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Medial-lateral centre of mass displacement and base of support are equally good predictors of metabolic cost in amputee walking

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ABSTRACT

Amputees are known to walk with greater metabolic cost than able-bodied individuals and establishing predictors of metabolic cost from kinematic measures, such as centre of mass (CoM) motion, during walking are important from a rehabilitative perspective, as they can provide quantifiable measures to target during gait rehabilitation in amputees. While it is known that vertical CoM motion poorly predicts metabolic cost, CoM motion in the medial-lateral (ML) and anterior-posterior directions have not been investigated in the context of gait efficiency in the amputee population. Therefore, the aims of this study were to investigate the relationship between CoM motion in all three directions of motion, base of support and walking speed, and the metabolic cost of walking in both able-bodied individuals and different levels of lower limb amputee. 37 individuals were recruited to form groups of controls, unilateral above- and below-knee, and bilateral above-knee amputees respectively. Full-body optical motion and oxygen consumption data were collected during walking at a self-selected speed. CoM position was taken as the mass-weighted average of all body segments and compared to each individual's net non-dimensional metabolic cost. Base of support and ML CoM displacement were the strongest correlates to metabolic cost and the positive correlations suggest increased ML CoM displacement or Base of support will reduce walking efficiency. Rehabilitation protocols which indirectly reduce these indicators, rather than vertical CoM displacement will likely show improvements in amputee walking efficiency.

1. Introduction

It is known that lower limb amputees walk less efficiently than able-bodied individuals, with progressively worse efficiency as the level of amputation increases [1–4]. To assess walking, and in particular walking efficiency in lower limb amputees, a range of biomechanical and physiological parameters have been used, including Centre of Mass (CoM) displacement and various respiratory measures [5]. Specifically, the respiratory measure considered most related to walking efficiency is the metabolic cost of walking and has been used to assess over-ground and treadmill walking [6–8] when comparing between able-bodied individuals or between amputee groups [1,2,9–11] or between different prosthetic devices within amputee groups [12–15]. To avoid confusion, this study considers more efficient gait to be when the metabolic cost, defined as the metabolic energy expended to move a unit distance, decreases.

As it is not always possible to obtain metabolic data, studies have sought to establish other predictors of the cost of walking, such as walking speed [16] or vertical CoM displacement [17,18]. This follows the work of Saunders et al. [19] who presented the six determinants of gait which were seen to influence CoM motion, the main biomechanical parameter historically believed to be related to the energetic cost of walking. This idea was based on the observation that pathological gait deviated from what was considered "normal". In particular, the observed greater CoM displacements in pathological gait suggested more mechanical work was being performed compared to a "normal" gait pattern,

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and therefore more energy would be required to achieve this. While excessive CoM motion in the medial-lateral and anterior-posterior directions were also considered undesirable, the focus of these determinants tended to be on avoiding excessive vertical CoM displacement. This is somewhat simplistic in that displacements of the CoM in a vertical direction allow for an interchange between kinematic and potential energy which almost certainly reduce the requirement for work to be done and thus the metabolic cost. While it is reasonable to assume excessive vertical displacement would be indicative of increased cost of walking, there is no obvious reason to assume minimising it would minimise energy cost. Recent studies have indeed shown that deliberately reducing CoM motion actually increases metabolic cost [17,18]. Studies have also shown that several of the determinants make negligible difference to CoM motion [20–22]. Additionally, the determinants have recently been assessed in the context of inverted pendulum walking [23], and have found the major cost of walking was attributed to redirecting the CoM during the step-to-step transitions [24]. There have been few studies attempting to relate metabolic cost of walking to biomechanical factors in people with pathologies but the most comprehensive suggested that vertical centre of mass excursion was not a good indicator of metabolic cost in people with myelomeningocele [25].

In addition to vertical CoM displacement and sagittal plane measures of walking in general, mediolateral (ML) measures have also been investigated, including ML CoM displacement and ML base of support in lower limb amputees who are known to be at greater risk of falling because they are less stable than able-bodied individuals [26–28]. However, while ML CoM displacement has been investigated in relation to stability and falls, this has not been investigated in relation to walking efficiency in lower limb amputees. Given that only vertical CoM displacement is considered unrelated to walking efficiency, which can be explained by energy-conserving theories such as the inverted pendulum model of walking [23], the relationship between ML as well as anterior-posterior (AP) CoM displacement and walking efficiency should be established as this may provide further insight into the biomechanics of efficient walking. In fact, lower limb amputees are known to walk with a wide base of support (BoS) [29,30], which is likely to affect ML CoM displacement and hence may influence walking efficiency and therefore warrants further investigation.

