International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249 – 8958, Volume-9 Issue-1, October 2019

Determination of Joint Load of Human Lower Limb by Using 2D Inverse Dynamics Modelling

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Abstract**: *The human lower limb is a major part of the human body that is exposed to high joint load during daily activities. Different lifestyles and cultural activities can affect the loading condition generated at the joint during motion. For instance, deep squatting is more frequently performed by Asians compared to Europeans e.g. kneeing on tatami among Japanese and sitting position during prayer among Muslims. The aim of this research is to determine the joint load of the human lower limb during the squat lifting movement by using inverse dynamics of 2-dimensional (2D) human lower limb model. The 2D inverse dynamics modelling was used to describe and compute all the joint force reactions from the known ground reaction and lower limb kinematics. In this study, 2D human lower limb model was analysed during the squat lifting movement. Inverse dynamics computation was performed using MATLAB programming based on Newton-Euler equations to determine the joint forces and moments. The joint loads at ankle, knee and hip joints for every knee flexion angle were obtained and the maximum forces at the ankle, knee and hip were 613.9, 614.1 and 596.1 N, respectively.***

Keywords**: *inverse dynamics, lower limb, squat lifting, joint load, joint moment***

I. INTRODUCTION

Biomechanics analysis of the human lower limb has received numerous attentions and is extremely useful in supporting the therapy and diagnosis in the medical field. The research on human lower limb kinematics and its corresponding kinetics are mostly associated with daily movement and lifestyle. Kinematics and kinetics analysis of lower limb are crucial in order to give more insight for the medical field practitioner e.g. to design a lower limb prosthesis and orthoses. Determination of lower limb joint loads during walking activities was carried out in several recent literatures [1-5]. These studies reported the effect of walking speed [3,5] and ground inclination [4] on lower limb joint forces and moments. However, the mechanics of lower limb joints during deep squatting activity was less pronounced among researchers. Deep squat is defined as a squatting motion in which the knee flexion angle reached is beyond 100° [6]. As compared to Europeans, this movement is more frequently performed by Asians during their cultural and spiritual activities e.g. kneeing on tatami among among

Japanese and sitting position during prayer among Muslims. To accommodate the requirement and loading condition for Asians in the design of hip, knee and ankle prostheses, it is essential to study the joint forces and moments during deep squatting motion.

Inverse dynamics is a technique of computing joint reaction forces and moments in a multi-body system by using measured kinematics and external forces [7]. This technique was used in biomechanical analysis to calculate joint loads and muscle forces in both upper [8-10] and lower limbs [1-5, 11-12]. Elliott et al. reported the effects of various tennis serving techniques on the shoulder and elbow joint loads. Kinematic data was measured using 200 Hz video cameras and the joint loads just before the racket-ball impact were determined using inverse dynamics technique [8]. Pontonnier and Dumont, meanwhile, proposed an optimization technique in cooperated with inverse dynamics solution to estimate the biceps and triceps muscles forces [9]. Application of inverse dynamics in human lower limb, however, was mostly concentrated on knee joint force and moment reactions. This paper considers determining the load and forces applied at the every joint: hip, knee and ankle during the deep squatting motion.

II. METHODS

It is important to develop an appropriate human biomechanics model that represents every structure and mechanics for each segment of the human lower part. In this study, a biomechanical model of the lower limb was developed which consists of three major segments namely thigh, calf and foot. The lower limb model was constructed corresponding to the relevant anatomical segments of human lower limb as shown in Figure 1. These three rigid bodies were connected by revolute joints and described by the basic point for each location of the joints to represent hip, knee, and ankle. The moments and forces at those joints were then analysed using the Euler-Newton Equations.

Revised Manuscript Received on October 30, 2019.

