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OpenSim Model for Biomechanical Analysis with the Open-Source Bionic Leg

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***Abstract*— Lower-limb robotic prostheses present a potential solution for enhancing the mobility of individuals with amputation. However, comparing results amongst different research groups is a challenge as there are many differences between research devices. A recent effort from the University of Michigan created and established an open-source design for an active knee and ankle prosthesis with embedded sensors, including a shank inertial measurement unit (IMU), a 6 DOF loadcell, and joint encoders. As the usage of this design grows, it is expected that the field will require additional analyses of the locomotion biomechanics when using the open-source leg beyond what the embedded sensors can provide. In this study, we present, validate, and release a model for the software OpenSim, that serves as a solution for the full body analysis of the inverse kinematics on optical motion capture data. Our model can adjust to different pylon heights, incorporate mass & inertial properties, and provide visualizations of the prosthetic leg. We validated the model kinematically by asking four individuals with amputation to walk on a force-instrumented treadmill. Our model shows an accurate match with the encoders embedded in the leg with an RMSE of 2.34 deg for the knee and an RMSE of 2.54 deg for the ankle. This work should help facilitate the use of motion capture with the open-source leg for the bilateral analysis of the locomotion utilizing the open-source prosthetic device.**

***Index Terms* — Prosthetics, biomechanics, modeling, robotic prosthesis, transfemoral amputation.**

I. INTRODUCTION

The number of individuals with transfemoral amputation is growing in the United States [1]. The common solution to restore mobility impairment is through the use of a prosthesis or exoskeleton. Biomechanical analysis of healthy and impaired gait is necessary to understand how assistive wearable devices can help individuals with gait deficits. Specifically, in the context of prostheses and exoskeletons it can serve as useful tool in designing control strategies to assist users in a more intuitive and natural manner. Most commercially available devices are passive, which do not inject net positive work as the user is ambulating. In recent decades, powered prosthetic technology has become more prominent in its effectiveness to help users walk better. Improvements in actuator design, battery density, and control show great promise in making these devices available for clinical use. However, many different research groups are developing powered prosthesis solutions. Therefore it is hard to easily compare whether methods developed on one device can transfer over to a different device. Recently, there was a new effort in developing an open-source leg (OSL) that would allow researchers to use similar hardware in order to foster better collaboration of control strategies needed to make these devices fully functional [2]. However, there is a need to develop tools for analyzing human locomotion whilst wearing the prosthetic device. The internal sensors of the prosthetic leg already capture the joint angles on the sagittal plane. However, these sensors are not sufficient for in-depth biomechanical analysis.

Musculoskeletal modeling is a common practice that allows for analyzing the kinematics and kinetics of human locomotion. Typically, experimental data is captured via motion capture and force plates and then transformed to a subject-specific model that can be used to quantify the results of a study. OpenSim is an open-source simulation software that has been extensively used in many studies over the last decade [3], [4]. There are many available models that analyze healthy individuals from the kinematics, kinetics, and even muscular perspectives. However, there are limited models available to study the locomotion of individuals with amputation. The simplest solution in practice is to use models of healthy individuals (ex. VICON plug-in gait model). However, modeling prosthetic devices similar to human morphology may not yield an accurate representation of the human and device interaction.

Recent efforts have focused on developing models to study the gait of individuals with amputation. Takahashi et al. developed and validated a unified deformable segment model to quantify the total power for below-knee structures [5]. A limitation of this method is that one cannot isolate the sources of power contributing within the structure, but can only give a holistic measurement. Lapre et al. generated a lower-limb bilateral model containing a powered ankle prosthesis and used the model in a single-subject study case to determine the joint angles, moment and power [6]. The results were validated only at the marker level, and no information from the prosthetic sensors were included. Similarly, Raveendranathan et al. created a model of a subject with an

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osseointegrated passive transfemoral prosthesis. The single-subject model was validated as a case of study by observing the resulting bilateral kinematics, and in comparison the default *plugin-gait* model from VICON [7]. These models provide a solution to the customization of the geometry of the standard healthy models to incorporate a prosthesis. However, their validation processes do not exploit the fact that artificial limbs provide means to directly measure the joint state, serving as a reference of ground truth data.

