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Raveendranathan, Vishal; Carloni, Raffaella

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Musculoskeletal Model of an Osseointegrated Transfemoral Amputee in OpenSim

Vishal Raveendranathan and Raffaella Carloni

***Abstract*— This paper focuses on the development and validation of a generic musculoskeletal model of an osseointegrated transfemoral amputee. The model has been developed using OpenSim with the final goal of obtaining a competent tool to study and better understand the biomechanics of osseointegrated transfemoral amputees. The model has been validated on the experimental data obtained on one osseointegrated transfemoral amputee during level ground walking.**

I. INTRODUCTION

Musculoskeletal modeling is a fundamental instrument for the analysis of the biomechanical characteristics of the human body. These models helps in understanding the kinematics and dynamics of the human gait, such as moments, forces, muscle activation, muscle forces, etc., as the output of such models [1], [2], [3], [4]. Generally, in a biomechanical experiment, the kinetic and kinematic information of the subject are captured via force plates and motion capture system respectively. With these experimental data, a rigid body model of the subject is constructed based on the degrees of freedom and focus of the experiment. The transformation of experimental data into subject specific simulation models are important to quantify the study.

Concordantly, musculoskeletal modeling enhances the understanding of gait and other activity of daily living to improve in the field of rehabilitation. For instance, in [5], subject specific modeling of children walking with mild crouch gait were analyzed to understand the muscle contributions during their gait. Such insights aid in performing the gait correction surgeries and improvise the rehabilitation techniques. Similarly, musculoskeletal models were introduced to measure the tibiofemoral forces during walking [6]. Such researches encourage in solving many aspects of the current biomechanical problems using a simulation environment.

OpenSim [7], [8], an open-source musculoskeletal simulation software has been extensively used for biomechanical study over the last decade. Using OpenSim, an elaborate procedure on how to translate the experimental data into a simulation environment for a healthy subject has been explained in [2]. However, there are limited research and musculoskeletal models available on the study of amputees. [9] has modeled a transtibial amputee with a socket interface to study the residumm-socket interface in a gait. Similarly, [3] has modeled a transtibial amputee with musculoskeletal system to understand the muscle contributions in a gait.

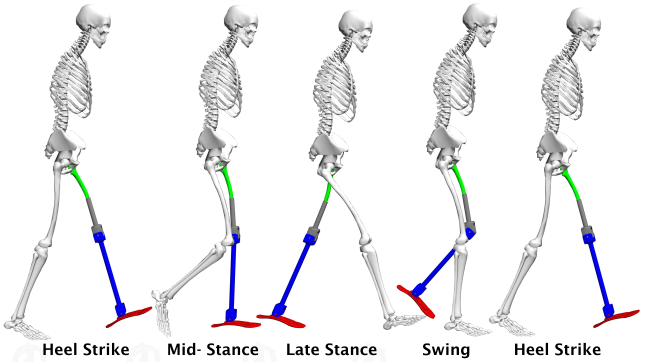

Fig. 1: Gait cycle representation of amputated left leg during level ground walking.

To the best of the authors' knowledge, a transfemoral amputee model has not been available in the research for such biomechanical study. Thus, we have described an osseointegrated transfemoral amputee model and validated the simulations for normal level ground walking activity. The model was iterated to minimize the experimental tracking errors before performing the simulations.

The remainder of the paper is organized as follows. Section II presents the generic musculoskeletal model that has been developed in OpenSim. The model is validated in Section III-C using the experimental data obtained on one osseointegrated transfemoral amputee during level ground walking. In Section IV, the results are discussed and compared with the VICON plug-in gait for lower body model. Finally, conclusions are drawn in Section V.

II. MUSCULOSKELETAL MODEL

In this Section, the generic musculoskeletal model of an osseointegrated transfemoral amputee is presented. Specifically, the musculoskeletal model of a healthy subject provided by the open-software OpenSim [7], [8] has been used and modified to create the musculoskeletal model of an osseointegrated transfemoral amputee with a generic transfemoral prosthesis.

