A Non-Invasive Method of Muscle Force Estimation of a Lower Limb with a Partial Foot Amputation

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Abstract

Background and Aim: Previous gait analysis of partial foot amputee subjects has focussed on quantification of joint angles, moments and powers without quantifying muscle forces. This research aimed to develop a subject-specific musculoskeletal model of a partial foot amputee gait to quantify muscle forces of a lower limb affected by a mid-foot amputation during walking non-invasively.

Technique: First, a musculoskeletal model of the subject was developed. Secondly, the time history of joint moments were predicted by the model and compared with those calculated by a non-musculoskeletal model to verify the model calculation and thirdly, the time history of muscle forces were predicted by the musculoskeletal model of the subject using collected kinematic and kinetic data of the subject during walking. The timings of generated muscle forces and EMG signals were used for the evaluation of muscle forces predicted by the musculoskeletal model.

Discussion: The timing of muscle forces and EMG signals of muscles indicated that the model predictions for individual muscle forces of the lower limb were reliable and the musculoskeletal model quantified the muscle forces to some degrees of confidence.

Clinical Relevance: Further research is required to understand the effects of partial foot amputation on muscle adaptation during walking, which should help to inform new surgical methods of tendon transfer designs of prosthetic/orthotic interventions, with greater focus on improving the gait patterns.

Keywords: Partial Foot Amputation; Musculoskeletal Modelling; Gait; Muscle Forces

Background and Aim

Partial foot amputation (PFA) is a common surgical intervention as a result of trauma, infection, birth defect, and advanced vascular disease secondary to diabetes [1,2]. The risk of PFA in diabetic patients is 15 times greater than for normal population [3]. It is estimated that the worldwide diabetic population will rise from 171 million in 2000 to 366 million in 2030; therefore, the number of people requiring PFA will also increase [4].

Despite the prevalence of PFA, the effects of amputation on lower limb muscle forces have not been studied yet. The effects of amputation and prosthetic devices have been studies on joint angles, joint moments and joint powers [5,6]. It has revealed that the amputation proximal to toes reduced the ankle joint power on the affected limb with amputation without quantifying the individual muscle forces around the ankle joint [5].

The invasive techniques of quantifying individual muscle forces are limited to a small number of muscles and are discouraged by ethical considerations [7,8]. The rational for this argument is being challenged as a result of emerging Computer-based musculoskeletal models quantifying muscle function during partial foot amputees’ walking non-invasively [9-11]. The objective of this study is to develop a computer-based musculoskeletal model of a subject with transmetatarsal amputation in order to quantify the muscle forces of lower limb affected by transmetatarsal amputation during walking. This musculoskeletal model may help surgeons to investigate the effects of tendon transfer on ankle foot muscles during walking.

**Technique**

The generic musculoskeletal model was developed. The ethics approval was received to use the available experimental gait data of a subject as inputs for the proposed generic musculoskeletal model. The pipeline of this study was presented in Figure 1.

Because the available experimental data belonged to the affected limbs of a subject with transmetatarsal amputation in the sagittal plane, a one leg musculoskeletal model was developed with six degrees of freedom. The modelled pelvis could move in x-direction and y-direction when it rotates in the sagittal plane. Hip, knee and ankle joint were modelled as hinge joints with only one degree of freedom as they could flex or extend in the sagittal plane.

The simplified musculoskeletal model was actuated by 16 muscles that consisted of 25 muscle-tendon units, each unit represented as a Hill-type muscle (Table 1). Their muscle-tendon parameters were defined in the model based on previous studies [9].

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The foot muscle tendons were updated based on the amputation [12]. The foot anthropometric parameters of the subject estimated in a previous study were updated after scaling the musculoskeletal model [5].

The subject (age, 54; height, 1.8 m; mass, 84.5 kg) had toe filler and had traumatic amputation for more than 3 years.

The proposed generic model and the marker position file for the subject during standing was used to scale the generic musculoskeletal model.

The scaled one-leg musculoskeletal model of the subject in the OpenSim software (Figure 2) was used for computational analysis of joint angles, joint moment and muscle forces of lower limb with transmetatarsal amputation during walking [11].

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Muscle Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iliacus psoas, rectus femoris</td>
<td>Hip flexors</td>
</tr>
<tr>
<td>Biceps femoris, gluteus maximus</td>
<td>Hip extensors</td>
</tr>
<tr>
<td>Biceps femoris, gastrocnemius, gracilis, sartorius, semitendinosis, semimembranosis</td>
<td>Knee flexors</td>
</tr>
<tr>
<td>Rectus femoris, vastus intermedius, vastus lateralis</td>
<td>Knee extensors</td>
</tr>
<tr>
<td>Flexor digitorum, flexor hallucis, gastrocnemius, soleus, tibialis posterior</td>
<td>Ankle plantarflexors</td>
</tr>
<tr>
<td>Extensor digitorum, extensor hallucis, tibialis anterior</td>
<td>Ankle dorsiflexors</td>
</tr>
</tbody>
</table>

Table 1: Muscles and corresponding muscle groups in the musculoskeletal model used in the present study.

Figure 2: Generic musculoskeletal model (A), scaled model (B).

Results and Discussion

The proposed musculoskeletal model re-produced very similar sagittal plane joint moments to that obtained from traditional gait analysis (Table 2). The net joint moments at hip, knee and ankle joints were computed by the subject-specific musculoskeletal model of the affected limb with transmetatarsal amputation (Figure 3).