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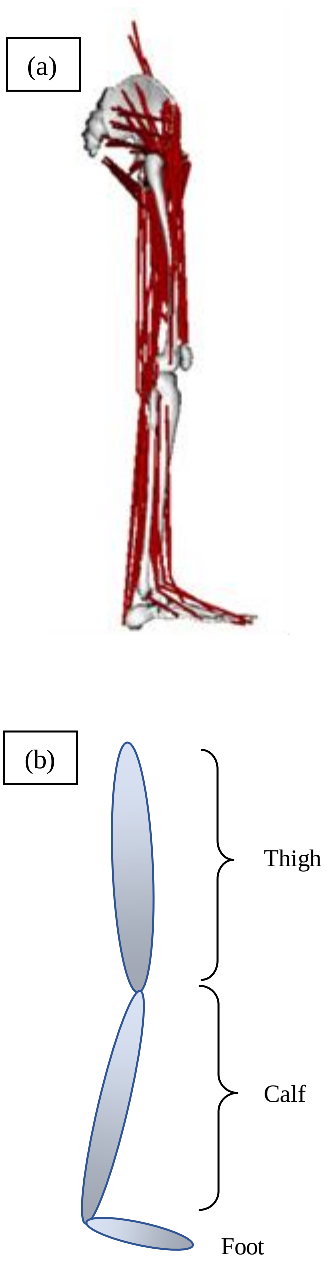

(b)

Fig. 1. (a) Musculoskeletal model of human lower limb [13]. (b) Lower limb segments which consist of foot, calf and thigh.

The anthropometric data is important in order to determine the measurement and physical geometry, mass properties and strength capabilities of human body [14]. The anthropometric dimension and mass properties of twelve subjects (H = 169.05 ± 1.45 cm, m = 66.0 ± 1.8 kg) were calculated according to Winter [14]. Based on the anatomical model, a link segment model was developed to estimate internal forces and moment of forces of lower limb joints.

The force and moment of force acting on each joint were calculated proximally from ground reaction force where acceleration of COM, angular acceleration and inertial properties of each segment were known. The calculated net forces and moment of forces represented the summation of net effects of forces of respective lower limb joint structures in producing movement. Each of the lower limbs joint is responsible for the individual steps of human movement [16]. The effects of forces and moment of forces acting at the joints were determined based on the free-body diagram and inertial force diagram of lower limb as shown in Figure 2 and Figure 3. and inverse dynamics solution by using Second Newton's Law general equation and moment equation as follows:

Newton's equation (Translation)

$$\sum \underline{F} = m\underline{a} \quad (1)$$

Euler's equation (Rotation)

$$\sum \underline{M} = I\underline{\alpha} \quad (2)$$

where F is force, m is the mass of segment, a is the acceleration of segment COM, M is moment or torque, I is the mass moment of inertia of segment and α is the angular acceleration of segment.

Nomenclature

g	gravitational acceleration (9.81 m/s^2)
m_t, m_c, m_f	mass of thigh, calf and foot
a_t, a_c, a_f	acceleration of COM of thigh, calf and foot
F_h, F_k, F_a	force reactions at hip, knee and ankle joints
M_h, M_k, M_a	moment reactions at hip, knee and ankle joints
GRF	ground reaction forces
x	component represents anterior-posterior direction
y	component represents proximal-distal direction

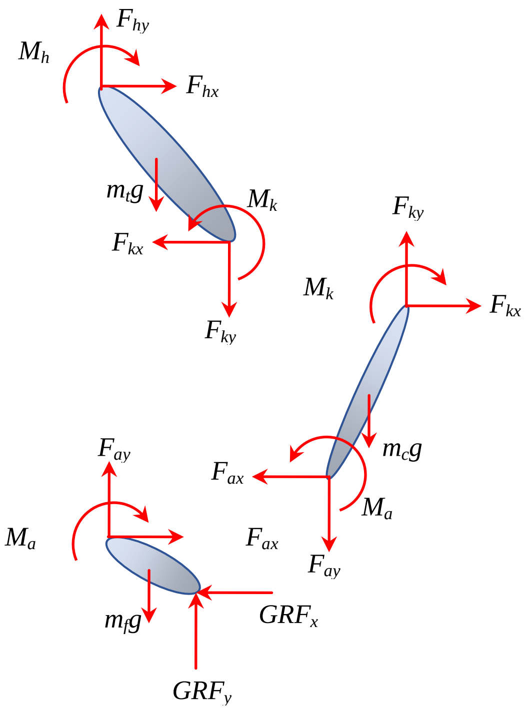

Fig. 2. The free-body diagram of the lower limb.

