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Original Research

Simulation of Lower Limb Muscle Moment and Total Muscle Fiber Force Using OpenSim for Knee Osteoarthritis

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ABSTRACT

Computational modelling is a tool that provide accurate readings and simulation by using a combination of trusted and tested mathematical models of materials and system dynamics. Existing study in gait analysis mostly focus on extrinsic parameter such as kinetics and kinematics measures. The analysis of gait especially for disease such as knee osteoarthritis (OA) can provides insight into muscle properties, activation pattern and potential impact on the knee stability and function. This study aims to simulate muscle activation properties in individuals with knee osteoarthritis (OA) during gait. This study used musculoskeletal modeling software, OpenSim, to analyze the total fiber force and moment of several key muscles (such as medial gastrocnemius, vastus lateralis, and rectus femoris) relative to knee flexion moments. The motion analysis data of three subjects (one normal subject and two knee OA patients) were used in this study. The results shows that total muscle fiber force and muscle moment for medial gastrocnemius and vastus lateralis muscle were higher among individual with knee osteoarthritis. Meanwhile, rectus femoris muscle behaved differently where both parameters were smaller among knee OA patient. This simulated suggest that muscle mechanism changed due to knee osteoarthritis disease. The muscles force and moment were observed in this study gave some insight on the devastating effect of the disease on the lower limb joint muscle. Thus, further study is still warranted to investigate the risk of muscle injury and alteration of gait on individual with knee osteoarthritis. It is highly recommended to repeat this study with larger number of subjects for a better data interpretation

INTRODUCTION

Computational modeling has become widely used in almost all different fields that are related to engineering. It assists researchers and engineers by providing accurate readings and simulation by using a combination of trusted and tested mathematical models of materials and system dynamics (Delp, 2007). One of such is the computational modeling and simulation of the human neuromusculoskeletal system, which provides modeling and simulation of the human body's internal muscles and the forces acting on them either from the joint loads or reaction forces from the ground. The fact that the internal forces cannot be measured or simulated, makes such software very important to understand the safe range of motion that will not cause any injuries to the performer and the muscle activation while performing daily living activities (Teo, 2021). Not only that but also guiding companies and healthcare providers, who provide rehabilitation treatments and assistive devices (Hicks et al., 2015).

All body movements are performed by the contraction and relaxation of the human body muscles. The movements are initiated when the muscle nerve receives an electrical potential

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that is sent from the brain indicating a specific movement. This electrical potential is a form of electrical signal that can be measured and detected by EMG or Electromyogram test (Sadikoglu, 2017).

A common joint ailment known as osteoarthritis (OA) is characterized by the slow degeneration of cartilage. Numerous joints may be impacted, especially those that bear weight, like the hip or knee. Joint stiffness and discomfort that restrict range of motion are common symptoms of osteoarthritis of the knees or hips (Ornetti, 2010). The most common cause of self-reported walking difficulties, which frequently leads to functional loss, is knee osteoarthritis (OA). Walking difficulties brought on by knee OA symptoms might make it difficult for older persons to engage in the physical exercise required to control comorbid conditions like diabetes and heart disease (Na, 2022). Many factors are involved in the analysis of difficulties related to gait of knee OA such as muscle activations, join kinetics and kinematics, limb dynamics and total duration of time to complete the gait cycle as shown in Figure 1, which represent the speed of the gait. Approximately 4.71M individual have sought a medication for knee OA. This number is expected to increase to 6.4M individual by 2035 (Aruk, 2013).

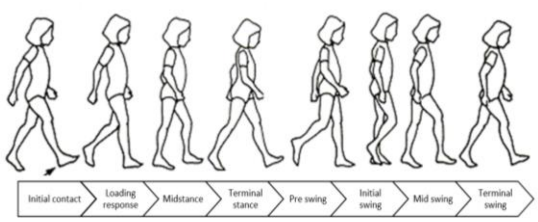

Fig 1 Gait phase

Understanding what muscles are heavily involved during the gait cycle, which will help in the production of assistive technology such as exoskeletons that can support knee OA patients as well as enabling rehabilitation organizations and physiotherapists to properly target the best exercising practices, which can improve patient overall health status. The majority of studies have done their investigation on the knee kinematics and kinetics, which means limited studies have analyzed the internal muscles moments. Furthermore, limited studies have analyzed the complete gait cycle, where most studies only analyze the stance phase.

