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Biomechanical Evaluation of Joint Torque and Muscle Activation Parameters for Single Leg Squat Activity

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Abstract

Background: Yoga, originated in ancient India, is a spiritual and ascetic discipline, a part of which, including variety of aasanas, and other yogic techniques through adoption of specific bodily postures, widely practiced for health and relaxation. "Eka Paada Kaakasana" or Single leg squat activity is one such aasana in yoga that helps in maintaining the lower extremity antigravity muscles. It is a dynamic posture in which muscles and joints of the lower human body are actively used to perform the activity. Hence, it is necessary to understand the muscle activation patterns and the joint mechanical parameters of the body.

Aim: The purpose of this study is to understand human body dynamics for "Eka Paada Kaakasana" or Single leg Squat activity. Human motion capture data is recorded through experimentation using inertial measuring units. Analyzing the activity, the moments/torque of the joints and muscle activation pattern of the lower human body (Ankle, Knee and Hip) is obtained.

Materials and Methods: x-IMUs, a combination of 3 accelerometers, magnetometers and gyroscopes is used to measure the angular displacement and position in 3D plane of different segments of the lower body. LifeMOD™, virtual human simulation software is used to simulate the motion. A mathematical model is formulated in Matlab to validate the results.

Results and Conclusion: The results obtained in the form of joint torques in various lower body is validated using mathematical model. Subsequently the major skeletal muscles actively participating the activity are studied using muscle activation patterns.

Keywords: Lagrangian dynamics; Muscle activation; Eka paada kaakasana; Inertial measurement unit; LifeMOD™

Introduction

Human body is a complex mechanical system capable of performing a wide variety of activities. Technological advancements such as optical sensor human motion tracking and body mounted measurement sensors integrated with a suitable virtual simulation models has helped us understand the biomechanical system satisfactorily [1]. Angular displacement, angular velocity and angular acceleration are a few biomechanical parameters to mention that helps us to understand the activity that takes place in various human segments during a motion [2]. These kinematic data parameters are basic data set for all inverse dynamic calculations and by knowing them, together with some basic anthropometry data, force, work, moment and other parameters can be calculated.

Yoga is practiced worldwide and providing a scientific base of approach and quantifying various biomechanical parameters becomes necessary to understand yoga and train better. Squatting is one exercise that is important component of athlete training [3]. "Eka Paada Kaakasana" or Single leg squat (Figure 1), a dynamic yoga posture is studied in this project.

Steps to follow to perform this aasana:

1. Stand upright with heel and toes together (mountain pose).
2. Slowly flex the knees taking the hips downward.
3. Stretch the arms forward and sit to the maximum possible extent.
4. Ensure that both the feet are completely on the ground; especially heels should not raise up.
5. Raise the right heel up and stretch the right leg forward.
6. Ensure that the right leg does not touch the ground.
7. Pull the knee cap and stretch the heel on the right leg; toes must point towards the knee.
8. Stay for 5-10 cycles of slow deep breathing and then take

Figure 1: Member performing single leg squat.

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the right foot back to position.

9. Repeat on the other leg.

Optical sensor human motion tracking is one of the most well known ways of human motion tracking. This method of tracking has a number of limitations. A specified software and hardware is required to carry out this process. A large space is required to carry out experimentation using this process [4,5]. Taking all these limitations into consideration, a more cost effective and efficient way of human tracking using inertial based motion sensors is adapted in this project [5].

These results are in turn validated using a mathematical model formulated using Lagrangian Dynamics. The main advantage of Lagrangian mechanics is that we don't have to consider the forces of constraints and given the total kinetic and potential energies of the system we can choose some generalized coordinates and blindly calculate the equation of motions totally analytically unlike Newtonian case where one has to consider the constraints and the geometrical nature of the system. The Lagrangian dynamic equations used in this study are obtained from [11,12], which are used widely for similar kind of validations.

Muscle Activation is movement of muscle fibres in response to force or load. This is an important aspect of study, since it helps us understand the way the muscle functions while performing an activity. A study is carried out on muscle activation while performing pull ups, high speed and, low speed yoga and gait using surface EMG [6-8]. Limited studies are carried out on this basis to understand yoga which is one of the motivations to carry out this project.

