KINEMATIC SIMULATION OF HUMAN GAIT CYCLE USING MSC ADAMS

J. Paul Chandra Kumar[1*], M.S.Alphin[2], M. Anbarasan[3], S.Naveen Kumar[3], M.Perarasan[3], M.A.Siva Shankaran[3]
[1]Dept. of Mechanical Engineering, Anna University, Chennai, India.
[2]Dept. of Mechanical Engineering, SSN College of Engineering, Chennai, India
[3]Dept. of Mechanical Engineering, Jeppiaar Engineering College, Chennai, India
***Corresponding author: Email: paulie1980@gmail.com**

ABSTRACT

This paper aims at performing a simulation of a normal gait cycle in Humans and to study the various forces and moments that are occurring at various joints in the lower extremities. To achieve this, computerized tomography of a normal subject's leg and foot are taken and the data are opened in Mimics software where the 2D slices are converted into a 3D model. For our study only the bones both cortical and cancellous are taken neglecting the soft tissues. The model obtained in an STL file which is further opened in MSC Adams package for performing a kinematic simulation. Forces and moments acting at the bone joints are plotted over time for a single gait which can further be processed in Adams/Flex using Finite Element Methods over the localized region of interest.

Keywords: Human Gait; Mimics; Adams.

INTRODUCTION TO GAIT CYCLE

Walking is one of the most practiced of all motor skills, with a very low level of variability associated with many biomechanical measures of this task. Walking is formulated as an optimal motor task subject to multiple constraints with minimization of mechanical energy expenditure over a complete gait cycle. This low level of variability is taken to mean that a very repeatable movement pattern has been attained. Functional descriptions for walking are provided along with a view of quantitative findings from mechanical software analyses. The dynamic characteristics of the symptom-free foot and ankle during the most common forms of upright locomotion provide the necessary basis for objective evaluation of movement dysfunction. The foot and ankle, by virtue of their location, form a dynamic link between the body and the ground. The foot and ankle are basic to all upright locomotion performed by the human. The body requires a flexible foot to accommodate the variations in the external environment, a semi rigid foot that can act as a spring and lever arm for the push off during gait, and a rigid foot to enable body weight to be carried with adequate stability. The gait cycle is measured from initial contact of one foot to the next initial contact of the same foot.

PHASES OF GAIT CYCLE

All segmental motions and ground reactions were predicted from only three simple gait descriptors (inputs): walking velocity, cycle period and double stance duration. The different phases of the human gait, it is needed to introduce a

- Reference foot: First foot.
- Opposite foot: Second foot.
- Stance phase: It begins when the heel contacts the ground and ends when the toes rise off the ground.
- Swing phase: It covers the period when the foot is not in contact with the ground.

Foot kinematics during stance phase are described by

$$\Delta x_{an} = f\left(\theta_{ft}\right)$$

$$\Delta y_{an} = g\left(\theta_{ft}\right) \quad (2)$$

Where

$$\Delta x_{an} = x_{an} - x_{an}^{(hs)}$$

Where x_{an} is the current x coordinate of the ankle joint, and $x^{(hs)}$ is the x coordinate of the ankle joint at heel strike.

Differentiating Equations (1) twice, the accelerations of the ankle joint centre are,

$$\ddot{x}_{an} = \frac{d^2 f}{d\theta_{ft}^2}\cdot\omega_{ft}^2 + \frac{df}{d\theta_{ft}}\cdot\alpha_{ft}$$

$$\ddot{y}_{an} = \frac{d^2 g}{d\theta_{ft}^2} . \omega_{ft}^2 + \frac{dg}{d\theta_{ft}} . \alpha_{ft} \quad \text{... (2)}$$

During walking there is at least one foot in contact with the ground throughout the gait cycle. Thus, the positions of the other joint centers in the multi-segment model were derived from the location of the stance ankle joint.

$$x_t = x_{an} + \sum_{j=1}^{m} (I(j) . l_j . \cos\theta_j)$$

$$y_i = y_{an} + \sum_{j=1}^{m} (I\ (j) . l_j . \sin\theta_j) \quad \text{...(3)}$$

Where m is the number of segments in the chain connecting the stance ankle joint to the Ith joint and I (j) is a sign function, which is equal to 1 when the segment belongs to the stance limb, or equal to -1 if the segment is in the contralateral limb.