Dynamic models of movement make it possible to examine athletic performance, study in neuromuscular synchronization, and calculate the internal stress of the musculoskeletal system. Additionally, simulations may be utilized to pinpoint the causes of problematic movement and create a solid scientific foundation for therapeutic preparation (Delp, 2007). One of the forward dynamic modeling approaches is EMG driven musculoskeletal modelling approach, which can be used in OpenSim to estimate several properties such as muscle forces or joint torques by using the data collected using EMG. This can be done by using one of the OpenSim plugins, which is called Calibrated EMG-Informed Neuromusculoskeletal modeling (CEINMS toolbox), which implements previously tested and validated EMG-driven algorithms (Seth et al., 2018).

OPENSIM AS SIMULATION TOOL

OpenSim is a tool that allow research and investigator to simulate musculoskeletal dynamics and neuromuscular control through building, manipulation, and interrogation (Seth et al, 2018). It provides full-body musculoskeletal model that consists of all upper body muscles combined with the lower body muscles. The model was developed by Andrea Menegolo and OpenSim 4.3 consists of the latest musculoskeletal model. Figure 2 (a) shows the lower limb model with all muscles.

OpenSim natively supports a wide variety of components, including those for modeling the skeleton as rigid bodies connected by joints, ligaments and other passive structures, muscles and motors, tracking and reflex-based controllers, external forces from the environment, and assistive devices composed of rigid bodies, joints, springs, and actuators. For this study, there are three parameters were used for the analysis purposes, which are total muscle fiber force, and muscle moment of knee.

The total fiber force represents that summation of passive fiber force and active fiber force. The muscle is a complex actuator that produces active force up maximum value based on the fiber length and muscle activation. On the other hand, the muscle produces a passive force that is independent of activation at the same time depending on fiber length (Aruk, 2013). Both forces are needed because muscles with single joints are weak to complete the contraction stage because these muscles are capable of producing maximum force when slightly beyond their resting length, which is 160%. After that, these muscles begin weakening when they are stretched and this is where the passive strength plays its role. The more the stretch increases the more the passive force increases, which help in the assisting the active force which is weakened. On the other hand, muscles with two joins can stretch beyond 160% of their resting length, which means the passive force is higher and provides most of the tension in the muscle. Figure 2 (b) below shows example of total muscle fiber force for medial gastrocnemius muscle during walking.

For muscle moment, OpenSim provide the estimation of muscle moment arm. Muscle moment arm is a measure of the effectiveness of a muscle at contributing to a particular motion over a range of configuration (Sherman et al, 2013). It is also representing the capacity of a muscle to exert a joint torque that is represented by the moment arm of the muscle force, which means the distance that is perpendicular between the instantaneous center the joint rotation and the muscle's line of action (Pandy, 1999). The amplitude of a muscle's moment arm, which symbolizes its leverage over a joint, and the direction of its moment arm, which determines whether joint movement is accompanied by muscle shortening or lengthening, are

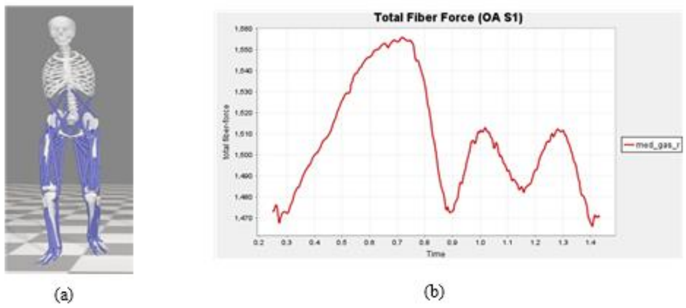

Fig 2. The figures can be divided into (a) musculoskeletal model of lower limb presented in OpenSim, (b) example of total muscle fibre force over time

indicators of the muscle's function in joint actuation (Ackland, 2010). The knee angle moment represents the knee flexion moment (Ghazwan, 2022).

METHODOLOGY

Lower limb motion analysis and electromyography (EMG) data of one healthy elderly and two knee osteoarthritis patients from previous study by Halim and Azaman (2022) were used in this study. Motion data was recorded using VICON system meanwhile EMG data was recorded using Delsys Trigno Avanti sensors. All data was saved in .c3d format. During the data recording, all subject were asked to walk in their comfortable pace on a 6 meters runaway. There were three muscles involved in this study which are rectus femoris, vastus lateralis and medial gastrocnemius.