Surface Electromyography (EMG) is an electro diagnostic medicine technique for evaluating and recording the electrical activity produced by skeletal muscles [9]. Surface EMG can have limited applications due to inherent problems associated with it. Adipose tissue (fat) can affect EMG recordings. As adipose tissue increases, the amplitude of the surface EMG signal directly above the centre of the active muscle decreases. EMG signal recordings are typically more accurate with individuals who have lower body fat, and more compliant skin, such as young people when compared to old. Muscle cross talk occurs when the EMG signal from one muscle interferes with that of another limiting reliability of the signal of the muscle being tested. Surface EMG is limited due to lack of deep muscles reliability. Deep muscles require intramuscular wires that are intrusive and painful in order to achieve an EMG signal. Surface EMG can only measure superficial muscles and even then it is hard to narrow down the signal to a single muscle [10]. Life MOD™ is one such software platform that helps us overcome these limitations and help us obtain muscle activation without any difficulties.

Postural/antigravity muscles [10] are the group of muscles that are primely studied in this paper to understand its activity while performing this aasana and in turn to gain knowledge and benefits of training with this posture for rehabilitation and various other purposes.

Experimentation and Methods Followed

Data recording

The test consisted of one individual, weight 65 kg, height 165cm; subject was healthy, without any acute or chronic problems of the musculoskeletal system. From the case history of the subject no neurological, visual or vestibular deficits were found. The test individual was fitted with 5 x-IMUs, one each on upper torso, right thigh, and shank and left thigh and shank. Initial calibrations were made in the x-IMUs using the GUI provided. The individual was trained to perform "Eka Paada Kaakasana" a number of times to make him familiar with the way the measurement unit works. Then the data was recorded in the x-IMUs at 128Hz with a Butterworth filter of order 6.

The x-IMU was designed to be the most versatile Inertial Measurement Unit (IMU) and Attitude Heading Reference System (AHRS) platform available. Its host of on-board sensors, algorithms, configureurable auxiliary port and real-time communication via USB, Bluetooth or UART make it both a powerful sensor and controller. The on-board SD card, battery charger (via USB), real-time clock/calendar and motion trigger wake up also make the x-IMU an ideal standalone data logger.

The x-IMU GUI can be used to configureure settings, view real-time sensor data, perform calibration and export data to user software; e.g. Microsoft Excel. The x-IMU MATLAB library provides all the tools required to import, organize and plot data in MATLAB. User software can be developed using the x-IMU API.

Quaternion and Euler angles are obtained from the x-IMUs. The quaternion obtained is converted into (x,y,z) co-ordinates data to obtain the position of the segments in 3D plane.

Mathematical modeling

Lagrangian dynamics is a base for the mathematical model created in our project. The equations of motion were derived from the basic equation for a better understanding of what are the important governing parameters in the equation. In performing this yoga posture, 2 different set of equations comes into picture as one leg is in contact with the ground throughout the posture and the other is lifted above the ground. For mathematical formulation one leg is considered to be fixed at the ground and the other to be fixed at the hip joint. In this experimentation left leg is considered to be in

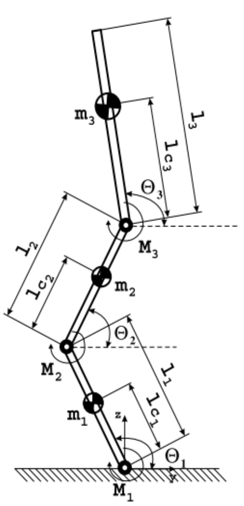

Figure 2: Mathematical model for leg in contact with ground.

contact with the ground and right leg free.