To the authors' knowledge, a model compatible with OpenSim has not been developed for the OSL. In this manuscript, we developed and validated a custom model of four individuals with amputation wearing the robotic prosthesis. Our contributions extend to (1) releasing unilateral generic models for both the left and right sides, (2) providing marker-sets and scaling methods to adjust the pylon length based on the prosthesis's fiducials, and (3) validating the joint level kinematics in comparison to the onboard OSL sensors. Furthermore, we provide all of the model files and scaling scripts in an open-source format to facilitate collaboration across different researchers.

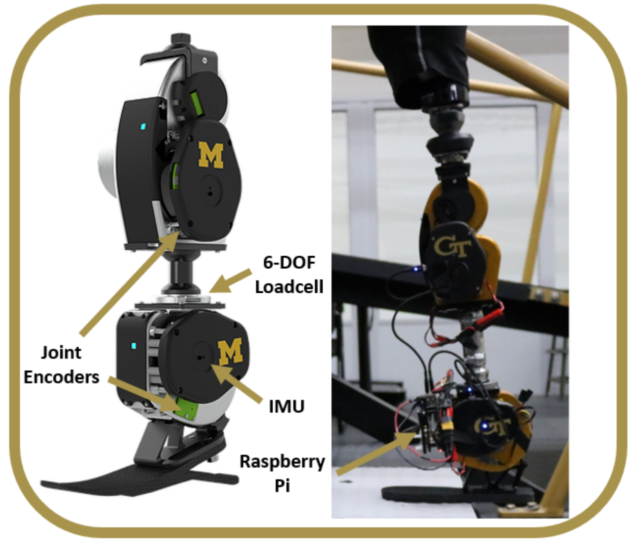

Fig. 1. The open-source leg (OSL) design (left) and a reproduction manufactured in-house at Georgia Tech (right). The OSL is actuated at the knee and ankle joints and instrumented with multiple sensors. Embedded sensors include 2 joint encoders, 1 shank IMU, and 1 6-DOF loadcell. The knee hinge terminates at a pyramidal connector for direct attachment to prosthetic sockets.

II. METHODS

A. Open-source Knee and Ankle robotic prosthesis

The University of Michigan open-source leg (OSL) is a robotic prosthesis with two actuators located at the knee and ankle joints [2]. The open-source integrated-hardware solution is focused on enhancing research applications in 3 key areas: customizable hardware, control software, and clinical use. This project has captured the attention and is being disseminated in the field of powered prostheses. The first clinical use of the OSL was tested with three individuals with unilateral amputation [2]. We are aware that more groups have started using this open-source design and have begun to perform their own research but with the advantage of using a similar hardware platform. Specifically, our team has studied the use of wearable sensors to develop locomotion classifiers and environmental estimators on powered knee and ankle prostheses [8], [9]. We have already begun to implement these control strategies over to the OSL and have started clinical research experiments.

The 2-DOF of the prosthesis correspond to the knee and ankle in the sagittal plane. These joints are commanded using BLDC motors controlled via a Dephy Actuator Package (i.e., Dephy ActPack), a commercial solution based on the MIT FlexSEA wearable robotic toolkit and a belt-driven transmission [10]. Two types of encoders are utilized: one on the motor level and one on the joint level. A 6-DOF loadcell is also used to measure forces and moments and is mounted in between the adjustable pylon configuration. Lastly, an embedded 6-DOF shank inertial measurement unit (IMU) is used to measure acceleration and gyroscopic information and is contained with the Dephy ActPack unit. To control the OSL, a Raspberry Pi 4 is programmed to control each Dephy ActPack using custom control software. The most commonly used mid-level control strategy is an impedance controller paired with a finite state machine to generate torque commands needed for different locomotion modes.