A. Musculoskeletal Model - Healthy Subject

OpenSim provides the complete musculoskeletal model of an healthy subject. The skeletal and muscular system of the lower extremity model have 23 degrees of freedom (DOF) and 92 musculotendon units, respectively. The model

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The authors are with the Faculty of Science and Engineering, Bernoulli Institute for Mathematics, Computer Science and Artificial Intelligence, University of Groningen, The Netherlands. {`v.raveendranathan`, `r.carloni`}`@rug.nl`

is designed with 6 DOF at pelvis, 3 DOF for the torso, 3 DOF at each hip joint and one DOF at each leg for knee, ankle, subtalar and toes. [10] The description of the musculotendon units is omitted since it is not the focus of this research.

The pelvis is connected to the ground via three translation joint to move across each axes. However, during the residual correction of the simulation model, external actuators are added on these joints to support the external forces. In an ideal scenario, all residual forces should be zero during the simulation.

B. *Musculoskeletal Model - Transfemoral Amputee*

The proposed generic musculoskeletal model of an osseointegrated transfemoral amputee in OpenSim has 19 DOF as shown in Table I. The musculotendon units have been disabled as it is not within the scope of this research. The left femur was cut and its mass, inertial properties, and center of mass have been modified accordingly. An osseointegrated titanium implant has been designed and welded to the posterior femur bone. For graphical representation, a generic prosthetic knee joint, a tibia pylon, an ankle joint, and a foot have been imported into OpenSim as in Figure 1. To simplify the model, subtalar and metatarsal joints were locked at their neutral position. The model has been scaled and the mass has been distributed to the body segments with respect to the subject mass and static calibration markers' positions. All the bony prominent markers and respective marker pairs have been used to scale each segment of the body. For instance, lateral knee and ankle markers were used to scale the tibia of the subject. Such practice helped in efficiently reducing the scaling errors.

TABLE I: Joints defined in the osseointegrated transfemoral amputee model.

Body	**Degrees of Freedom**	**Joint Type**
Lumbar	3	Ball and Socket
Pelvis	6	Ball and Socket + Translation
Hip	3 + 3	Ball and Socket
Knee	1 + 1	Revolute
Ankle	1 + 1	Revolute

III. MODEL VALIDATION

In this Section, the generic musculoskeletal model of an osseointegrated transfemoral amputee is validated with experimental data collected on an osseointegrated transfemoral amputee.

A. *Amputee Data*

The experimental data were collected at Radboud University Medical Center in Nijmegen (The Netherlands), with the ethical approval on one osseointegrated amputee. The selected subject is a left leg amputee, wearing an Ottobock C-Leg knee prosthesis and an Ottobock 1C63 Triton LP foot (Ottobock, Germany, `www.ottobock.com`). The kinematic data collection was taken as per the guidelines of VICON lower extremity gait plugin marker protocol for healthy subjects (Vicon Motion Systems Ltd, United Kingdom, `www.vicon.com`) [11], using motion capture cameras at 100 frames per second. The kinetic information has been collected by using an instrumented treadmill with two type two embedded Motekforce Link force plates (Motek Medical B.V., The Netherlands, `www.motekmedical.com`) at a sample rate of 2 kHz.

During the data collection, the subject walked at a speed of 4 Km/hr on the treadmill. The handrails were used only in case of necessity. Using the VICON gait plug-in for lower body model, the kinematic and kinetic information were exported using the VICON NEXUS application. Therefore, joint angles and moments were produced as an outcome of the VICON gait plug-in model. Similarly, the raw marker positions and force plate data were exported as a c3d file, which is used to import the data into OpenSim.

B. *Calibration of the Model*

In this Section, the calibration procedure and the choices related to the amputee subject are presented.

The raw motion capture data along with kinetic information, exported from VICON Nexus, were made available in c3d files. Using the MATLAB toolbox MOtoNMS [12], the c3d files were converted to OpenSim usable files for scaling, inverse kinematics, and inverse dynamic analysis.