The mathematical model for the fixed leg and the equations of motion for the same is as follows (Figure 2) [11]. The segment l_1 represents shank, l_2 represents thigh and l_3 represents HAT. The mass of each segment is considered to be concentrated at the centre of each segment. The shank is considered to be fixed to the ground. (Equation 1 to 3).

$$\ddot{\theta}_1\left(m_1 l_{C1}^2 + m_2 l_1^2 + m_3 l_1^2 + l_{X1}\right) + \ddot{\theta}_2\left(m_2 l_1 l_{C2} + m_3 l_1 l_2\right)\cos\left(\theta_1 - \theta_2\right) + \ddot{\theta}_3 m_3 l_1 l_{C3}\cos\left(\theta_1 - \theta_3\right)$$
$$+\ddot{\theta}_2^2\left(m_2 l_1 l_{C2} + m_3 l_1 l_2\right)\sin\left(\theta_1 - \theta_2\right) + \ddot{\theta}_3^2 m_3 l_1 l_{C3}\sin\left(\theta_1 - \theta_3\right)$$
$$+g\left(m_1 l_{C1} + m_2 l_1 + m_3 l_1\right)\cos\theta_1 = M_1 - M_2$$

For the shank,…………………………………………..(1)

$$\ddot{\theta}_2\left(m_2 l_{C2}^2 + m_3 l_2^2 + l_{X2}\right) + \ddot{\theta}_1\left(m_2 l_1 l_{C2} + m_3 l_1 l_2\right)\cos\left(\theta_1 - \theta_2\right) + \ddot{\theta}_3 m_3 l_1 l_{C3}\cos\left(\theta_2 - \theta_3\right)$$
$$-\ddot{\theta}_1^2\left(m_2 l_1 l_{C2} + m_3 l_1 l_2\right)\sin\left(\theta_1 - \theta_2\right) + \ddot{\theta}_3^2 m_3 l_2 l_{C3}\sin\left(\theta_2 - \theta_3\right) + g\left(m_2 l_{C2} + m_3 l_2\right)\cos\theta_2$$
$$= M_2 - M_3$$

For the thigh,…………………………………………..(2)

$$\ddot{\theta}_3\left(m_3 l_{C3}^2 + l_{X3}\right) + \ddot{\theta}_1 m_3 l_1 l_{C3}\cos\left(\theta_1 - \theta_3\right) + \ddot{\theta}_2 m_3 l_2 l_{C3}\cos\left(\theta_2 - \theta_3\right) - \ddot{\theta}_1^2 m_3 l_1 l_{C3}\sin\left(\theta_1 - \theta_3\right)$$
$$-\ddot{\theta}_2^2 m_3 l_2 l_{C3}\sin\left(\theta_2 - \theta_3\right) + g m_3 l_{C3}\cos\theta_3 = M_3$$

For the hat…………………………………………….(3)

Where,

li – segment length,

l_{Ci} – position of segment CoM in respect to distal joint,

l_{Xi} – segment moment of inertia,

m_i – segment mass.

theta - angular displacement

theta’ – angular velocity

theta” – angular acceleration

The mathematical model for free leg and the equation of motion for the same is as follows (Figure 3) [12]. The hip is considered to be fixed in this mathematical model. Relative angles are obtained which are then converted to angles with respect to horizontal plane. (Equation 4 to 14).

The following are the parametric equations considered in the mathematical model

$$X_3 = -m_f h_{G_f} \quad (4)$$

$$Y_3 = m_f L_{G_f} \quad (5)$$

$$X_2 = m_s\left(L_s - L_{G_s}\right) + m_f + L_s \quad (6)$$

$$Y_2 = m_s h_{G_s} \quad (7)$$

$$X_1 = m_t\left(L_t - L_{G_t}\right) + m_s L_t + m_f L_t \quad (8)$$

$$Y_1 = m_t h_{G_t} \quad (9)$$

$$J_3 = I_f + m_f\left(h_{G_f}^2 + L_{G_f}^2\right) \quad (10)$$

$$J_2 = J_3 + I_s + m_s\left(\left(L_s - L_{G_s}\right)^2 + h_{G_s}^2\right) + m_f L_s^2 \quad (11)$$

$$J_1 = J_2 + I_t + m_t\left(\left(L_t - L_{G_t}\right)^2 + h_{G_s}^2\right) + m_s L_t^2 + m_f L_t^2 \quad (12)$$

where,

$L_{f,s,t}$ – segment length,

$L_{Gf,s,t}$ – position of segment CoM in respect to distal joint,

$H_{gf,s,t}$ – offset distance,

$m_{f,s,t}$ – segment mass.