All the data were processed followed the steps mentioned in Figure 3. The process started with data modification where raw data from motion analysis system originally in .c3d format is converted to OpenSim format using File Adapters. Then, the process proceeds to scaling process where the anthropometry of a model was altered so that it matches a particular subject as closely as possible. This process typically performed by comparing experimental marker data to virtual markers placed on a model. After that, Inverse Kinematics (IK) Tool was used so that the experimental markers were matched by model markers throughout the motion by varying the joint angles (generalized coordinates) through time. The output data generated contains a motion file of the generalized coordinate trajectories. Next, the data were process using the Inverse Dynamics (ID) Tool to determine the generalized forces (e.g., net forces and torques) at each joint responsible for a given movement. For this study, total muscle fiber force and knee joint moment parameter were measured. In order to generate the information, the output data were analyses according to gait phases as shown in Figure 1.

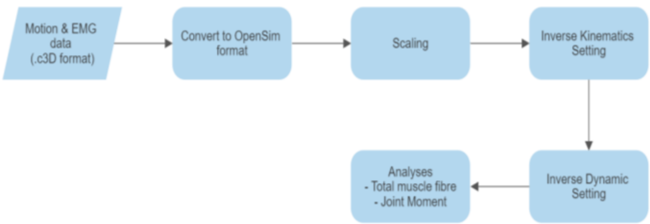

Fig 3. Flow of data processing

Table 1 The occurrence of phases in the gait cycle for the three different subjects

Subject	Loading Response	Mid Stance	Terminal Stance	Pre-swing	Initial Swing	Mid Swing	Terminal Swing	Total time to complete gait
Normal	0.10	0.25	0.40	0.50	0.60	0.75	0.90	0.90 s
Knee OA S1	0.30	0.45	0.60	0.75	0.85	1.00	1.30	1.05 s
Knee OA S2	0.85	1.10	1.30	1.50	1.60	1.75	2.00	1.25 s

*Highlighted data shows the highest value.

RESULT

Gait Phase Detection

The gait phases were detected based on models' observation during the gait simulation of the three different subjects. As shown in the table below, each subject has a different duration to complete one cycle of gait, where the normal subject completed the whole gait cycle within 0.9 second. However, the Knee OA S1 took 1.05 seconds meanwhile Knee OA S2 took 1.25, which means longer time by 0.15 and 0.35 second compared to normal subject respectively.

Total Muscle Fiber Force based on Gait Phase.

Table 2 shows total muscle fiber force of three different muscles based on the occurrence of each gait phases. For medial gastrocnemius muscle, it can be seen to has almost similar forces at all gait phases. Normal subject has the lowest total muscle fiber force with average of 1372.50 N followed by Knee OA S2 and Knee OA S1 with average of 1432.19N and 1507.94 N respectively. For this muscle, the highest force was recorded during pre-swing and initial swing phases.

Furthermore, for rectus femoris muscle, normal subject has the highest force compared to individual with knee osteoarthritis with average 1102.50 N over all gait phases. However, the force was observed higher during initial swing, and mid swing. Vastus lateralis muscle has the highest force during mid swing and terminal swing except for Knee OA S1. But, in the case of vastus lateralis muscle, knee OA subject has highest total muscle fiber force compared with normal subject with average of 1488.12N for Knee OA S1.

Muscle Moment at Knee based on Gait Phase

Result in Table 3 shows muscle moment of fiber three different muscles which are medial gastrocnemius, rectus femoris and vastus lateralis. Simulated muscle moments for medial gastrocnemius muscle were negative values which indicate tibial bending during the movement. Higher muscle moment was observed among patient with knee OA (Knee OA S1 and Knee OA S2). This pattern also observed for vastus lateralis muscle. However, it is different pattern was observed for rectus femoris muscle where normal subject recorded highest muscle moment with average of 52.14 Nm. By looking at the muscle moment according to the gait phases, the highest moment occurs almost similar phases as total muscle fiber force. This is because the force and length are directly proportional to each other especially for gastrocnemius mucle (Rassier et al, 1999).

Table 2 Total muscle fiber force of 3 different muscles based on the occurrence of gait phases.

Total Muscle Fiber Force (N)								
Subject	**Loading Response**	**Mid Stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Mid Swing**	**Terminal Swing**	**Average**
Medial Gastrocnemius								
Normal	1460.00	1370.00	1500.00	1550.00	1540.00	1085.00	1050.00	1372.50
Knee OA S1	1473.00	1472.50	1507.50	1547.00	1554.00	1487.50	1511.00	1507.94
Knee OA S2	1380.00	1425.00	1515.00	1540.00	1550.00	1387.50	1250.00	1432.19
Rectus Femoris								
Normal	925.00	1155.00	1105.00	1135.00	1165.00	1160.00	1165.00	1102.50
Knee OA S1	1015.00	1040.00	1000.00	1020.00	1080.00	1090.00	1040.00	1028.13
Knee OA S2	870.00	920.00	965.00	990.00	1070.00	1090.00	1060.00	977.50
Vastus Lateralis								
Normal	1160.00	1395.00	1270.00	1125.00	1245.00	1690.00	1865.00	1386.88
Knee OA S1	1505.00	1580.00	1525.00	1425.00	1480.00	1520.00	1470.00	1488.13
Knee OA S2	1550.00	1520.00	1395.00	1375.00	1510.00	1800.00	1860.00	1576.25

*Highlighted data shows the highest value

Table 3 Muscle moment of three difference muscles based on the occurrence of gait phases.