B. OpenSim Model

Using visualization files and accurate location of the joints based on the CAD model of the OSL, we modified a standard lower limb model included in OpenSim (*Simbody gait2392*) to replace the tibial and foot segments with an OSL. The prosthetic part of the model consists of the serially connected rigid body segments: the knee drive output rigidly attached to the socket, the knee assembly that is connected with a hinge joint, the pylon, the ankle assembly, and the foot that is also connected with a hinge joint. Figure 2 presents the schematic kinematic model of the prosthesis.

Matching the biological length and joint centers is a critical objective when fitting the physical prosthesis. For this, the knee center of rotation of the prosthesis is aligned with the sound side and the pylon length is adjusted to match the length of the contralateral side, when componentry and limb length allow. Thus, to attach the OSL to the biological segments in our model, we located the knee center of the prosthesis to align with the original knee center of the model. In addition, we defined the pylon length as a model parameter that is adjusted to satisfy that the location of the markers in the knee assembly and the ankle assembly.

We defined a lower limb marker set based on the Helen Hayes marker set, including bilateral information and defining markers for each rigid body segment [11]. Figure 2 illustrates the marker set consisting of 25 markers distributed bilaterally and on the torso segment. The markers on the leg are placed on specific leg landmarks that facilitate visual identification.

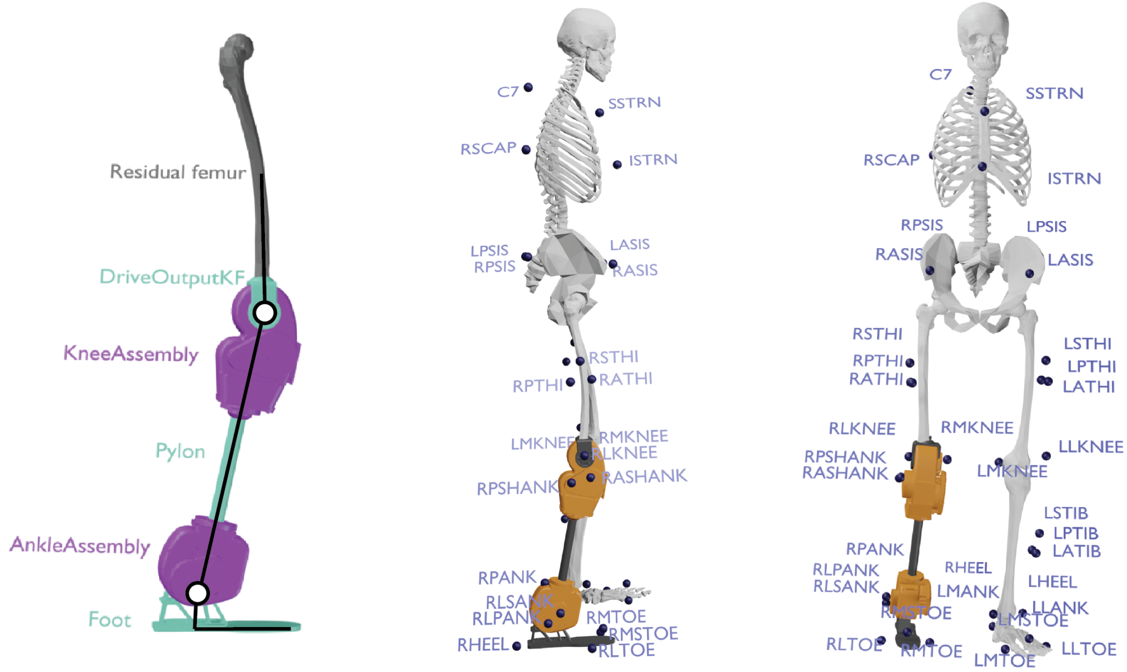

Fig. 2. Scaled OpenSim model adjusted to a subject with amputation on the right side. The model includes a bilateral lower limb marker set and defines leg markers that are of easy identification based on the leg landmarks. Since the pylon length is adjustable on each subject, our model automatically identifies and adjusts for the distance based on static marker data.