Differentiating Equation (3) twice, the accelerations of the joint centres are,

$$\ddot{x}_i = \ddot{x}_{an} - \sum_{j=1}^{m} (I\ (j) . l_j . (\ \alpha_j . \sin\theta_j + \omega_j^2 . \cos\theta_j))$$

$$\ddot{y}_{an} = \ddot{y}_{an} - \sum_{j=1}^{m} I(j) . l_j . (\omega_j^2\ . \sin\theta_j - \alpha_j\ . \cos\theta_j)) \quad (4)$$

Thus, given the segment angles, Equations (1) to (4) were used to calculate the coordinates of the joint centres and their accelerations. Thereafter, the positions and accelerations of each body segment mass centre were derived using anthropometric data.

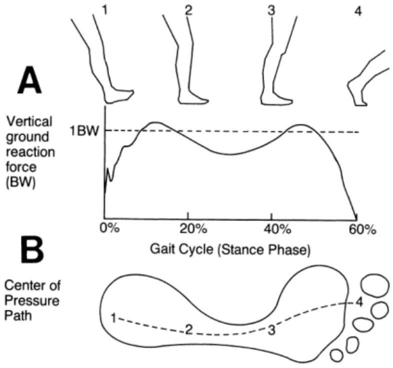

Figure.1.Phases of gait cycle

In human gait modeling there is huge number of variables obtained by means of different measurement techniques such as height, limb length, walking speed, acceleration along axes, foot forces, etc., thus making the obtaining of an accurate model a very complex task. The gait cycle is a periodical phenomenon which is defined as the interval between two successive events (usually heel contact) of the same foot. It is characterized by a stance phase (60% of the total gait cycle), where at least one foot is in contact with the ground, and a swing phase (40% of the total gait cycle), during which one limb swings through the next heel contact. These phases can be quite different between individuals but when normalized to a percentage of the gait cycle they maintain close similarity.

The gait cycle consists of two phases: 1) stance (when the foot is in contact with the supporting surface) and 2) swing (when the limb is swinging forward, out of contact with the supporting surface). Along with providing forward momentum of the leg, the swing phase also prepares and aligns the foot for heel strike and ensures that the swinging foot clears the floor. Stance comprises about 60% of the total gait cycle at freely chosen speeds and functions to allow weight-bearing and provide body stability. Five distinct events occur during the stance phase: heel-strike (HS), foot flat (FF), mid-stance (MS), heel rise (HR), and toe-off (TO).The movements of the foot and ankle during walking and other portions of the lower extremity must be included. The heel contact with the ground is lateral to the center of the ankle joint where body weight is transmitted to the talus, stresses the structures of the medial arch. The foot quickly turns about 10 degrees within the first 8% of stance at an average walking speed. As the leg and foot are swung forward, the forefoot just clears the ground and then rises to a second peak just before HS. Because the toe is the last part of the foot to leave the ground, and because of the accompanying leg and foot angles, the toe rises to no more than 2.5 cm above the ground and then drops to only 0.87 cm of clearance at mid-swing. As the knee extends and foot dorsiflexes, the toe rises to a maximum of 13 cm just before HS.

KINEMATICS IN GAIT CYCLE

Kinematics refers to the description of motion, independent of the forces that cause the movement to take place. Kinematic information can be collected using direct measurement techniques (i.e., goniometers, accelerometers) and with indirect measurement using imaging techniques (ie, cinematography, high-speed video, stroboscopy. In this study, the femur was modelled as a rigid body with knee joints, and the other lower extremities were considered as curved surfaces rolling on the ground without slipping, such that the foot kinematics during the stance phase were determined by using ADAMS software stimulation. The ankle joint was considered to be the mid-point between lateral and medial malleolus .The relative timings of heel-strike and toe-off were based on measurement data. During walking there is at least one foot in contact with the ground throughout the gait cycle. Thus, the positions of the other joint centres in the multi-segment model were derived from the location of the stance ankle joint.

A. Femur: The femur is the longest and strongest bone which is used to transmit the forces from the hip region to the tibia which is about quarter of the person's height. The length of the femur from the head of the femur to that of the medial epicondyle is about 487 mm. The angle of inclination also allows the obliquity of the femur within the thigh, which permits the knees to be adjacent and inferior to the trunk. At the inferior or the distal end of the femur, the linea aspera divides into medial and lateral supracondylar lines, separated by an intercondylar fossa but joined in front by a trochlear surface for the patella which leads to the medial and lateral femoral condyles.