During the scaling process, a static calibration trial of the subject standing still in the motion capture volume was utilized. Thirty four virtual markers were placed on the OpenSim amputee model with respect to the VICON marker placement protocol for lower body gait study. Further, the model body segments such as torso, pelvis, femur, tibia and foot were scaled according to the bony prominent markers. After few iterations of adjusting the virtual marker placements in the amputee model, the total squared error and root mean square error for the markers were 4.6 mm and 13 mm, respectively. Precautions have been taken to perform every simulation step to validate the quality of the achieved results. The guidelines in [13] have been helpful to benchmark the process. All virtual markers in the area of focus were reduced to a maximum error lower than 20 mm.

The inverse kinematics has been performed on the scaled model to compute the joint angles from raw motion capture marker positions of the experiment, by solving the weighted least squares problem. Similarly, inverse dynamics has been performed to compute the moments generated at each joints of the amputee model with respect to the ground reaction forces by solving the classical equations of motion.

Additionally, residual reductions was performed using OpenSim's Residual Reduction Algorithm (RRA) on the amputee model to make the dynamic result consistent with the kinetic forces applied. During this iterative process, a total mass change of 1.769 kg was added to the subject mass of 59.3 kg. Upon these, adaptations, the residual forces induced at the pelvis were reduced to the 0.28 N on the sagittal plane. This step further ensures that the resulting simulation model is valid for comparison with experimental data. The model after performing residual reduction was

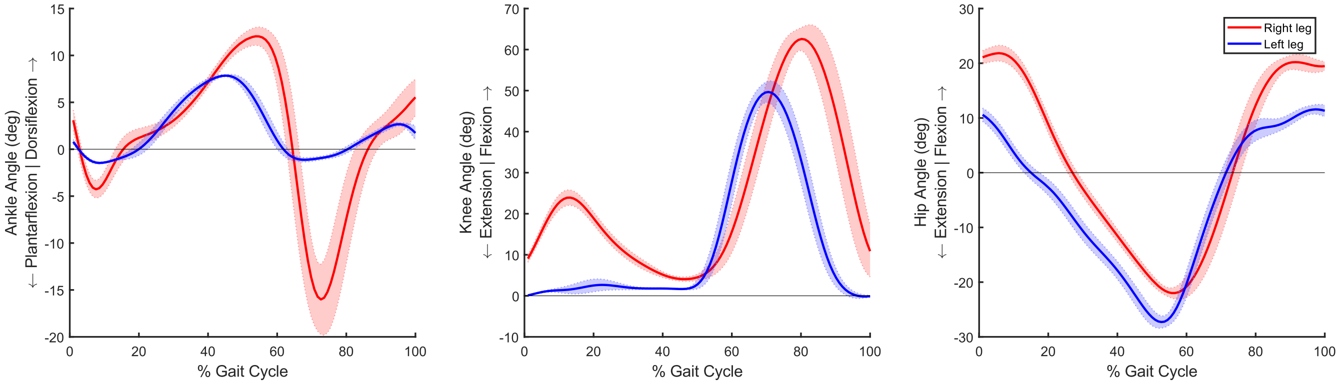

Fig. 2: Sagittal joint angles of ankle, knee and hip during level ground walking as a result of inverse kinematics for the osseointegrated transfemoral amputee model in OpenSim. The dark red and blue lines shows the mean joint angles. The shaded region represents the standard deviation of the joint angles in ten gait cycles.

