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Communication

The gait\textsuperscript{1415+2} OpenSim musculoskeletal model of transfemoral amputees with a generic bone-anchored prosthesis

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ABSTRACT

This short communication presents the gait\textsuperscript{1415+2} musculoskeletal model, that has been developed in OpenSim to describe the lower-extremity of a human subject with transfemoral amputation wearing a generic lower-limb bone-anchored prosthesis. The model has fourteen degrees of freedom, governed by fifteen musculotendon units (placed at the contralateral and residual limbs) and two generic actuators (one placed at the knee joint and one at the ankle joint of the prosthetic leg). Even though the model is a simplified abstraction, it is capable of generating a human-like walking gait and, specifically, it is capable of reproducing both the kinematics and the dynamics of a person with transfemoral amputation wearing a bone-anchored prosthesis during normal level-ground walking. The model is released as support material to this short communication with the final goal of providing the scientific community with a tool for performing forward and inverse dynamics simulations, and for developing computationally-demanding control schemes based on artificial intelligence methods for lower-limb prostheses.

1. Introduction

This short communication presents a lower-extremity musculoskeletal model of people with an unilateral transfemoral amputation wearing a generic lower-limb bone-anchored prosthesis.

The musculoskeletal model, named gait\textsuperscript{1415+2} and shown in Fig. 1, has been developed in the open-source simulation software OpenSim [1] and consists of 14 degrees of freedom. The movements of the model are generated by 15 musculotendon units (placed at the contralateral and residual limbs) and 2 ideal actuators (one placed at the knee joint and one at the ankle joint of the prosthetic leg).

The OpenSim literature presents a musculoskeletal model of transtibial socket-users amputees [2,3], a skeletal model of transfemoral amputees with a bone-anchored prosthesis [4], and a skeletal model of transfemoral amputees wearing the Open-Source bionic leg [5]. More recently, we have released a complete musculoskeletal model of transfemoral amputees (19 degrees of freedom and 76 musculotendon units) with a bone-anchored prosthesis [6]. However, to date, a simplified musculoskeletal model of a transfemoral amputee wearing a generic bone-anchored prosthesis, as presented in this work, has not been released yet.

The model has been developed with the intention of providing the scientific community with a simplified model for performing forward and inverse dynamic simulations of people with a bone-anchored transfemoral prosthesis, and for developing and testing control schemes for the prosthesis that rely on computationally-demanding methods based on, e.g., artificial intelligence [7,8].

The remainder of the paper is organized as follows. Section 2 presents the proposed musculoskeletal model of a transfemoral amputee in OpenSim, which is validated by inverse kinematic and inverse dynamic simulations on the experimental data from one transfemoral amputee wearing a bone-anchored prosthesis in Section 3. Conclusion are drawn in Section 4.

2. Musculoskeletal model

2.1. Musculoskeletal model gait\textsuperscript{1422}

OpenSim provides the lower-extremity musculoskeletal model gait\textsuperscript{1422} of a healthy subject (contained in the file gait\textsuperscript{1422}_body.osim) [9].

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The model consists of 14 degrees of freedom (DOFs) and 22 musculotendon units [10]. Table 1 summarizes the 14 DOFs of the model (6 for the pelvis, 2 for each hip joint, 1 for each knee joint, and 1 for each ankle joint), and their range of motion. The lumbar extension is locked to $-5^\circ$, while the hip rotation is locked to $0^\circ$. Table 2 summarizes the 22 musculotendon units, which are modelled as Hill-type muscles [11] and are symmetrically distributed over the left and right side (i.e., 11 for the movements of each leg), together with the corresponding movements that they can generate.

### 2.2. Skeletal model gait1415+2

In this study, the gait1422 model has been modified to create the lower-extremity musculoskeletal model gait1415+2 of a transfemoral amputee wearing a generic transfemoral bone-anchored prosthesis. Without loss of generality, the gait1415+2 model refers to a left-side amputation but it can be analogously described for a right-side amputation. The gait1415+2 model, specified for both left- and right-side amputation, is provided as support material to this study, and made available at [https://simtk.org/projects/oi-tfp-reduced](https://simtk.org/projects/oi-tfp-reduced).

#### 2.2.1. Musculotendon-units and actuators

The gait1415+2 model consists of 14 DOFs, 15 musculotendon units and 2 ideal actuators. The 14 DOFs are the same as the ones of the gait1422 model, as summarized in Table 1 (6 for the pelvis, 2 for each hip joint, 1 for each knee joint, 1 for each ankle joint), as well as their range of motion. The lumbar extension is locked to $-5^\circ$, while the hip rotation is locked to $0^\circ$.