The center line of the long axis of the shaft intersecting with that the long axis of the head and the neck at the greater trochanter in between forms the inter-trochanteric line is normally at an angle of about 126°. The long axis of the shaft line meeting at the interior (or) distal end in between the medial epicondyle and the lateral epicondyle with the normal drawn from the long axis of the head and neck meets at the fovea of the ligament of the head. The oblique line drawn called the weight bearing line (line of gravity). If the superior view demonstrating torsion angle of femur is viewed, the meeting point of obtuse angle of inclination of the axis of femoral head and neck and the transverse axis of femoral condyles inclined at 120^0 is called the long axis of shaft of femur, at the greater trochanter. This allows rotatory movements of the femoral head within the obliquely placed acetabulum to convert into flexion and extension, abduction and adduction, and rotational movements of the thigh. During walking, rotation of the pelvis causes the femur, fibula, and tibia to rotate about the long axis of the limb. The pelvis undergoes a maximum rotation in each gait cycle of about 6 degrees. This narrow ridge has medial and lateral lips. In the standing position, the shaft passes downwards and medially and this inclination is evident when the femur is held vertically with both its condyles in contact with a horizontal surface.

B.Patella: The patella (knee cap) is the largest sesamoid bone in the quadriceps tendon plays on the articular surface of the femur in which the load is to be distributed over the intercondylar eminence and is generally convex. The lateral femoral condyle and the medial femoral condyle thus placed below stabiles the patella. The patella by which connects with that of the femur at the inferior end placed between the lateral and medial epicondle connects with the fibula and tibula known as knee joint normally rotates about the angle of 100 where only one degree of freedom is allowed known as the hinge joint. The most medial facet is in contact with the medial femoral condyle only in flexion; the larger lateral facet contacts the lateral condyle throughout all phases of knee joint movement.

The patella is attached distally to the tuberosity of the tibia by the patellar ligament. This is attached to the lower border of the patella and to the distal non-articular part of the posterior surface of the bone. The patella pointed at the distal end for attachment to the patellar ligament, which connects the patella to the tibia and fibula. When standing, the lower part of the patella is just next to the level of the knee joint (tibial plateau).

C. Fibula And Tibia: The tibia connects with the condyles of the lower end of the femur and the talus inferiorly, and fibula or calf bone are connected by a dense interosseous membrane which is made up of strong oblique fibers to transmits the body's weight mainly functions for the stability of the ankle joint descending from the tibia to the fibula. The proximal end widens to form the medial condyles one slightly concave and the lateral condyles one slightly convex and overhang the shaft medially, laterally, and posteriorly, forming a relatively flat superior articular surface, or tibia plateau. This plateau consists of two smooth articular surfaces that articulate with the large condyles of the femur. The tibia is large at its upper end, extensively by the medial and lateral condyles, and a lower end having a prominent medial malleolus and it is in the vertical standing position. The surface on the medial condyle is oval but the lateral surface is smaller with circular in conformity with the medial femoral condyle and meniscus. Between the condylar surfaces the tibia plateau is projected into the intercondylar eminence, which is then grooved anteroposteriorly to form medial intercondylar tubercles and lateral intercondylar tubercles.

The length of the fibula is to be measured about 484 mm in length and the width of about 20.34 mm. The head of the fibula by which it is about 48.50mm as measured in mimics software and the tibia undergoes a rotation of about 18 degrees in the same period. At HS, the tibia is rotated medially about 5 degrees from its neutral position, and the ankle joint is either in its neutral position or in slight plantar flexion. The upper epiphysis which is also known as the growing end shows a centre immediately after birth then it descends to form the smooth part of the tibial tuberosity to which the patellar ligament is attached. The calcaneus is the most posterior of the tarsal bones and is commonly known as the heel. This is responsible for controlling the majority of foot motion relative to the leg. The ankle joint allows approximately 30 to 50 degrees of plantar flexion and 20 degrees of dorsiflexion.

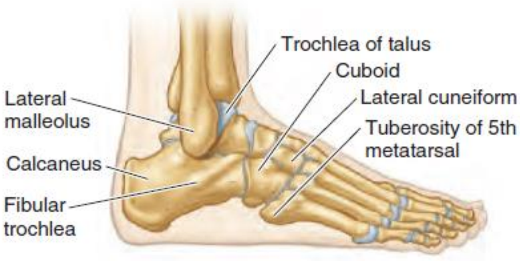

Figure.2.Bones of foot

D.Ankle Joints: The true ankle joint (talocrural joint or talotibial joint) is made up of the distal tibia, which sits on the talus with the medial malleolus of the tibia fitting down around the medial aspect of the talus, and the lateral malleolus of the fibula, which fits down around the lateral aspect.