Therefore, the primary aim of this study was to investigate whole-body CoM displacement in all 3 directions in relation to the metabolic cost of walking in amputees with different levels of lower limb amputation as well as in a control group of able-bodied individuals. Also, as there may be a link between metabolic cost and CoM displacement as well as between CoM displacement and the BoS, a secondary aim of this study was to investigate the relationship between BoS and metabolic cost. Finally, as walking speed is also considered an indicator of gait quality, investigating the relationship between walking speed and metabolic cost was a final aim.

2. Methods

2.1. Participant information and study protocol

The required walking data came from another study on walking of amputees and able-bodied individuals, which was recently completed in part by 2 authors of the current study and gives all the details of the data collection protocol [4]. In brief, this involved thirty amputees to form 3 groups of ten unilateral trans-tibial (UTT), ten unilateral trans-femoral (UTF) and ten bilateral trans-femoral (BTF) amputees, as well as ten able-bodied individuals. For the amputees, the study inclusion criteria were: aged eighteen to forty, lower limb amputation as a result of trauma, attending Defence Medical Rehabilitation Centre (DMRC) Headley Court for routine prosthetics treatment, at least 6 months after receiving their definitive prosthesis, no pain consequent to prosthesis usage (minor “discomfort” was acceptable), and capable of walking comfortably for twelve minutes continuously. Study exclusion criteria were: any neuromusculoskeletal pathology (except for the amputation) that may affect the participants’ walking. Each amputee’s definitive prosthesis was chosen and set up on an individual basis, but broadly, amputees were provided with energy storage and return (ESR) feet and micro-processor knees for the trans-femoral amputees. Complete details of the prosthesis prescription for all amputees can be found in the Supplementary materials. Ten able-bodied military individuals needed to be asymptomatic and were also recruited from DMRC Headley Court to provide age- and height-matched control data for comparative purposes (Table 1).

All participants followed the same protocol, which began with 5 min quiet standing while a baseline of oxygen consumption was established using a portable breath analyser (MetaMax 3B, Cortex, Leipzig, Germany). Steady state breathing was verified during data collection by visual inspection of the oxygen consumption data not varying significantly in the final minute compared to the preceding minutes and confirmed retrospectively by comparing the mean and standard deviation of each minute of quiet standing oxygen consumption data to the preceding minute. They then walked for 2 min back and forth along an approximately ten-metre long overground laboratory walking path to establish their self-selected walking speed. Next, they walked for 5 min at their self-selected walking speed to record their oxygen consumption data as well as forceplate data at 1000 Hz (Kistler, Winterthur, Switzerland) and optical motion data at 100 Hz (Vicon, Oxford, U.K.). Due to participant discomfort with the oxygen consumption breathing mask and a failed calibration of the MetaMax system, 3 participants were unable to provide oxygen data and hence their data were excluded from analysis.

A minimum of 5 clean foot contacts were recorded for each limb and analysed separately, with outputs from each gait cycle time-normalised to 100%. A clean foot contact was defined as fully within the boundary of the forceplate. A gait cycle was defined as the time between ipsi-lateral heel contacts, with heel contact being defined by a vertical force greater than 20N applied to the forceplates within the walkway. For all participants, data from the left and right limb were averaged. The mean oxygen consumption from the final minute of both the static trial and walking trial were used to calculate net non-dimensional cost of walking between groups [31,32].

The body was represented as a linked thirteen-segment model consisting of the head, trunk and pelvis, and the left and right upper and lower arm, thigh, shank and foot. Body CoM position was based on the mass-weighted average of body segment parameters scaled according to subject mass and height using

Table 1
Participant demographic information. Values given as mean (S.D.). Note: UTT and UTF groups had fewer than the originally intended 10 participants per group due to problems with the metabolic cost measuring system.

Participants	Mass [kg]	Height [m]	Age [years]
control (n = 10)	78.0 (7.6)	1.82 (0.05)	29 (4)
UTT (n = 8)	88.1 (15.2)	1.83 (0.05)	30 (3)
UTF (n = 9)	88.1 (6.9)	1.80 (0.07)	28 (4)
BTF (n = 10)	86.7 (19.2)	1.81 (0.08)	29 (4)