C. Accessing and using the OpenSim Model

The models for left and right amputation with OSL can be accessed on the website https://epic.gatech.edu/oslmodels. This reference includes the scaling scripts to adjust the generic model from static marker data and additional demonstration scripts that cover the use for inverse kinematics analysis. The scripts are implemented in MATLAB 2021a.

Figure 3 presents the workflow to use the models in two stages: (A) scaling and (B) inverse kinematics. For scaling, starting with the generic models and a static motion capture recording, the script *"Scale.m"* is used to adjust the model dimensions to match the markers' locations. This process includes the adjustment of the size of each biological segment and length of the pylon, generating a custom model for the subject. The scaling process extracts the labeled markers from a static motion capture and determines scaling factors of individual bone segments based on relative distances between markers. The pylon length is calculated based on the distance between the (L/R) LPANK and the (L/R) SHANK markers (Figure 2). The mass properties of each segment are compensated accordingly. Finally, the marker positions in the model are adjusted to match the static motion capture data by least squares fitting. Given that the robotic prosthesis has clear visual landmarks, the markers attached to the device are selected with increased weight (x10) relative to other markers. Once the scaled custom model is generated for an individual subject, motion capture data of the user's locomotion is used to compute the joint angles with the OpenSim inverse kinematics tool (Figure 3: workflow B). In this study, we validated this workflow by comparing the angle data from the biomechanics model to the information from the onboard encoder sensors.

TABLE I
SUBJECT DEMOGRAPHICS

	TF01	TF02	TF03	TF04
Age (yrs)	*48*	*56*	*69*	*70*
Mass (kg)	*68*	*79*	*98*	*67*
Height (m)	*1.83*	*1.68*	*1.96*	*1.57*
Sex	*Male*	*Male*	*Male*	*Female*
Side of Amputation	*Right*	*Right*	*Left*	*Left*
Pylon Height (cm)	*18*	*3.7*	*16.5*	*3*

D. Experimental Validation

Four individuals (3 males/1 female) were recruited and provided informed consent in accordance with the Georgia Institute of Technology Institutional Review Board. The subject demographics are reported in Table I. The prosthetic device was configured to each user by a certified prosthetist for appropriate comfort and alignment. The prosthetist guided the subjects in adjusting their gait to overcome any exaggerated or over-compensatory movements. The device was actively controlled via a custom controller that employed an impedance controller paired with a finite state machine (see II-A for more details).

First, a static pose was recorded with the subject in standard position. The marker positions were used to generate a custom model by scaling the generic model with the corresponding amputation side (e.g., right side for TF01 in Figure 2). Subjects were instructed to walk on an instrumented treadmill (Bertec, Ohio, US) at a constant speed of 0.8