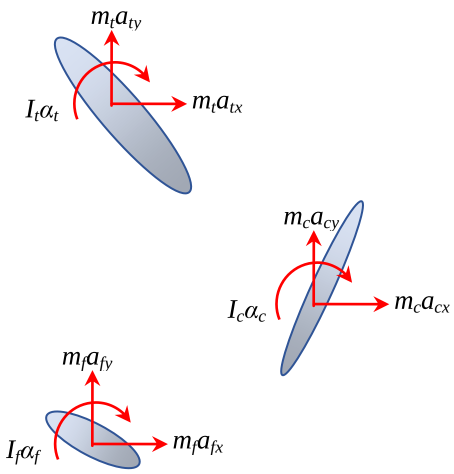

Fig. 3. The inertial force diagram of the lower limb.

The process by which the reaction forces and muscles moment are calculated is called link segment modelling [10]. The full kinematic of the lower limb and the anthropometric data of the subject and external and ground forces, will allow the determination of the load joint by computing the forces acting on the link segment model. There were a few assumptions made during the link segment model development. First, each segment was modelled as a fixed mass and was considered as a point mass at its COM. Second, the location of the COM was assumed to be constant throughout the movement. Third, the mass moment of inertia of each link segment about its COM was assumed to be constant during the movement. Method of section was applied which considered the forces acting on the link segment such as ground reaction, force reactions and gravitational forces which were due to gravitational acceleration (g = 9.81 m/s²).

In the case of slow squat lifting, the forces described in the preceding section, the original link-segment is divided into three segments starting from the ground to the ankle, ankle to the knee joint and knee to the hip. Considering the joint reaction forces on the bone, the calculation was started from the ground which took the value of vertical reaction force acting on the foot, exerting upward forces on the leg that equal to the weight of foot in net summation of external forces in Newton's equation. The load joint at the ankle was obtained from calculation and the consequence calculations were used to determine the knee joint load when the net forces and moment summation counted in all the external forces such as weight of leg segment and mass moment of inertia. As far as the higher segment was concerned, the net reaction of the load at the hip joint was determined by summing up all the forces acting on the thigh segment and the corresponding thigh movement via Newton's Equation.

The vertical ground reaction forces during squatting were taken from previous work by Vahdat and Tabatabai [17]. In the present study, the squat lifting was assumed to be performed in slow motion, hence the acceleration of COM of each segment and its angular acceleration were approximated to be nearly zero. Subjects were assumed at the same body posture when the squat lifting initiated.

III. RESULTS AND DISCUSSION

Figure 4 shows the result of the forces acting at every joint of the lower limb. Following the squat lifting movement, it was observed that the load at every joint decreased with knee flexion angles. According to the results, the maximum force was obtained at 20° at every joint.

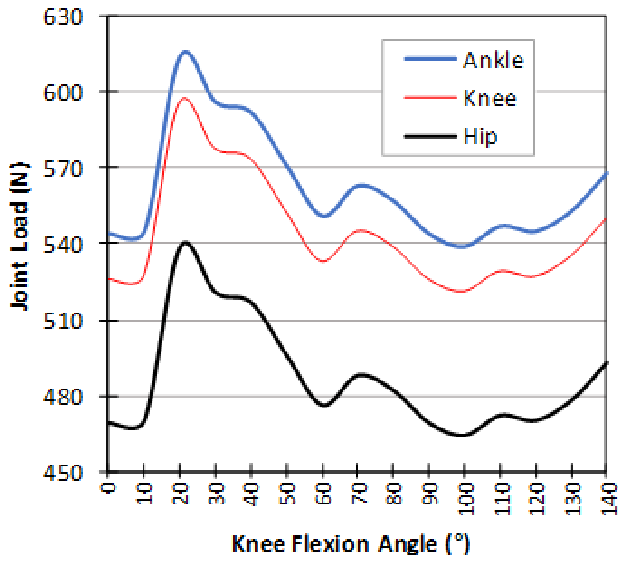

Fig. 4. Joint load versus knee flexion angle.

