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# Energy flow analysis of amputee walking shows a proximally-directed transfer of energy in intact limbs, compared to a distally-directed transfer in prosthetic limbs at push-off

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ABSTRACT

Reduced capacity and increased metabolic cost of walking occurs in amputees, despite advances in prosthetic componentry. Joint powers can quantify deficiencies in prosthetic gait, but do not reveal how energy is exchanged between limb segments. This study aimed to quantify these energy exchanges during amputee walking.

Optical motion and forceplate data collected during walking at a self-selected speed for cohorts of 10 controls, 10 unilateral trans-tibial, 10 unilateral trans-femoral and 10 bilateral trans-femoral amputees were used to determine the energy exchanges between lower limb segments.

At push-off, consistent thigh and shank segment powers were observed between amputee groups (1.12 W/kg vs. 1.05 W/kg for intact limbs and 0.97 W/kg vs. 0.99 W/kg for prosthetic limbs), and reduced prosthetic ankle power, particularly in trans-femoral amputees (3.12 W/kg vs. 0.87 W/kg). Proximally-directed energy exchange was observed in the intact limbs of amputees and controls, while prosthetic limbs displayed distally-directed energy exchanges at the knee and hip.

This study used energy flow analysis to show a reversal in the direction in which energy is exchanged between prosthetic limb segments at push-off. This reversal was required to provide sufficient energy to propel the limb segments and is likely a direct result of the lack of push-off power at the prosthetic ankle, particularly in trans-femoral amputees, and leads to their increased metabolic cost of walking.


## 1. Introduction

Despite advances in prosthetic lower limbs, amputees are still known to walk with increased metabolic costs compared to able-bodied individuals, and with increasing metabolic cost as the level of amputation becomes more proximal or when bilateral amputation occurs [1–4]. To better understand why this may be the case, studies have investigated the kinematics of lower limb amputees [5] and have consistently found reduced knee flexion during weight-acceptance and reduced ankle plantar-flexion during late stance. Recently however, studies have focused on the kinetics and muscular activity of amputee gait to provide a more complete picture of the biomechanics of the limbs and trunk during amputee walking. Studies assessing the effect of different prosthetic components [6–8] and of amputation level [9–14] during amputee gait have led to consistent findings of reduced peak ankle plantar-flexion moment and power and increased peak hip power generation and absorption in amputees. This has led to several avenues of research, particularly the design and development of active (powered) prosthetic limbs [15–17]. However, given the majority of amputees use passive prosthetic limbs, understanding how these devices interact with the body during locomotion should remain a priority and may lead to improved passive devices with better energy storage and return characteristics, perhaps utilizing intelligent control.

An efficient gait will likely be dependent on energy conserving exchanges between limb segments and also on energy storage and

*Abbreviations:* BTF – Bilateral Trans-Femoral, Con – Control, DMRC – Defence Medical Rehabilitation Centre, DoF – Degree of Freedom, ESR – Energy Storage and Return, JFP; Joint Force Power, STP; Segment Torque Power, UTF – Unilateral Trans-Femoral, UTT – Unilateral Trans-Tibial.

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**Table 1**
Participant demographic information.

| Groups | Mass [kg] | Height [m] | Age [years] |
|---|---|---|---|
| Control | 78.0 (7.6) | 1.82 (0.05) | 30 (6) |
| UTT | 89.8 (14.3) | 1.82 (0.05) | 28 (4) |
| UTF | 88.3 (6.5) | 1.80 (0.07) | 29 (3) |
| BTF | 86.7 (19.2) | 1.81 (0.08) | 29 (4) |

*Note*: values are presented as mean (s.d.).

return mechanisms, typically utilizing strain energy in tendons and prosthetic components. In unilateral amputees, it is known that the intact limb often compensates for deficiencies on the prosthetic side, which leads to characteristic gait asymmetries of reduced stance time and increased swing time and step length on the prosthetic side [10,11]. However, despite these asymmetries, fit individuals with a trans-tibial amputation as a result of trauma often have a metabolic cost of walking that is close to that of healthy able-bodied controls [4,18], suggesting that, in certain cases at least, it is possible to overcome the deficiencies associated with the loss of limb. While unilateral amputees are able to compensate with their intact limb, this is not possible in bilateral amputees, who are known to have a significantly increased metabolic cost of walking [4,19,20].

While standard gait analysis techniques have been able to identify joint-level differences between amputee and able-bodied gait, it remains unclear what impact the inability to produce active ankle power has on the way in which energy is transmitted through the limb as a whole. Quantifying the energy exchanges that occur between limb segments in amputee gait may result in a better understanding of the underlying causes of inefficient gait in unilateral and bilateral amputees, as this would provide a more complete picture of lower limb amputee biomechanics during walking. Such an approach has previously been used to assess the energy exchanges in the lower limbs in both healthy and pathological gait [21–26] and in trans-tibial amputees to assess energy exchanges at the ankle [8,27]. However, whole limb energy flow analyses of trans-femoral and trans-tibial amputee populations have not been previously performed, which has previously limited our ability to characterize amputee gait to joint-level measures. Therefore, it was the aim of this study to investigate how reduced ankle push-off power alters lower limb energy flows during amputee walking. The hypothesis of this study is that changes in energy flows in the lower limbs of amputees during walking can help to explain the substantial increases in metabolic demands commonly reported for this population.