The gait1415+2 model has been obtained from the gait1422 model by removing seven musculotendon units on the amputated (left) leg and by adding two ideal actuators of the generic transfemoral prosthesis, which are placed at the knee and ankle joints [6]. The 15 musculotendon units are modelled as Hill-type muscles [11]. The two actuators are modelled as OpenSim activation coordinate actuators that produce a generalized force using first-order linear activation dynamics, i.e., the activation $a$ of the actuator follows the dynamics given by $\dot{a} = (x - a)/r$, where $x$ is the excitation constant (set to 0.01), and $r$ is the activation time constant (set to 0.02). The maximum optimal force of these actuators is limited up to 300 N, which is plausible for microcontrolled prosthetic joints. Table 2 details the 15 musculotendon units (11 at the right leg, 4 at the residual left leg) and the 2 actuators, together with the corresponding movements that they can generate. Fig. 2 shows the gait1415+2 musculoskeletal model, where the 15 muscles and 2 actuators are highlighted.

### 2.2.2. Scaling

The skeleton of the gait1422 model has been modified as follows. The left femur has been transected and an osseointegrated implant has been welded on it. The osseointegrated implant, the tibia pylon, and the foot have been modeled in Solidworks (Dassault Systèmes SolidWorks Corporation, Waltham, USA, [www.solidworks.com](http://www.solidworks.com)) and imported as .stl files in OpenSim [6]. The CAD design shown in this model is for visualization purposes [12], and does not contribute to the computation apart from its geometric properties. Table 3 summarizes the mass, length, center of mass, and inertia of the body segments based on the material properties. The mass of the osseointegrated implant is based on the material density of the Ti6Al4Nb alloy. The mass of the commercial microprocessor-controlled prosthetic knee and ankle-foot were used for the weight of the tibia pylon and of the foot, respectively.

#### 2.2.3. Scaling

The gait1415+2 model has been scaled on the experimental data that have been collected on one participant at the Radboud University Medical Center in Nijmegen, The Netherlands.

The participant (female, left amputation, height 1.69 m, weight 59.3 kg), wearing an Ottobock C-Leg microcontrolled knee and an Ottobock Trias energy-storing-and-releasing foot (Ottobock, Duderstadt, Germany, [https://www.ottobock.com](https://www.ottobock.com)) was asked to walk on an instrumented treadmill (Motek Medical B.V., Houten, The Netherlands, [www.motekmedical.com](http://www.motekmedical.com)) for 5 minutes at her comfortable walking...
The musculotendon units of the gait1422 and gait1415+2 models, and the corresponding movements. The gait1422 model has 22 musculotendon units (11 at the right leg, 11 at the left leg). The gait1415+2 has 15 musculotendon units (11 at the right leg, 4 at the residual left leg) and two actuators (at the knee and ankle joints).

<table>
<thead>
<tr>
<th>Muscles &amp; Actuators</th>
<th>Movements</th>
<th>gait1422 (right leg)</th>
<th>gait1422 (left leg)</th>
<th>gait1415+2 (right leg)</th>
<th>gait1415+2 (left leg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluteus maximus</td>
<td>Hip extension</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Iliopsoas</td>
<td>Hip flexion</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Hip abductor</td>
<td>Hip abduction</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Hip adductor</td>
<td>Hip adduction</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Hamstring (biarticular)</td>
<td>Hip extension, Knee flexion</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rectus femoris (biarticular)</td>
<td>Hip flexion, Knee extension</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vasti</td>
<td>Knee flexion</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biceps femoris</td>
<td>Knee flexion</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soleus</td>
<td>Ankle extension (plantarfexion)</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gastrocnemius (biarticular)</td>
<td>Knee flexion, Ankle extension</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tibialis anterior</td>
<td>Ankle flexion (dorsiflexion)</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee actuator</td>
<td>Knee flexion/extension</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Ankle actuator</td>
<td>Ankle dorsiflexion/plantarflexion</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
</tr>
</tbody>
</table>

The mass, length, center of mass (x, y, z), and inertial properties ($I_{xx}$, $I_{yy}$, $I_{zz}$) of the body segments in the gait1415+2 model.

<table>
<thead>
<tr>
<th>Body</th>
<th>Mass (kg)</th>
<th>Length (m)</th>
<th>Center of Mass [x, y, z] (m)</th>
<th>Inertia $[I_{xx}, I_{yy}, I_{zz}]$ (kg m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfemur</td>
<td>6.65</td>
<td>0.19</td>
<td>0, -0.07, 0</td>
<td>0.02269, 0.0026, 0.03292</td>
</tr>
<tr>
<td>Osteointegrated Implant</td>
<td>0.35</td>
<td>0.205</td>
<td>0, -0.133, 0</td>
<td>0.0013, 0.0001, 0.0013</td>
</tr>
<tr>
<td>Tibia pylon</td>
<td>1.4</td>
<td>0.43</td>
<td>0, -0.213, 0</td>
<td>0.0324, 0.0005, 0.03215</td>
</tr>
<tr>
<td>Foot</td>
<td>0.8</td>
<td>0.37</td>
<td>0.0186, -0.0213, 0</td>
<td>0.00036, 0.0025, 0.0025</td>
</tr>
</tbody>
</table>

Fig. 3. Ankle, knee, and hip joint angles during level ground walking as a result of inverse kinematics for both the contralateral (blue) and the prosthetic leg (red). The thick lines represent the mean joint angles over five gait cycles, while the shaded regions represent their one-standard deviation.