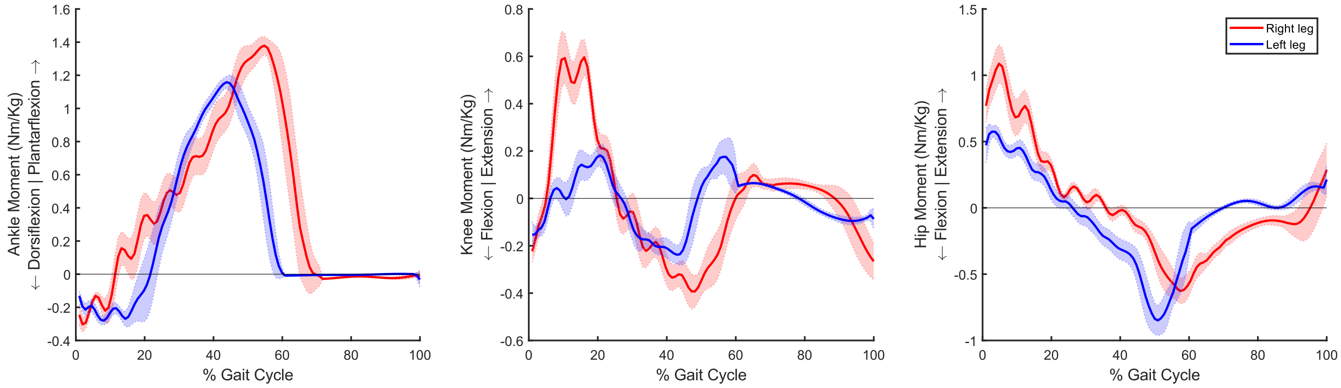

Fig. 3: Sagittal joint moments of ankle, knee and hip during level ground walking as a result of inverse dynamics for the osseointegrated transfemoral amputee model in OpenSim. The dark red and blue lines shows the mean normalized joint moments. The shaded region represents the standard deviation of the normalized joint moment in ten gait cycles.

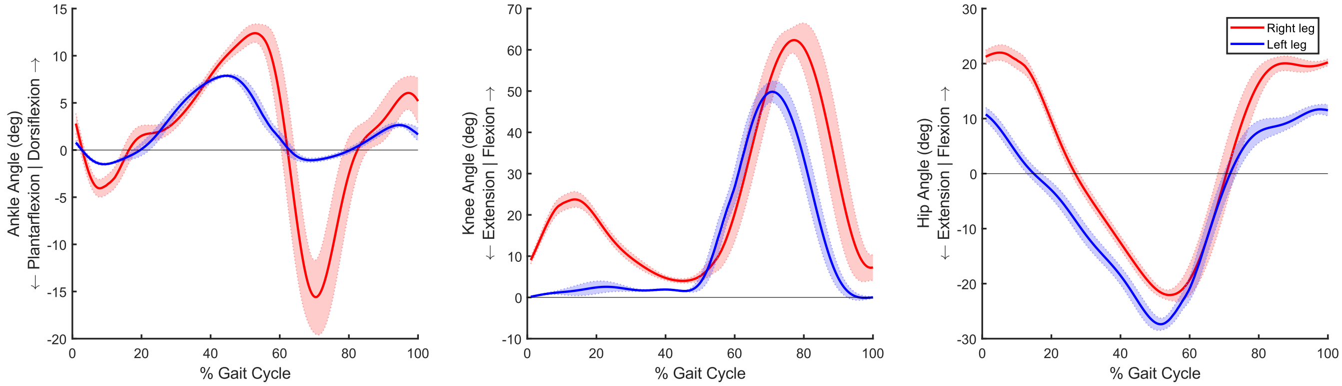

Fig. 4: Sagittal joint angles of the ankle, knee and hip during level ground walking after performing the residual correction on the osseointegrated transfemoral amputee model in OpenSim. The dark red and blue lines show the mean joint angles. The shaded region represents the standard deviation of the joint angles in ten gait cycles.