BONES OF FOOT

The bones of the foot include the tarsus, metatarsus, and phalanges. There are 7 tarsal bones, 5 metatarsal bones, and 14 phalanges.

A. Tarsus: The tarsus (posterior or proximal foot consists of seven bones namely talus, calcaneus, cuboid, navicular, and three cuneiforms. The tarsus is the only one bone that articulates with the leg bones. The talus has a body, neck, and head. The superior surface of the talus is gripped by the two malleoli and receives the weight of the body from the tibia. The talus transmits that weight in turn, dividing it between the calcaneus, on which the body of talus rests, and the forefoot.

B.Calcaneus: The calcaneus is the largest and strongest bone in the foot. While standing, the calcaneus transmits the majority of the body's weight from the talus to the ground.

C.Metatarsus: The metatarsus consists of five metatarsals that are numbered from the medial side of the foot. In the articulated skeleton of the foot, the tarsmetatarsal joints form an oblique tarsmetatarsal line joining the midpoints of the medial and shorter lateral borders of the foot. Thus, the metatarsals and phalanges are located in the anterior half forefoot and the tarsals are in the hind foot.

D. Phalanges: The 14 phalanges of the lower limb are as follows: the 1st digit (great toe) has 2 phalanges (proximal and distal); the other four digits have 3 phalanges each: proximal, middle, and distal. Each phalanx has a base (proximally), a shaft and a head (distally).

PROCESS LAYOUT

The following processes are carried out in this research.

Introduction to MIMICS and MSC Adams

1. MIMICS 10.01: Mimics (Materialise's Interactive Medical Image Control System) is a software for processing CT or MRI scanners images and generating 3D models. Mimics uses 2D cross-sectional medical images such as from computerized tomography (CT) and magnetic resonance imaging (MRI) to develop 3D models, which can to be directly linked to rapid prototyping, CAD, simulation tools and advanced engineering analysis.

2. MSC Adams: ADAMS (automated dynamic analysis of mechanical systems). ADAMS/View is a modeling and simulation environment. It enables us to create, visualize, and modify our mechanical system model to build a physical prototype. Using ADAMS/View we can submit simulations to ADAMS post processor to compute the force and motion behavior of our system and to write that information to output files. In the process of refining, the

computer model becomes more precise and accurate. After completion of the model, tests can be iterated by changing parameters and variables, in order to optimize the model. This saves time in that we can run many simulations that are cheap, accurate, and can be done completely. Adams enables engineers to evaluate and manage the complex interactions between disciplines including motion, structures, vibrations, and controls to better optimize product designs for performance, safety, and comfort.

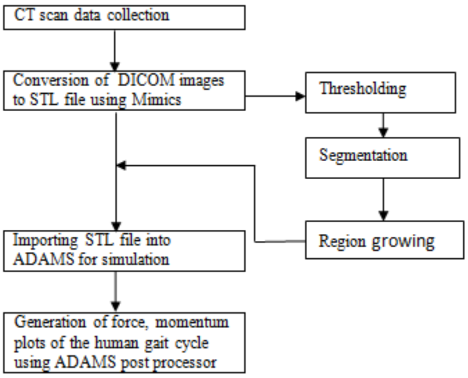

Figure.3.Process sequence

Figure.4.CT image to 3D model

B.CT Scan Images to 3D Model: A stack of images can be loaded into the Mimics, and this usually consists of images in the XY plane. Mimics later calculates and creates images in the XZ and YZ direction. This enables a more inclusive 3D feel of the 2D data. The tool used to convert 2D data from images to 3D models is a process called segmentation. During segmentation the user pick the structure(s) of interest in the sliced image data. This information is then used to recreate a 3D model from the segmented structures. To obtain the outer surface of the 3D model, Mimics uses the STL format, which is the common file format in RP. The STL format allows describing of the most complex geometries accurately. This is necessary, since 2D data is in general very complicated. Accurate segmentation is important in order to extract required information from images.

C.STL File (Stereo Lithography): STL file is a triangulated surface mesh file. The file contains the three nodes of each triangle and defines the normal direction of the triangle. This file format is ideal for anatomical geometry because of its simple file structure and flexibility to match any contour desired. It is not controlled by parametric constraints such as true CAD files and IGES files.