Note that θ_{12} denotes $\theta_1+\theta_2$, θ_{23} denotes $\theta_2+\theta_3$ and θ_{123} denotes $\theta_1+\theta_2+\theta_3$. Similarly, θ_{12} denotes $\theta_1+\theta_2$ and so on. Offset distance is $h_{Gf,s,t}$ is 0.

The torque equation for knee joint is,……………….(13)

$$[J_2 + 2L_s\left(X_3\cos\theta_3 - Y_3\sin\theta_3\right) + L_t\left(X_3\cos\theta_{23} - Y_3\sin\theta_{23}\right)$$
$$+L_t\left(X_2\cos\theta_2 - Y_2\sin\theta_2\right)]\ddot{\theta}_1 + \left[J_2 + 2L_s\left(X_3\cos\theta_3 - Y_3\sin\theta_3\right)\right]\ddot{\theta}_2$$
$$+\left[J_3 + L_s\left(X_3\cos\theta_3 - Y_3\sin\theta_3\right)\right]\ddot{\theta}_3 + L_t\left(X_2\sin\theta_6 - Y_2\cos\theta_6\right)\dot{\theta}_1^{2}$$
$$+L_t\left(X_3\sin\theta_{23} - Y_3\cos\theta_{23}\right)\dot{\theta}_1^2 + L_s\left(X_3\sin\theta_3 - Y_3\cos\theta_3\right)\left(\dot{\theta}_{12}^2 - \dot{\theta}_{123}^2\right)$$
$$+g\left(X_2\sin\theta_{12} + Y_2\cos\theta_{12} + X_3\sin\theta_{123} + Y_3\cos\theta_{123}\right) = T_2$$

The torque equation for hip joint is,………………..(14)

$$[J_1 + 2L_s\left(X_3\cos\theta_3 - Y_3\sin\theta_3\right) + 2L_t\left(X_3\cos\theta_{23} - Y_3\sin\theta_{23}\right)$$
$$+2L_t\left(X_2\cos\theta_2 - Y_2\sin\theta_2\right)]\ddot{\theta}_1 +$$
$$\left[J_2 + 2L_s\left(X_3\cos\theta_3 - Y_3\sin\theta_3\right) + L_t\left(X_3\cos\theta_{23} - Y_3\sin\theta_{23}\right) + L_t\left(X_2\cos\theta_2 - Y_2\sin\theta_2\right)\right]\ddot{\theta}_2$$
$$+\left[J_3 + L_s\left(X_3\cos\theta_3 - Y_3\sin\theta_3\right) + L_t\left(X_3\cos\theta_{23} - Y_3\sin\theta_{23}\right)\right]\ddot{\theta}_3$$
$$+L_t\left(X_2\sin\theta_6 + Y_2\cos\theta_6\right)\left(\dot{\theta}_1^2 - \dot{\theta}_{12}^2\right) + L_t\left(X_3\sin\theta_{23} + Y_3\cos\theta_{23}\right)\left(\dot{\theta}_1^2 - \dot{\theta}_{123}^2\right) +$$
$$L_s\left(X_3\sin\theta_3 + Y_3\cos\theta_3\right)\left(\dot{\theta}_{12}^2 - \dot{\theta}_{123}^2\right) +$$
$$g\left(X_1\sin\theta_1 + Y_1\cos\theta_1 + X_2\sin\theta_{12} + Y_2\cos\theta_{12} + X_3\sin\theta_{123} + Y_3\cos\theta_{123}\right) = T_1$$

Matlab is a programming and numerical analysis environment that is used for processing the required parameters that is modelled mathematically.