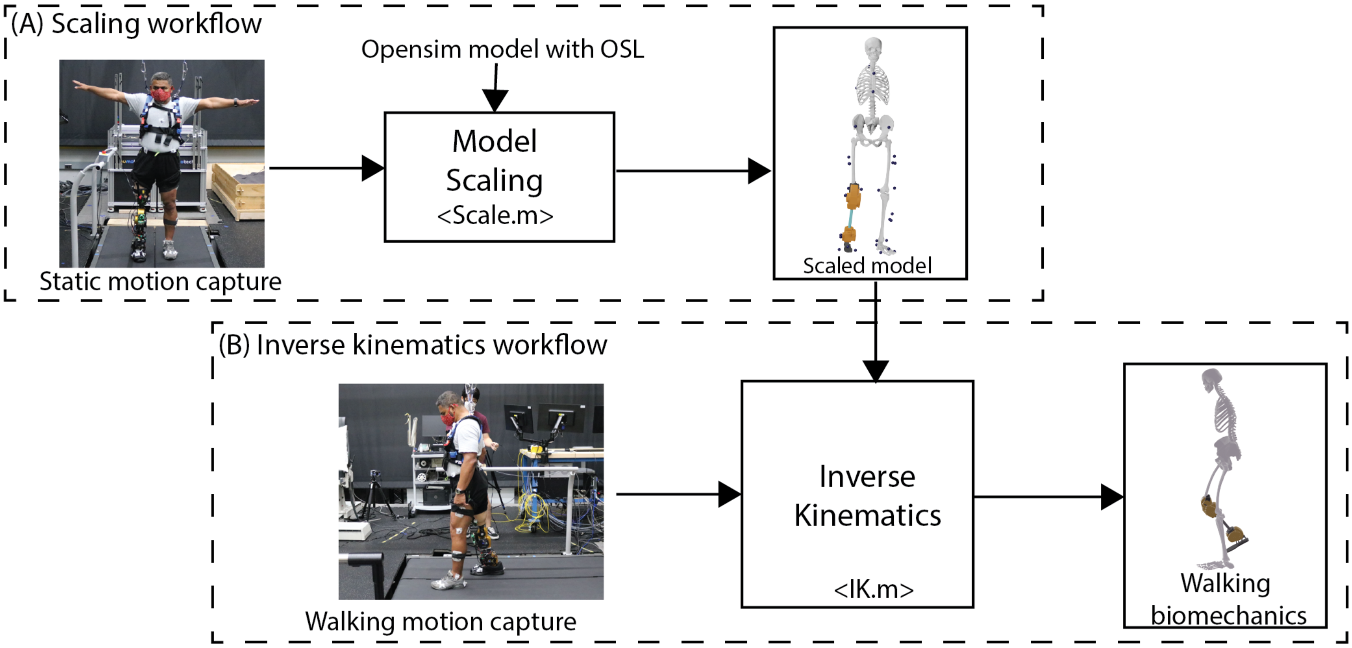

Fig. 3. Workflow for using the OSL OpenSim models by (A) scaling followed by (B) inverse kinematics. (A) A static recording is used to adjust the generic model to the user, including automatic scaling of the pylon length. (B) The generated model is then used for analyzing dynamic data of the user's locomotion. Users walked on a treadmill at 0.8m/s using the OSL device. Motion capture data using markers and VICON software was collected. Additionally, prosthetic sensor data was recorded to validate the quality of the biomechanical analysis with the proposed models and workflow.

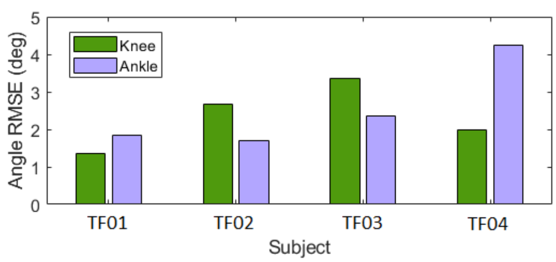

Fig. 4. Joint angle RMSE for each subject. Prosthesis encoder data was used as ground truth.

m/s. For the walking trials, we recorded the motion capture data and the joint encoders on board the prosthesis. We synchronized the two data sources by cross-correlation of the prosthesis loadcell, which is synchronized with onboard sensors, to the instrumented treadmill forceplate, which is synchronized to the motion capture data. The scaled model was used to compute the inverse kinematics for each of the walking trials as explained in Section II-C.

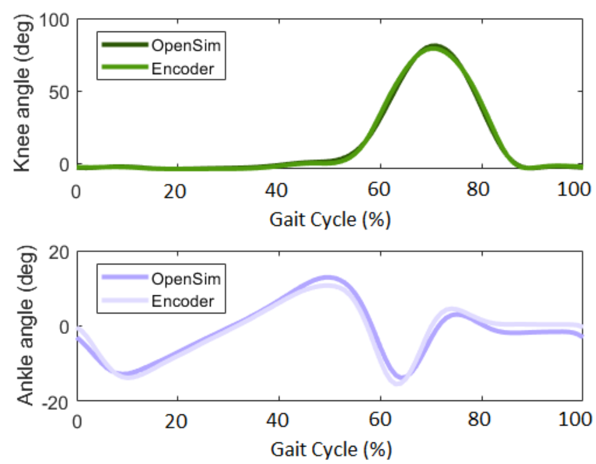

Fig. 5. Representative gait kinematics, average across all prosthesis users. Our OpenSim model captures the kinematics finding the same average profile characteristics as the one determined with the encoder information.