Ankle joint reached the highest maximum joint force (614 N), followed by knee joint (596 N) and hip joint (538 N). As lifting from the squat position, it can be observed that the load value decreased as it reached the normal standing position. During squat lifting, the COMs of thigh and calf were shifted to the proximal distal axis (vertical axis) of the human body. The moment exerted by the muscles to actuate the movement were reduced, led to the reduction of joint reaction at every joint. The knee joint load determined in this study however was much lower as compared to inverse dynamics solution by Dahlkvist et al. [11]. In the present study, the motion was assumed to be quasi static where the acceleration and angular acceleration of the segments approached zero. Dahlkvist et al. have taken into consideration the dynamic force exerted by each segment, hence the force reaction computed at every joint became substantially higher.

Figure 5 shows the joint moment reactions obtained at different joint angles. The joint moment was found to decrease with flexion angle from squat to standing position. The maximum joint moment was recorded between 0.6 to 1.1 Nm/kg whereas the ankle joint exerted the highest maximum joint moment while knee joint obtained the lowest maximum joint moment (0.64 Nm/kg). The muscle at the ankle joint exerted higher magnitude of force to actuate the rotation of this joint which is subjected to the weight of calf, shank and upper limb which are more proximal from ground.

The knee joint moment exhibited similar pattern with moment profile of double leg squat lifting obtained by Nagura et al. [18]. The maximum knee joint moment of 0.65 Nm/kg however was far lower compared with 2 Nm/kg as reported by Nagura et al. due to underestimation of inertial force generated by the movement of thigh and calf segments.

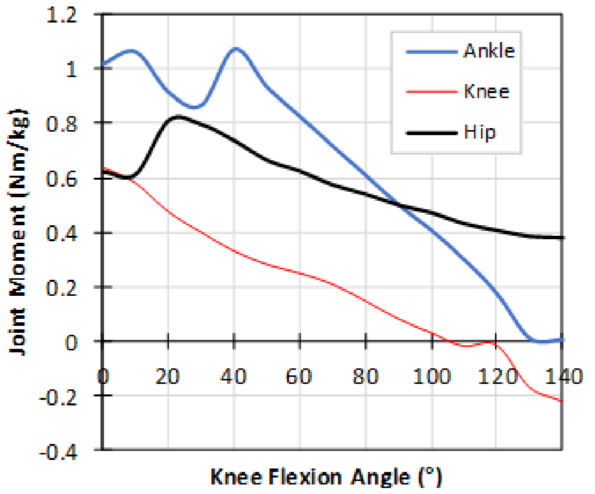

Fig. 5. Joint moment reaction versus knee flexion angle

This study was subjected to some limitations. The analysis was carried out by using a two-dimensional model of lower limb. Human lower limbs can undergo a complex movement and perform a multiple-degree of freedom of motion. However, the component of joint reaction force in mediolateral direction is predicted to be negligible as compared to other two components during squatting motion. Morrison has reported that the knee joint force in mediolateral component was only 0.2 times body weight during walking gait and could be much lower during squatting motion [19]. Apart from that, the inverse dynamics technique was applied by assuming that the lower limb was undergoing a quasi-static motion. The kinematics data includes acceleration of COM and angular acceleration of each segment should be taken into consideration during the computation of joint reaction forces and moments to produce more realistic joint kinetics of human lower limb.

IV. CONCLUSION

In this study, the joint load of the human lower limb by using inverse dynamics modelling during the squat lifting movement was successfully carried out. Dynamics analysis has clarified that deep squat flexion gave substantial amount of loads to the joint and can contribute to the deterioration of the human joint. The data of joint loads of human lower limb under squatting motion is beneficial for the development of joint implants as well as for therapy purposes for patients among Asians.

ACKNOWLEDGMENT

The author would like to thank the Research Management Institute (RMI) of Universiti Teknologi MARA (UiTM) and Ministry of Education, Malaysia for financial support through Research Grant awards 600-IRMI/DANA 5/3 BESTARI(P)(058/2018).

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Muhamad Sharifudin Mat Intan was an undergraduate student at Faculty of Mechanical Engineering, Universiti Teknologi MARA, Malaysia from 2015 to 2018. He has carried out his final year project under the supervision of Dr. Mohd Afzan on inverse dynamics of human lower limb under deep squatting motion using MATLAB programming. He is currently a Process Engineer at Kossan Industries Sdn. Bhd., Malaysia.

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