## 2. Materials and methods

### 2.1. Subject details and protocol

In a previously published study [4], 30 amputees were recruited to form three cohorts of 10 unilateral trans-tibial (UTT), 10 unilateral trans-femoral (UTF) and 10 bilateral trans-femoral (BTF) amputees (Table 1). Study inclusion criteria were: Aged 18 to 40, amputation as a result of lower limb trauma, attending Defence Medical Rehabilitation Centre (DMRC) Headley Court for routine prosthetic appointment, at least 6 months after fitting of definitive prosthesis, no pain consequent to prosthetic fitting or alignment (minor “discomfort” was acceptable) and capable of walking comfortably for 10 min continuously. Study exclusion criteria were any neuromusculoskeletal pathology (aside from the amputated limb) which would likely affect the participants' walking. All amputees were fitted with energy storage and return (ESR) feet, trans-femoral amputees with micro-processor knees (Table 2), and had undergone similar rehabilitation regimes at Headley Court. 10 healthy military personnel were also recruited to provide age- and height-matched control data for comparative purposes.

All participants performed the same protocol, which began with walking for 2 min up and down the gait laboratory walkway to establish their self-selected walking speed, before 5 min of walking at the established self-selected walking speed. The instrumented gait laboratory walkway was 10 m in length, and the participants turned around at the ends of the laboratory before returning again. This was repeated for the duration of the data collection while whole-body optical motion (Vicon, Oxford, U.K.) and forceplate (Kistler, Winterthur, Switzerland) data were recorded at 100 Hz and 1000 Hz respectively.

### 2.2. Energy flow analysis

A custom-written lower limb model comprised of a pelvis and bilateral thighs, shanks and feet all linked by 6 degree of freedom (DoF) joints was used for inverse dynamics analysis to provide the necessary data for the subsequent energy flow calculations [21,27] and was implemented in Matlab 2014b (The Mathworks Inc., Natick, MA, U.S.A.). Body segment parameters for both the intact and prosthetic limb were scaled according to subject mass and height using the anthropometric measures of de Leva [28]. Optical marker clusters attached to a rigid base were used to track each body segment's motion, and individual optical markers placed bilaterally on the following landmarks were used to determine segment end points and scale the model to each participant: posterior and anterior superior iliac spine, medial and lateral femoral epicondyles, medial and lateral malleoli, posterior and lateral calcaneus, on the dorsal surface of the 1st, 2nd and 5th metatarsal heads. Optical motion and forceplate data were used to calculate inter-segmental angles and moments at the ankle, knee and hip joints of each limb separately following established inverse dynamics utilizing Newton–Euler equations of motion for the segment dynamics [29].

The approach of Winter & Robertson [21] was used to calculate energy exchanges across the ankle, knee and hip joints. In summary, this approach uses inter-segmental moment ($\mathbf{M}_{\mathrm{Joint}}$) and force ($\mathbf{F}_{\mathrm{Joint}}$), derived from the inverse dynamics, and the segment's angular velocity ($\boldsymbol{\omega}_{\mathrm{Seg}}$) and translational joint velocity ($\mathbf{V}_{\mathrm{Joint}}$), all of which are vector quantities expressed in the global coordinate frame, as inputs to calculate the power transferred between segments. Referring to Fig. 1, at a joint the power flows into the two segments ($\boldsymbol{P}_{S2,\ Dist}$ and $P_{S1,\ Prox}$) are each the sum of the Segment Torque Power (STP) and Joint Force Power (JFP) which are given by:

$$STP = \boldsymbol{M}_{Joint} \cdot \boldsymbol{\omega}_{Seg} \quad (1)$$

$$JFP = \boldsymbol{F}_{Joint} \cdot V_{Joint} \quad (2)$$

Assuming no loss of energy at a joint, the net muscle power generated or absorbed at the joint (hereafter referred to as joint power) is given by:

$$P_{Joint} = \boldsymbol{P}_{S2,Dist} + P_{S1,Prox} \quad (3)$$

We define the directions of positive power flows to be as shown in Fig. 1.

### 2.3. Statistical analyses

From the 5 min of walking at a self-selected walking speed, a minimum of 5 full gait cycles (with clean force plate contacts) were recorded for each limb were used as data inputs for the full inverse dynamics and energy flow analysis. Each trial and each gait cycle was analyzed separately, with outputs from each gait cycle