D.Segmentation: The 2D images coming from CT or MRI scanners consist of grayscale information. Mimics allows the user to create models based on the gray values within these images. A gray value is a number associated with an image pixel defining the shade (white, or gray) of the pixel. There is a direct association between material density of the scanned object and the gray value assigned to each pixel in the image data. Because of this, Mimics has the flexibility to create models from any geometry distinguishable within the scanned data. By combining together similar gray values, the image data can be segmented, and models created. This type of segmentation is called thresholding models. Many of the segmentation tools in Mimics are common in image editing and can be applied in any of the views (XY, XZ or YZ), but Mimics also has a unique 3D editing tool; an initial segmentation can be optimized in a 3D preview (figure1). This makes editing very easy, since it allows true editing in 2D. Using the segmentation and known information of the pixel size and the distance between the image slices, Mimics can calculate a 3D model. The accuracy of a Mimics image matches the accuracy of an object captured within the scan.

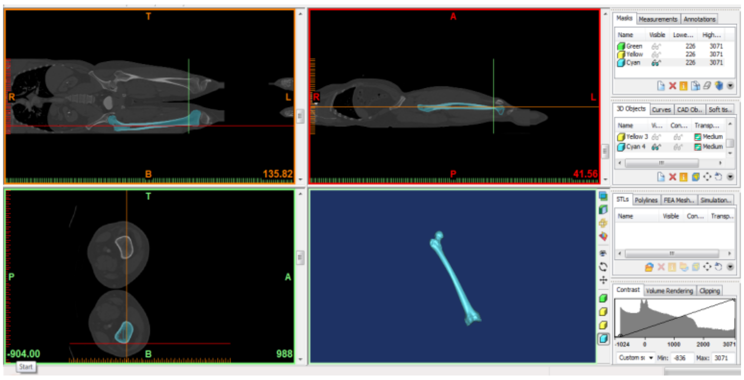

Figure.5.Editing a Mimics model in 3D to capture the femur

E.Compilation of the Model in MSC Adams: Using basic tools, we import a model of the adult right leg in MSC Adams/View. The leg will be projected in several steps as described in the following sections.

The following assemble model of adult right leg is fully constructed by ADAMS.

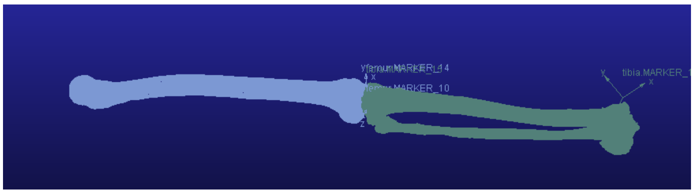

Figure.6.ADAMS assembly model of femur and tibia

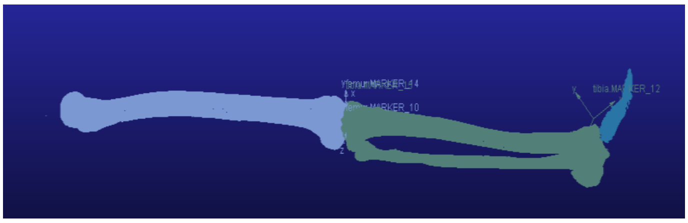

Figure.7.ADAMS fully reconstructed 3D model

We have imported the STL file of each link from Mimics. We have decided to initially import the femur and based on that femur reference, import second link tibia. Femur position is taken as the reference value according to which the tibia's orientation is done. The tibia's one end is fixed with femur and another end is left free. Then tibia's orientation value is measured and noted down. Now that we have prepared the model of human leg, it is ready for simulation. Before performing simulations, it is required to decide degrees of freedom of each joint. Here femur free end is a fixed joint so the motion is constrained. Knee joint and the ankle joint each have one degree of freedom. So here it was decided to use revolute joints for both knee and ankle.