III. RESULTS

Figure 4 presents the RMSE for each joint per subject. On average, the knee reported 2.34 $\pm$ 0.44 deg and the ankle 2.54 $\pm$ 0.58 deg. This corresponds to 1.95% and 8.46% of the range of motion for the knee and ankle, respectively. Figure 5 shows the average kinematic profiles between the OpenSim output and the joint encoders embedded on the OSL.

IV. DISCUSSION

In this manuscript, we present and validate an open-source OpenSim model that serves as a starting point to perform a full body biomechanical analysis using the OSL. The models here are intended to be a baseline in which researchers can use to analyze the effects of the powered device. We hope that by making these models accessible and open-source, this will allow for better research collaborations and improvements to making these devices clinically viable. The advantage of using open-source tools and models will help to standardize the analysis of the OSL across different research groups. Through this study, we provide a validated model that shows accurate kinematics comparable to the information you would expect from the onboard joint encoders. By utilizing a convenient and easy-to-use marker-set allows for ease of comparison across lower limb joints. Key features of the model allow to adjust to different subjects, different leg heights, and scale automatically based on marker information from a static pose.

A limitation of the presented model is that the modeling of accurate actuator dynamics is difficult (i.e., friction effects, dissipation of energy, losses in transmission efficiency, etc.). This results in inverse dynamic (ID) calculations that do not follow the commanded torque commands given to the actuators. Recent work from LaPre et al. showed that ID profiles could be generated using computed muscle control (CMC) theory [6]. Nguyen et al. showed that modeling actuator dynamics could create better and more accurate simulations of human movement augmented via assistive devices. The results showed that although the effects of device mass and inertia were small, the electrical dynamics of the motor could significantly impact the inverse dynamics results [12]. Another limitation that must be considered is the dynamic effects between the residual limb and socket interface for individuals with amputation. Methods have been developed to evaluate the effects using a least-squares global optimization kinematic approach to estimate 4 out of 6 degrees of freedom for this residuum-socket joint [13]. However, this approach was only done for a model with transtibial amputation. Accounting for motion and load present between the user and the prosthesis can lead to a better understanding of the effects of a prosthetic device. Future work could take some of these findings to improve upon the current model to yield more accurate inverse dynamic profiles of user's lower limb joints.

Currently in the field, the biomechanical effects of lower-limb powered prostheses are not well understood on the remaining intact joints. There is limited knowledge of how these devices affect user movements across different tasks such as ramps and stairs. The objective of this study was to release open-source files and scripts to allow other researchers to use a biomechanical model to study gait characteristics of individuals with transfemoral amputation more accurately. We hope that other research groups will use these models to collaborate and compare biomechanical results and lead to improvements in advanced prosthetic control strategies, making them one step closer to clinical acceptance.

V. CONCLUSIONS

We present the development and validation of an open-source OpenSim model of the OSL to better understand the biomechanical effects of a powered prosthesis in tandem with the user. Our model is able to adjust to different pylon heights, incorporate device properties, and scale with different users. The objective is to make these models and scripts accessible to everyone to facilitate collaboration across research groups and to compare biomechanical results utilizing a similar open-source design. Our results show that we are able to achieve similar kinematic profiles between our OpenSim results and encoder sensors, demonstrating the validity of this model. By understanding how these devices affect the biomechanics of the user, future design and implementation of prosthetic control strategies can be improved to yield optimal human outcome measures such as gait symmetry and symmetric loading.

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