beneficial for determining the moment of force at human joints. The statistical values of torques (max. and min.) produced by three subjects in lifting task are presented in Table 1. It shows the values of torque are obtained at each joint, such as the ankle and knee joint, while subject is performing the lifting task. Lifting posture in time variation is defined by selecting the statistical values (maximum and minimum) of torque for each joint. As can be seen, in each of events have own values of joint torque whether in positive and negative value.

TABLE 1
Selected statistical values of torques (max. and min.) produced by human body in three

Subjects	Joints	Values of torque in three phases (Nm)					
		Standing (1)		Lowering (2)		Lifting (3)	
		Max.(peak)	Min.	Max.	Min.(peak)	Max.(peak)	Min.
1	**Ankle**	650.4278	-798.186	1142.574	-5798.04	3789.361	-1911.42
	Knee	414.0394	-613.325	1025.968	-5456.44	2419.127	-1399.62
2	**Ankle**	866.2527	-1323.69	2918.828	-4857.15	3749.484	-3444.68
	Knee	664.6865	-1027.26	2284.641	-4367.09	2847.696	-2934.52
3	**Ankle**	1240.259	-1848.47	764.3639	-2925.16	3944.329	-4013.94
	Knee	1078.351	-1748.34	611.4754	-2733.29	2692.748	-3833.3

A two link-segment analysis yields the moment of force at every joint during the time course of lifting movement. Figure 4 illustrates value of torques has changes as movement of subject. The figure is depicted value of torques (Nm) in vertical axes while time in frames in horizontal axes. In Figure 3, three events are divided for segmentation process with synchronize on motion analysis. There is a standing, lowering and lifting events. Through these figures, trajectory of ankle and knee torque was nearly to the zero torque at starting time. In lowering condition, however, the ankle and knee torque decreased sharply for three subjects then increased slowly until exist a lifting event. All description of lifting movements is examined by using the moment of force curves or pattern.



(a) (b) (c)

FIGURE 4
Torques of joints at each segment from standing posture, lowering, and lifting position. The knee torque is represents in dash line while a solid line for ankle torques value. These figures are instantiated in three subjects of joints torques.

In joint movement terminology, bending and straightening movement are donated as flexion (negative sign) and extension (positive sign), respectively. The phase of flexion movement (standing and lowering) was significantly different values of torque with extension movement (lifting). Based on Table 1, standing and lowering events are considered as a maximum (max) values to demonstrate their movement equated to lifting event which selected a minimum (min) value. As explained details on the above discussion, Figure 4 has been illustrated on the changes or transition of torque on the joint in each position.

Nonetheless, while subject is in standing or initial position, forces to make next movement are generated by upper body to generate the downward vertical component of force. Then the force gained transferred from upper by sequential to the trunk toward to lower extremity. Afterward, the trunk rotates then force is transmitted to the knee and ankle to achieve an event of lifting a load from floor to waist height of subject. At this point, subject 1 produced the value of torque for ankle joint is greater than knee joint which is 3789.361 Nm while subject 2 and subject 3 are committed 3749.484 Nm and 3944.329 Nm, respectively. The greater value of torque at ankle joint contributes to bend of the knee for keeping the back straight.

During the extension movement of lower extremity, the lower extremity has full force to execute the standing back. Hence, the transfer force from knee to ankle acceleration. Finally, in the follow through phase, the value of torque at each joint decrease as subject in initial condition (standing phase).The convention for the moment of force is assign in counterclockwise moments acting on a segment distal to the joint are positive, hence clockwise moments are negative (Hall,2007). Thus, a knee and ankle flexor moment is shown to be negative and also knee and ankle extensor moment is positive during a person lifted a load. Therefore, the direction of a torque is the most important to characterize some of lifting movement. Otherwise, results of model simulation in figure also demonstrated a comparison between value of knee and ankle torque. The primary finding of this study was that significantly observed in order to understand value of moment of force during lifting task. Through this simulation, it was shown that the greater peak (min) knee torque are tangible than ankle torque during lowering event. In contrast to lifting event, the ankle torque is obtained greatest values (max. peak) than knee torque. Andrew et al. pointed out that knee torque are produced a greatest value than ankle torque during lowering condition (Fry et.al.,2003). They examined that squat lifting may minimize the stress on knee when the knees were permitted to move anteriorly past the toes.

In this research work, a model development using dynamic equation of motion via Kane's method is proposed. The model is valuable for biomechanics research whose is going in depth in mathematical model which represent the reality of human movement especially in lifting task. An accurate result because of derivation for each segment of body is inter-related that may be better produced. All of variables have been considered systematically. This model also can be utilized the any method to represent the dynamic equation of motion such as Newton- Euler, Gordon method and other related methods. Interestingly, Kane's method have own beneficial studies due to derivation procedure that first order derivation are considered. They emphasized all movement on each rigid bodies of human movement.

5.0 CONCLUSIONS

In conclusion, the lower extremity are in flexion position during lowering phase has achieve negative value of torque compared to extension position during lifting material. Therefore, a mathematical model has been presented by using Kane's dynamical equations of motion is able to provide the torques values and description of trunk motion during lifting techniques especially in squat lifting. This work is important because it shows that a motion analysis coupled with Kane's method provides human with revelation information about where their greatest torque when performing an activity especially this task.

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