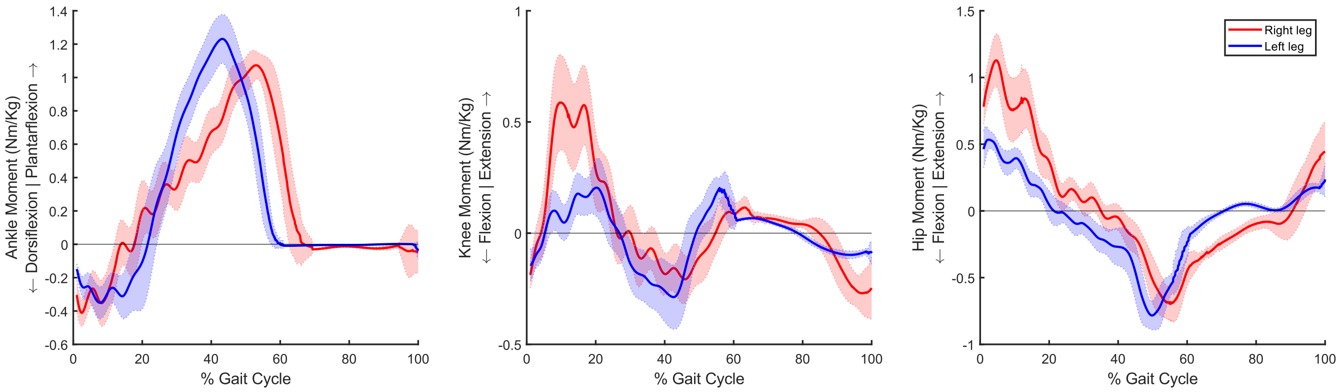

Fig. 5: Sagittal joint moments of the ankle, knee and hip during level ground walking after performing the residual correction on the osseointegrated transfemoral amputee model in OpenSim. The dark red and blue lines shows the mean normalized joint moments. The shaded region represents the standard deviation of the normalized joint moment in ten gait cycles.

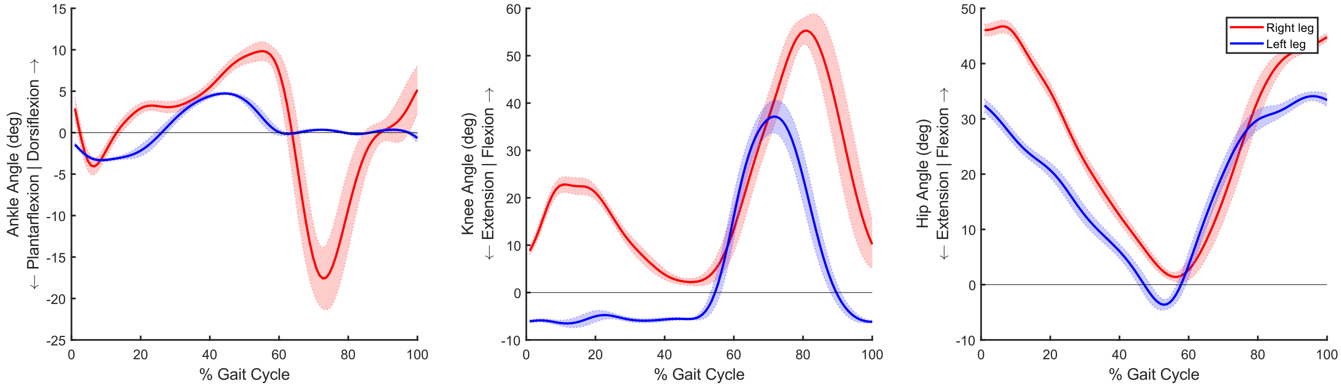

Fig. 6: Sagittal joint angles of the ankle, knee and hip during level ground walking from the VICON plug-in gait for lower body. The dark red and blue lines show the mean joint angles. The shaded region represents standard deviation of the joint angles in ten gait cycles.