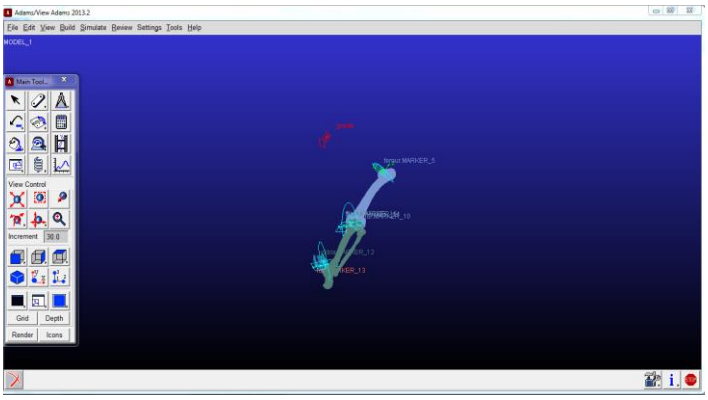

Figure.8.ADAMS simulation model

Motion is then given to the constructed joints, which travel through an angle previously defined in ADAMS. Now the adult leg is ready for simulation and various parameters are analyzed.

F.Kinematic Variables of the Joints: To determine the values of the parameters it is necessary to define several properties in measurement. In this paper, the angle, velocity and acceleration of the joint motion of the human gait cycle is determined. The time course angle of rotation member 2 tibia is shown in figure 9. The plot indicates the angle of joint 2 at varying time. It is found that the variation of this angle along the z axis is directly proportional to time. Joint 2 refers to the knee joint.

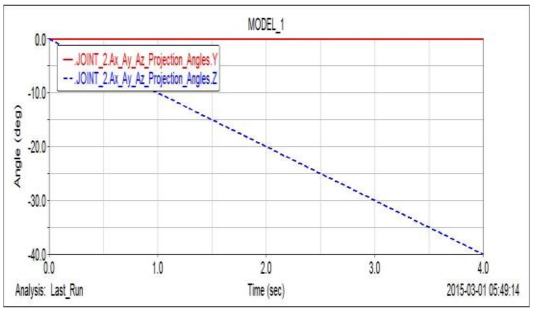

Figure.9.Rotation angle of tibia vs time

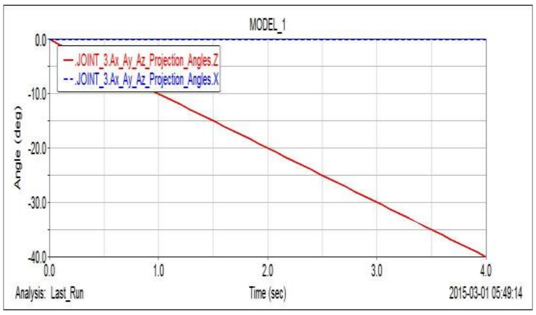

Figure.10.Rotation angle of foot vs time

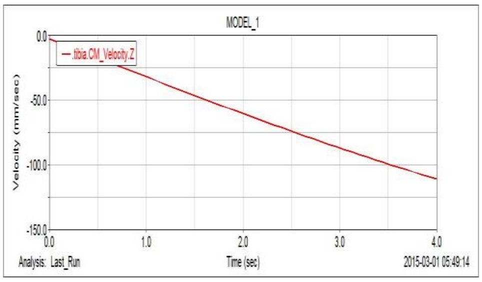

Figure.11.Tibia velocity vs time

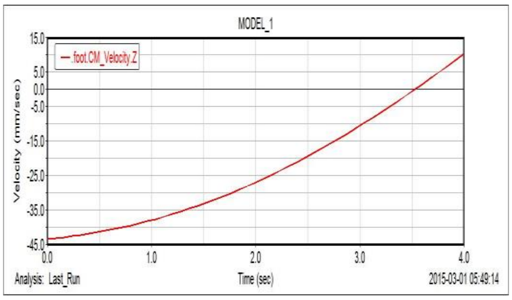

Figure.12.Foot velocity vs time

Figure 10 indicates the angle of joint 3 at varying time. It is found that the variation of this angle along the z axis is directly proportional to time. Joint 3 refers to the ankle joint. The graph in figure 11 indicates variation of the tibia velocity with time. We can observe that velocity decreases gradually from the starting point. From figure 12, we can infer that the foot velocity is increasing gradually with time.

CONCLUSION

Rather than using EMG sensors as a tool to measure forces acting on the joints and the muscles where the system involves human interactions, a different approach has been discussed here where the same study and behavior can be studied using the latest simulation packages. The advantage involves that the study be extended to orthopedic implants and prosthetics. Here the results are restricted to providing a relation between force, velocity, rotation angle of foot vs. time. The work can further be extended to calculate deformation on bones using finite elements but restricted to a localized region of interest.

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