Figure 3: Net joint moments of the affected limb with transmetatarsal amputation computed by the subject-specific musculoskeletal model of the subject. HM: Hip Moment; KM: Knee Moment; AM: Ankle Moment.
The proposed musculoskeletal model for gait analysis of people with PFA produced very similar sagittal plane net joint moments to that obtained from traditional gait analysis for a subject with transmetatarsal amputation (Table 2).

<table>
<thead>
<tr>
<th>Points of Interest</th>
<th>Joint moment (Nm/kg)</th>
<th>Timing (%Stance)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dillon and Barker, 2008</td>
<td>Current research</td>
</tr>
<tr>
<td>HM1</td>
<td>-0.67</td>
<td>-0.76</td>
</tr>
<tr>
<td>HM2</td>
<td>0.28</td>
<td>0.38</td>
</tr>
<tr>
<td>KM1</td>
<td>-0.29</td>
<td>-0.19</td>
</tr>
<tr>
<td>KM2</td>
<td>0.32</td>
<td>0.31</td>
</tr>
<tr>
<td>AM1</td>
<td>-0.06</td>
<td>-0.04</td>
</tr>
<tr>
<td>AM2</td>
<td>0.84</td>
<td>0.42</td>
</tr>
</tbody>
</table>

**Table 2:** Comparison of joint moments derived by using musculoskeletal model and traditional kinetic model.


The timing of EMG activity of some muscles obtained from the traditional gait analysis were consistent with the timing of muscle forces estimated by the musculoskeletal model during walking (Figure 4). This is a good indicator for reliability of muscle contraction predicted by the musculoskeletal model. In a subject with transmetatarsal amputation, the timing of EMG activity for some available muscles was consistent with timing of forces predicted by the musculoskeletal model for those muscles (Figure 4). A delay between EMG activity and generated force in muscle actuators may be go back to the fact that there is a time lag between electrical activity and force development.

![Image](image.png)

**Figure 4:** Predicted muscle contraction by the musculoskeletal model for vastus lateralis and tibialis anterior (red dash line). The thick solid line presents the timing of EMG data recorded for the two muscles of the subject with transmetatarsal amputation during walking.

In a subject with transmetatarsal amputation, knee extensors, hip extensors and knee flexors had a peak maximum muscle contraction during the first 40% of the stance without generating much force during the rest of the stance phase (Figure 5). In contrast, knee extensors, hip extensors and knee flexors generated two peak maximum muscle forces during the stance phase (Figure 5).

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The knee flexion moment was around 0.2 Nm/kg to absorb the shock generated from the contact of the heel with the ground (Figure 3, AM1). During this period of time, the ankle dorsiflexors controlled the speed of contact of the foot with the ground by generating ankle dorsiflexion moment around 0.04 Nm/kg (Figure 3, AM1) and peak muscle force of 0.3 N/BW in tibialis anterior.

During loading response, the magnitude of knee extension moment was 0.29 Nm/kg. However, the peak knee extensors including rectus femoris and vasti was 0.55 Nm/kg (Figure 5). The magnitude of peak force of rectus femoris and vasti may highlight the increased need for stability and support during this period of the gait cycle.

From mid-stance to terminal stance (50 - 86% stance), no flexion/extension moment was observed in the knee joint (Figure 3). The subject maintained the knee extension by placing the ground reaction force line in front of the knee joint perhaps by adjusting the position of the trunk. During terminal stance, knee flexors of the subject contracted to avoid knee hyperextension (Figure 3).

There are some limitations in this research project which should be considered. First, only stance phase of a gait cycle was investigated because the ground reaction forces can be measured during stance phase of the gait and the used approach in this research was inverse dynamics. The model may need some more modification to calculate joint moments and muscle force during other tasks, such as running. There may be some errors during data collection in the data set used for the simulation of the gait. For example, the fifth metatarsal head was located on the estimated location of the absent fifth metatarsal head on the toe filler. The movement of the toe filler related to the remaining foot may affect the calculation of joint moments and as such muscle force. Only the gait of a subject with transmetatarsal amputation was quantifies. Thus, no statistical differences were presented and discussed in this research. The gait analysis was performed in the

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Figure 5: The forces for an affected limb with a transmetatarsal amputation. KE: Knee Extensors Including Rectus Femoris, Vastus Intermedius and Vastus Lateralis; HE: Hip Extensors Including Biceps Femoris and Gluteus Maximus; AD: Ankle Dorsiflexors Including Extensor Digitorum, Extensor Hallucis and Tibialis Anterior; KF: Knee Flexors Including Biceps Femoris, Gastrocnemius, Gracilis, Sartorius, Semitendinosis and Semimembranosis; HF: Hip Flexors Including Iliacus Psoas and Rectus Femoris; AP: Ankle Plantarflexors Including Flexor Digitorum, Flexor Hallucis, Gastrocnemius, Soleus and Tibialis Posterior.
sagittal plane for the affected limb with PFA; however, walking is a three-dimensional bipedal task. Limitation of available experimental data did not allow a three-dimensional bipedal modelling of walking. A three-dimensional simulation of gait using full-body musculoskeletal model with a reasonable sample size is suggested, using the methodology of this thesis.

**Key Points**

- A developed musculoskeletal model for a subject with transmetatarsal amputation predicted the net joint moments accurately.

- The model predicted the time history of individual muscle forces of an affected lower limb with PFA during walking to some degrees of confidence because the timing of predicted muscle forces and EMG signals were consistent.

**Author Contribution**

The authors contributed in the musculoskeletal model's development, data analyses, data interpretation and writing the draft.

**Declaration of Conflicting Interests**

The authors declare that there is no conflict of interest.

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**Bibliography**


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