Simulation of the motion in LifeMOD™

The data sets obtained from x-IMUs are then used in Life MOD™. First the anthropometric data is set. The required joints in the human body are defined and the soft tissues are added. The motion agents to obtain the posture are then exported from the x-IMU data. Then once the model is ready the motion is analyzed. This procedure followed is called as Inverse Dynamics. Then the muscles and joints are trained and the motion is again analyzed with the motion agents disabled. This is called as forward dynamics (Figure 4). Once the motion is obtained the biomechanical parameters are checked. First the orientation of

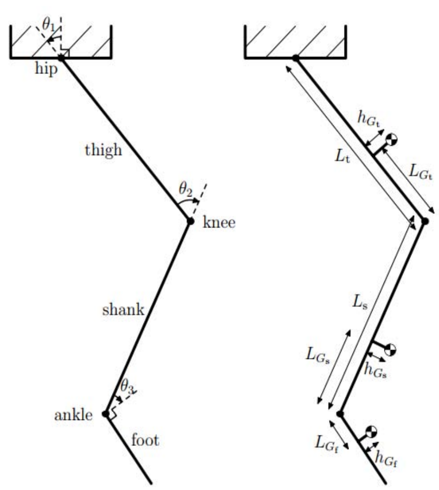

Figure 3: Mathematical model for free leg.

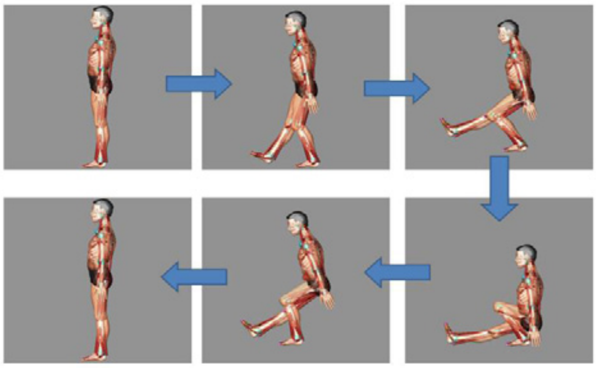

Figure 4: Eka Paada Kaakasana simulation in LifeMOD™.

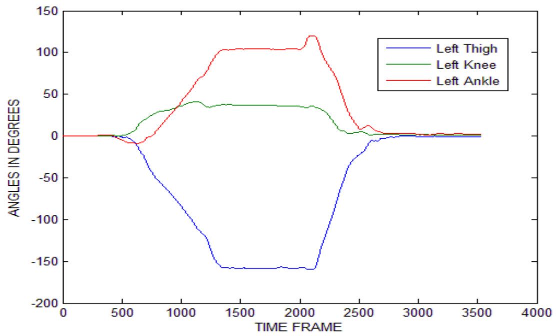

Figure 5: Angles of the fixed leg.

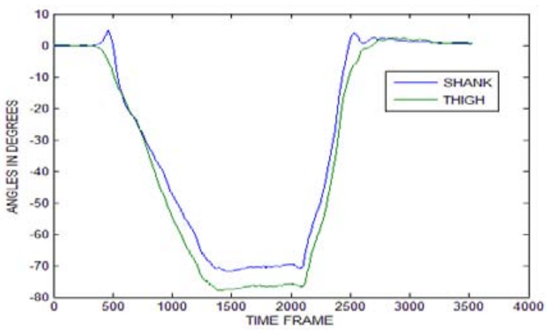

Figure 6: Angles of the free leg.

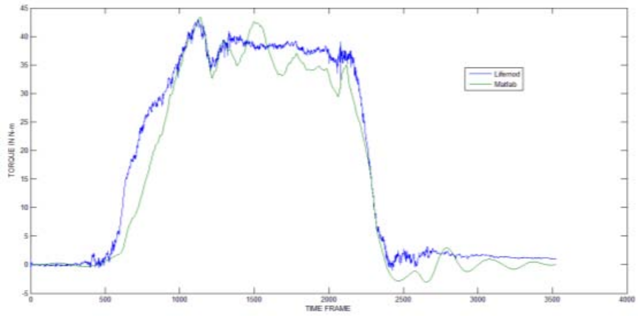

Figure 7: Torque in the ankle joint of the leg in contact with ground.

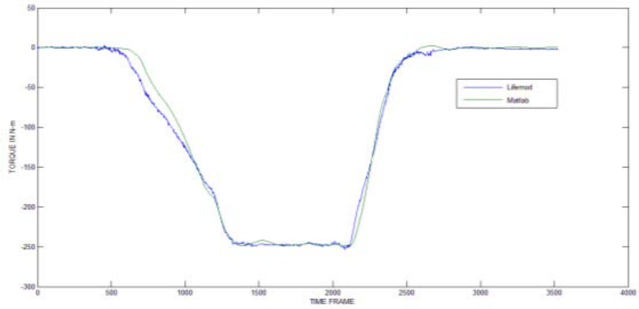

Figure 8: Torque in the knee joint of the leg in contact with the ground.