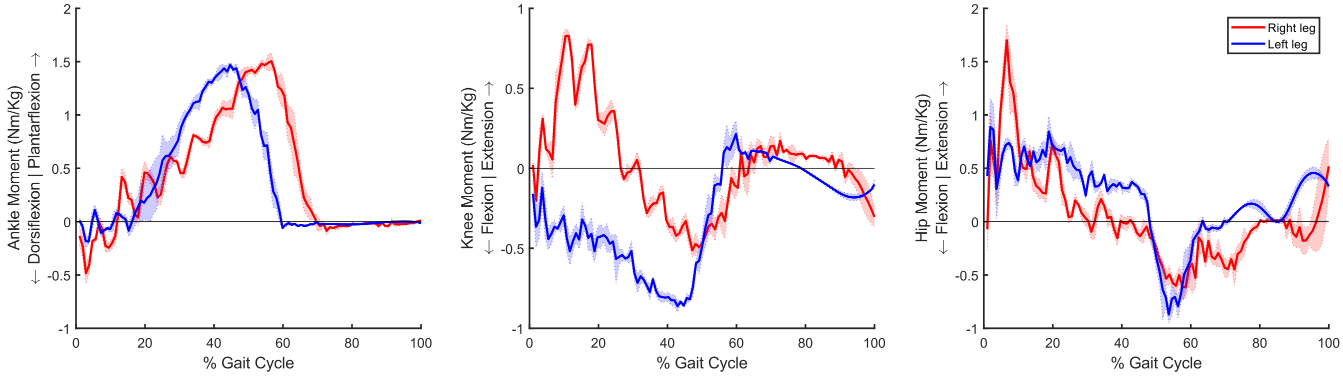

Fig. 7: Sagittal joint moments of the ankle, knee and hip during level ground walking from the VICON plug-in gait for lower body. The dark red and blue lines shows the mean normalized joint moments. The shaded region represents the standard deviation of the normalized joint moment in ten gait cycles.

used to perform inverse kinematics and dynamics to check if there are any inconsistency in the kinematics or kinetics with respect to the previous simulations.

C. Simulations & Results

In this section, the subject specific simulations on the osseointegrated transfemoral amputee model are presented. Specifically, the results obtained from the VICON lower body gait plug-in and the developed model in OpenSim are shown. Furthermore, the results obtained from residual corrected model are also shown.

The experimental data of the osseointegrated transfemoral amputee have been split into gait cycles with focus on amputated leg (left) and intact limb (right). The gait cycle starts and ends with heel strike of the same leg as shown in Figure 1. Ten gait cycles have been analyzed for each limb from a continuous level ground walking over the instrumented treadmill. During these trials, the subject did

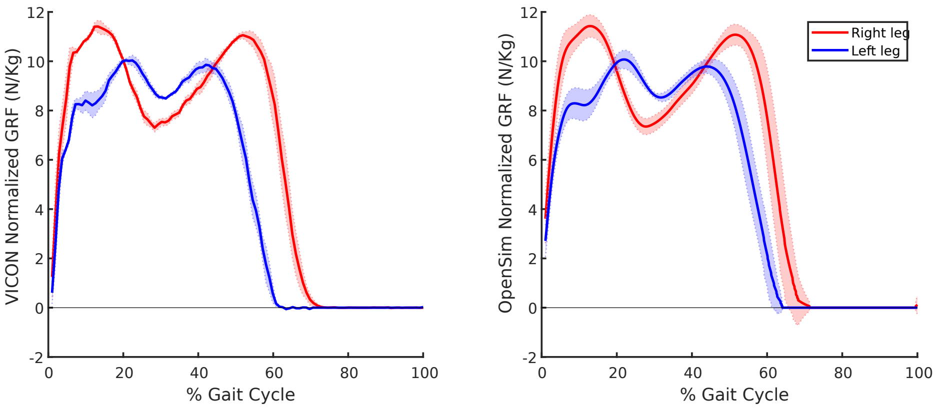

Fig. 8: Normalized ground reaction force used for the inverse dynamic computations in VICON plug-in (left) and OpenSim (right).

not hold the hands on the rails for support.

1) Inverse Kinematics: As mentioned in Section III-B, after scaling, the inverse kinematics was performed to identify the joint angles of the osseointegrated amputee model developed in OpenSim. Figure 2 shows the joint angles of ankle, knee, and hip during level ground walking after performing inverse kinematics on the scaled model. The gait cycles of both right and left leg were plotted on the same graph to visualize the gait symmetry.

The ankle angle of prosthetic limb is always in a dorsiflexed position as the subject is using a passive prosthetic foot (1C63 Triton LP). From Figure 2, it can be observed that around 70% of the gait cycle, there is an active plantarflexion of right ankle whereas the prosthetic ankle fails to do so. Similarly for the knee angle, intact limb shows the compliance of active flexion during the heel strike, whereas the prosthetic knee shows an active damping. Interestingly, Figure 6 shows the joint angles produced as an output of the VICON gait plug-in. Significant changes in the joint angles can be noted for the knee and hip flexion, which will be discussed in the next section. A simulation video of the gait is provided as a supplement to this paper for reference.