Total Muscle Fiber Force (N)								
Subject	**Loading Response**	**Mid Stance**	**Terminal Stance**	**Pre-swing**	**Initial Swing**	**Mid Swing**	**Terminal Swing**	**Average**
Medial Gastrocnemius								
Normal	1460.00	1370.00	1500.00	1550.00	1540.00	1085.00	1050.00	1372.50
Knee OA S1	1473.00	1472.50	1507.50	1547.00	1554.00	1487.50	1511.00	1507.94
Knee OA S2	1380.00	1425.00	1515.00	1540.00	1550.00	1387.50	1250.00	1432.19
Rectus Femoris								
Normal	925.00	1155.00	1105.00	1135.00	1165.00	1160.00	1165.00	1102.50
Knee OA S1	1015.00	1040.00	1000.00	1020.00	1080.00	1090.00	1040.00	1028.13
Knee OA S2	870.00	920.00	965.00	990.00	1070.00	1090.00	1060.00	977.50
Vastus Lateralis								
Normal	1160.00	1395.00	1270.00	1125.00	1245.00	1690.00	1865.00	1386.88
Knee OA S1	1505.00	1580.00	1525.00	1425.00	1480.00	1520.00	1470.00	1488.13
Knee OA S2	1550.00	1520.00	1395.00	1375.00	1510.00	1800.00	1860.00	1576.25

*Highlighted data shows the highest value.

DISCUSSION

Analyzing the dynamics of the whole cycle either stance or swing is critical to fully understand the effects and impacts of the disease at all muscles moment and total fiber forces. Only a little amount of study has been done to determine the relationship between muscle activation patterns, especially the moment of the vastus lateralis, medial gastrocnemius, and rectus femoris in connection to the knee OA development. Patient with knee osteoarthritis was reported has a slow walking speed compared to normal individual (Akimoto et al., 2022). Walking speed also has become one of the important predictors of outcome for knee OA intervention (Harkey, et al, 2021). Besides that, both knee OA subjects spent longer at all gait phases compared with normal subjects.

In previous study, patient with knee OA demonstrate reduce in functional capability mostly due reducing muscle force-generating ability of quadricep muscles like rectus femoris and vastus lateralis muscles (Alnahdi et al., 2012). Quadricep muscle provides stability to the knee joint during gait. However, in this study, the similar situation only occurs on rectus femoris muscle. Activity of rectus femoris muscle increases with gait speed. It is also reported that rectus femoris muscle is active during initial swing and work independently with vastus lateralis during the phase (Nene et al., 1999).

Vastus lateralis and gastrocnemius muscle behaved similarly in this study. These muscles displayed homogeneity in providing a functional synchronicity in locomotion activities. Furthermore, medial gastrocnemius muscle is important for forward propulsion during walking. Based on previous report, gastrocnemius and hamstring muscle force were higher among knee OA patient especially at loading response phase (Kumar et al., 2012). This finding almost similar with simulated data in current study. On the other hand, in previous study, it was reported that individuals who had knee OA were having moment increasing of vastus lateralis, rectus femoris, and gastrocnemius (Hsu, 2013). It was suggested that this is because the reduction of the knee flexion moment may cause shifting of muscle activation patterns toward the studied muscles (Ekstrand et al., 2013).

CONCLUSION

To conclude, analyzing the whole gait cycle is critical to enhance the overall health of knee OA individuals as it has been observed by this current study. A lot of dynamical changes that worth highlighting occur. Kinematics parameter is important but not enough to fully understand the whole functionality. Hence, dynamics analysis through simulation of the gait cycle is needed. The muscles force and moment were observed in this study gave some insight on the devastating effect of the disease on the lower limb joint muscle. Thus, further study is still warranted to investigate the risk of muscle injury and alteration of gait on individual with knee osteoarthritis. It is highly recommended to repeat this study with larger number of subjects for a better data quality and interpretation.

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