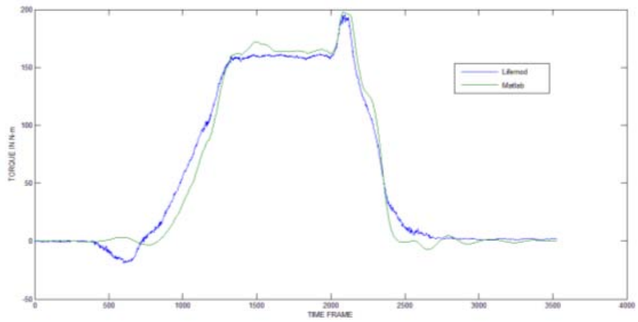

Figure 9: Torque in hip joint of the leg in contact with the ground.

the angles and torque graphs is checked with the one obtained in the Matlab code. Once the orientation matches the magnitude of the graph values are matched by altering the stiffness value of the joints. The stiffness value that gives the exact magnitude is the stiffness of the joint while performing the yoga posture. The muscle activation results are then extracted from the results data display window.

Results

From the equation considered in the mathematical model, it is noticed that torque/moment primarily depends upon the angular displacement. It is of prime importance to ensure that the angles used in Life MOD™ and the ones in Matlab (recorded from x-IMUs) matches satisfactorily so that right torque values can be obtained and validated. (Note torque is in N-m and angles are in degrees).

From (Figure 5) it is seen that the angular displacement of the left leg in knee and hip joint is maximum and the angular displacement in the ankle joint is minimum.

From (Figure 6) the angular displacement of the right hip and knee is depicted which is almost similar in magnitude. The ankle of the right leg remains in the same posture throughout the a asana. Hence, the angular displacement is quite negligible and is omitted.

The following Figureures (Figures 7-11) shows the torque graphs in various joints while performing the aasana. A comparitive graph is shown in each Figureure which contains a graph result from Life MOD™ and Matlab plotted together for validation purpose. It is observed that the torque increases in the joints when the performing member reaches down to the final position and decreases (increases in the opposite direction) when returning back to the initial position. The torque validation is complete at this stage and results is tabulated

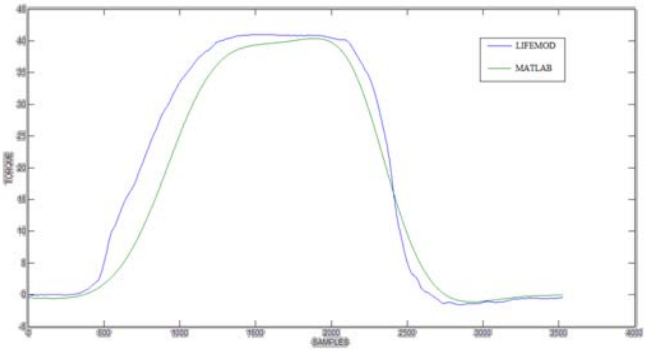

Figure 10: Torque in hip joint of the leg not in contact with ground (Torque in N-m).

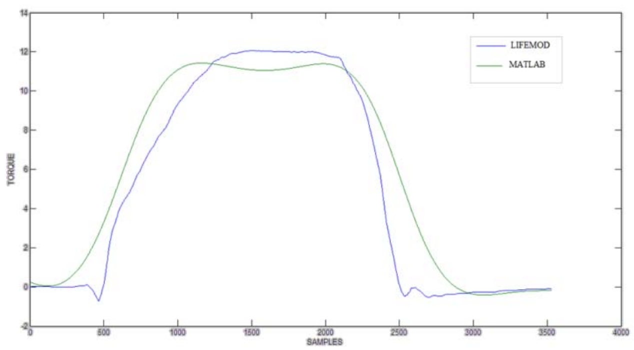

Figure 11: Torque in knee joint not of the leg not in contact with ground (Torque in N-m).