2) Inverse Dynamics: In Figure 8, there are no significant changes in the plots because it is the same analog information from the instrumented treadmill being used. However, in MOtoNMS [12], a second order zero-lag Butterworth filter was used with a cutoff frequency of 10 Hz was used to filter the noise before performing inverse dynamics in OpenSim. In Figure 3, the normalized moments across hip, knee and ankle joints are plotted for a scaled amputee model. It can be noticed that the left leg generates lower moments compared to the intact limb. During heel strike, the required knee moments of 0.6 Nm/Kg is not achieved by the prosthetic limb as it is being damped. Similarly, peak ankle moment of 1.2 Nm/Kg in left leg is generated during the roll-over phase from $20-45\%$ of the gait cycle but not during the push-off phase compared to the intact limb.

3) Residual Reduction: Figure 4, shows the result of inverse kinematics on the RRA adjusted amputee model. Minor changes in the phase of hip flexion can be observed for the intact limb. However, there are no significant changes in the magnitude of gait. Furthermore, in the Figures 4 and 5, it can be noticed that a delay in the gait of prosthetic leg during late stance has been introduced. We will discuss more about it in the next section.

IV. DISCUSSION

In this Section, we compare the gait data obtained from the proposed subject-specific osseointegrated transfemoral amputee model in OpenSim, and the gait data generated by using the lower extremity model in the VICON NEXUS application. The VICON gait plugin model consists of seven segments (pelvis, femur, tibia, and foot) and it uses a static calibration trail to scale the segments subject specific with respect to the used marker protocol

From Figures 2 and 6, it can be noticed that, in the left limb, there is a peak ankle dorsiflexion of 5° in VICON, whereas it is at 7° in OpenSim. In the knee join of the left leg, there is an offset of 10° in VICON. The reason could be because of the marker placement on the prosthetic limb was not recognized by the gait plugin as it is designed for healthy subjects. Similarly, there is a huge offset in the hip flexion angle between the VICON and OpenSim plots. As mentioned in the previous section, in Figure 4, there is a small phase shift of 3% in the gait cycle between the scaled and RRA adjusted model. This could be introduced in RRA because of the forward dynamics approach of RRA algorithm [7].

From Figures 3, 5, and 7, it can be noticed that the joint moments in VICON are higher when compared to the OpenSim inverse dynamics results. One of the reason could be due to the inaccurate scaling of model that could result in a higher moment arm while performing inverse dynamics in the VICON plugin. There is a difference of 0.614 Nm/kg and 0.235 Nm/kg for the intact limb hip and knee moments, respectively. Similarly, a difference of 0.29 Nm/kg is observed for the left ankle moments. In Figures 3 and 5, it can be noticed that there is a reduction in the peak of the ankle moments for the intact limb by 0.307 Nm/kg. This is due to the change of mass of the segments after performing the RRA. Similar reduction in the moment is observed for the knee as well but not for the hip.However, the nature of the plots of the joint moments are similar in all the three cases. The behavior of knee damping during heel strike of the left foot can be noticed in Figure 7.

In general, the kinematics and moments of the simulation can be compared with [14], to analyze the symmetry in biomechanics for a healthy subject and transfemoral amputee during level ground walking. Direct comparison on the kinematics and moments is not possible with the other literature due to the unavailability of osseointegrated amputee data. However, in [15], a comparative study on control subjects and transfemoral amputees is done. Interestingly, similar range of motion for knee and hip joint angles are observed from the aforementioned study when compared to Figure 2.

V. CONCLUSION

This paper presented the development and validation of an osseointegrated transfemoral amputee model using OpenSim. This model can be used for subject specific simulations by editing the model parameters and markers' protocol. The inverse kinematics and inverse dynamic simulations in the OpenSim model are more accurate than the conventional systems since it is designed specifically for the subject. An elaborate study with more osseointegrated amputees would benefit in establishing this area of research.

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