3.1. Inverse kinematics

The OpenSim inverse kinematics toolbox uses the 3D poses of the experimental markers to compute the generalized joint positions of the model. The toolbox positions the model to best match the experimental data by minimizing a sum of weighted squared errors of the real markers (placed on the participant as in the experimental data set) and the virtual markers (on the model).

Fig. 3 reports the ankle, knee, and hip joint angles of both the contralateral and the prosthetic leg, during level ground walking, after performing the inverse kinematics on the scaled model. The thick lines represent the mean of the joint angles over five gait cycles, while the shaded regions represent their one-standard deviation. The root mean square error between the kinematics obtained from the experimental data and the model is 0.0116 (with a max error of 0.034 on the sternum marker), which signifies that the model can satisfactorily resemble the kinematics of the participant.

From the plots, it is possible to notice that the participant is using an energy-storing-and-releasing foot, which is able to provide only part of the plantarfexion/dorsiflexion range of motion when compared to the contralateral (right) ankle [15], and a microcontrolled prosthetic knee, which remains locked at 0° during the stance phase of the gait cycles to support the weight of the participant [16]. Moreover, it can be noted...
that an offset is present in the hip flexion due to the fact that, while the neutral position is at 0° in the gait1415+2 model, the neutral position of the hip flexion is set at −12° to −13° in clinical studies [15].

3.2. Inverse dynamics

The OpenSim inverse dynamics toolbox uses the generalized joint positions, as computed by the inverse kinematic toolbox, and the experimental ground reaction forces to determine the generalized forces at each joint of the model (i.e., net joint torques) so that it reproduces the movements described by the experimental markers. The OpenSim inverse dynamics toolbox was modified to account for the introduction of the ideal actuators at the knee ad ankle joints of the transfemoral prosthesis, as described in our previous work [6].

Fig. 4 reports the ankle, knee, and hip joint torques (normalized per body weight) of both the contralateral and the prosthetic leg, during level ground walking after performing the inverse dynamics on the scaled model. The thick lines represent the mean joint torques over five gait cycles, while the shaded regions represent their one-standard deviation.

From the plots, it is possible to notice that the participant is using an energy-storing-and-releasing foot, which is able to provide almost all the torque required in the gait cycle as it is slightly smaller then the torque of the contralateral (right) ankle [15], and a microcontrolled prosthetic knee, which dissipates the impact forces at heel-strike but does not provide torque to support the gait.

3.3. Static optimization

The OpenSim static optimization toolbox further resolves the net joint torques into the individual muscle forces. The toolbox was modified to account for the introduction of the ideal actuators at the knee and ankle joints of the transfemoral prosthesis, i.e., the muscle forces as well as the actuator torques are computed by minimizing the sum of the squared muscle activations and of the squared actuator torques as presented in our previous work [6].

Fig. 5 reports the muscle’s activations during level ground walking after performing the static optimization on the scaled model. The thick lines represent the mean muscles’ activations over five gait cycles, while the shaded regions represent their one-standard deviation. From the plots, it is possible to notice that the muscles’ activations are in accordance to the literature [17,18], hereby validating the proposed model.

The video, accompanying this short communication, shows the results of the study. Specifically, the video compares the experimental data, visualized by means of the Mokka software (Motion Kinematic & Kinetic Analyzer, Biomechanical ToolKit, https://biomechanical-toolkit.github.io/mokka/), and the static optimization simulation.

4. Conclusions

This short communication presented the gait1415+2 musculoskeletal model that describes the lower-extremity of a human subject with transfemoral amputation wearing a generic lower-limb bone-anchored prosthesis in OpenSim. The model has been made subject-specific by scaling it on a participant’s experimental data. Afterwards, it has been shown that the model is capable of reproducing the participant’s walking gait in terms of its kinematics and dynamics, while producing plausible muscles’ activations. The model, specified for both left- and right-side amputation, is provided as support material to this study and made available at https://simtk.org/projects/oi-ifp-reduced with the final goal of providing the scientific community with a tool for performing forward and inverse dynamics analyses, and for developing control schemes for lower-limb prostheses based on computationally-demanding artificial intelligence methods.

Future work will focus on further validating the model while performing other activities of daily living, e.g., ascend/descend ramps and stairs.

Ethical approval

The study, under protocol number NL2018-4919, was evaluated and received a waiver by the Medical Ethics Review Committee Arnhem-Nijmegen (Nijmegen, The Netherlands) on December 10, 2018, and complied with the guidelines as defined in the Declaration of Helsinki (World Medical Association, 2013). Participants signed a written informed consent before participating.

CRediT authorship contribution statement

Raffaella Carloni: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Supervision, Project administration, Funding acquisition.

Rutger Luinge: Software, Validation, Investigation, Data Curation, Writing - Review & Editing, Visualization.

Vishal Raveendranathan: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Review & Editing.

Declaration of competing interest

No conflict of interest.

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Fig. 5. Muscles’ activations during level ground walking as a result of static optimization. The thick lines represent the mean muscles’ activations over five gait cycles, while the shaded regions represent their one-standard deviation.

candidate) at the Radboud University Medical Center in Nijmegen, The Netherlands, for the data collection on the participant.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.medengphy.2023.104091.

References