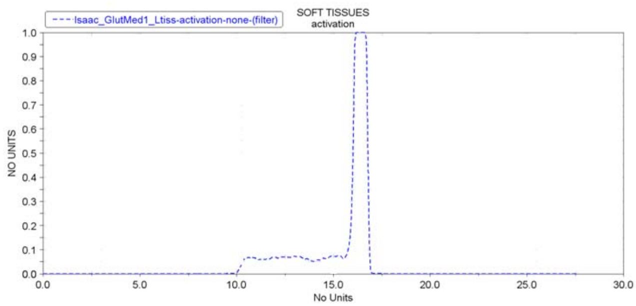

Figure 12: Gluteus medius.

Table 1: Maximum Torque in various joints while performing the yoga posture.

SL NO.	NAME OF THE JOINT	MAXIMUM TORQUE(IN NM)
11	LEFT ANKLE	45(+)
22	LEFT KNEE	250(-)
33	LEFT HIP	200(+)
44	RIGHT HIP	40(+)
55	RIGHT KNEE	12(+)

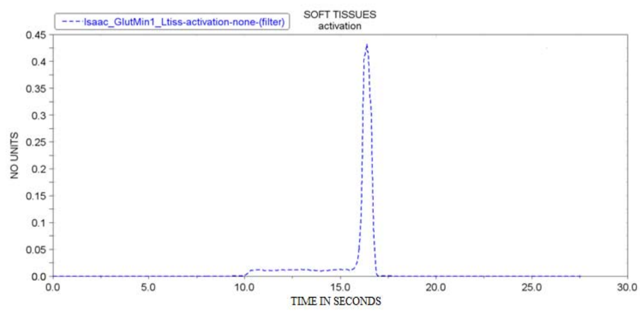

Figure 13: Gluteus minimus.

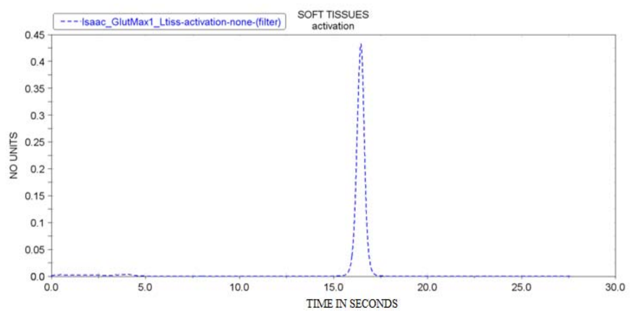

Figure 14: Gluteus maximus.

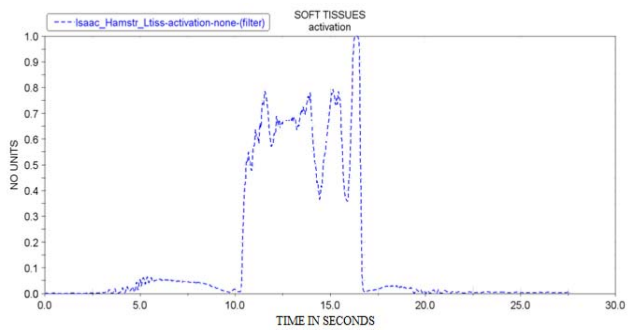

Figure 15: Hamstring.

(Table 1).

Once the torque results from Life MOD™ and Matlab matches satisfactorily, the simulation is reliable to draw out other required results such as power, energy, and muscle activation etc in the different segments of the lower body.

Any of the muscle groups involved in the stabilization of joints or other body parts by opposing the effect of gravity are called as antigravity muscles [13]. Muscle activation of the list of antigravity muscles [14] along with the other muscle group is extracted from LifeMOD™ (Figures 13-19).

Discussion and Conclusion

A mathematical model for this yoga posture is developed based on the Lagrangian dynamics. The angles and the moments encountered by the various joints are computed. It is observed that most of the movements in this yoga posture are in the saggital plane. Maximum torque is encountered while approaching the yoga posture and while returning back to the normal position. The torque of the right angle is not calculated since it remains static throughout the posture. The results obtained in Matlab are filtered using a suitable filter for simplicity. The results obtained in Matlab and Life MOD™ matches satisfactorily. The mathematical model developed can not only be

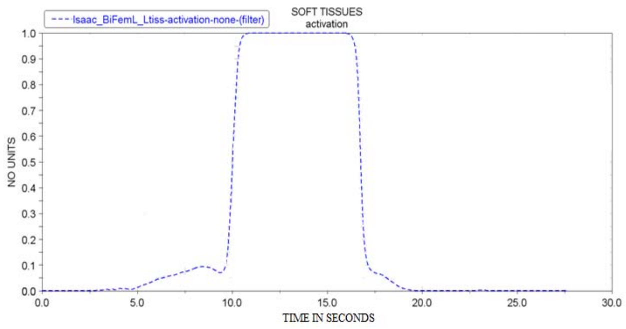

Figure 16: Biceps femoris (L).

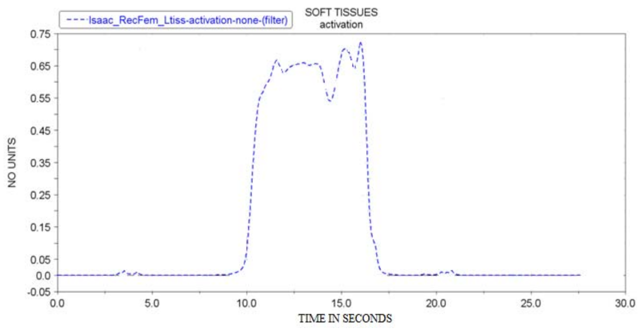

Figure 17: Rectus femoris.

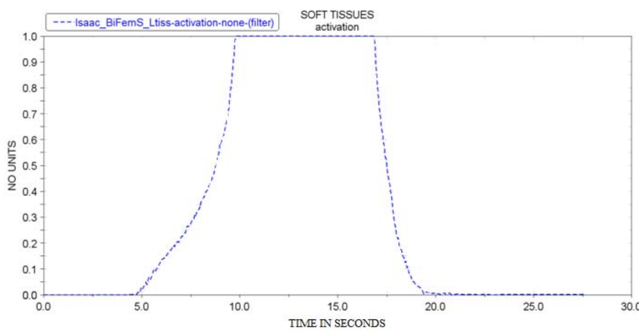

Figure 18: Biceps femoris (S).

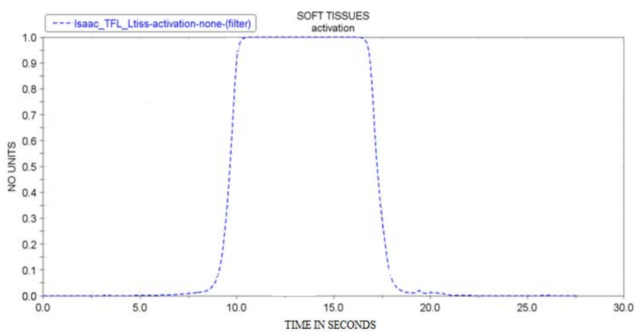

Figure 19: Tensor fasciae latae.

used for this yoga posture, but also for the other yoga postures have similar contact parameters and movements in the saggital plane.

Since this posture mainly concentrates on the segments in the lower body, muscle activation in the lower body is considered and results are amplified using suitable methods for better understanding of the activation pattern. The muscle activation around the hip area is quite significant. While TFL, Biceps Femoris, Rectus Femoris and Hamstring helps in maintaining this yoga posture, the Gluteus Maximus, Gluetus Medius and Gluetus Minimus helps in moving back to the neutral position. Therefore the first set of muscle activates when the body is in the final position of the aasana and remains constant while holding the position. The second set of muscles activate at the instance of moving in upward direction towards the neutral position.

Certainly, the present data would suggest that an important benefit of Single Leg Squat is that the joints involved are subject to optimal loading and this dynamic posture can be used as a lower body training technique. The data obtained can be used as a benchmark while training and rehabilitation with this aasana. Since the movement in the upper body while performing this posture is quite minimal, results for the same is not computed, but if required the same dynamic equations can be used to formulate suitable equation, data can be recorded and the results can be validated.

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