Accepted Manuscript

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PII: S0003-9993(16)31230-8

DOI: 10.1016/j.apmr.2016.09.134

Reference: YAPMR 56719

To appear in: *ARCHIVES OF PHYSICAL MEDICINE AND REHABILITATION*

Received Date: 29 April 2016

Revised Date: 13 September 2016

Accepted Date: 30 September 2016

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Word count 2,981 (manuscript text without abstract, acknowledgements or references)

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Acknowledgments

Mr Mark Thoburn (BSc (Hons) Prosthetics and Orthotics), Lead Clinical Prosthestist, DMRC, Headley Court and Gillian Conway BSc (Hons) Prosthetics and Orthotics) were instrumental in supporting the logistics of data collection, giving advice on prosthetic componentry and obtaining clinical data.

Conflicts of Interest

The authors declare that there are no conflicts of interest

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Abstract

Objective

The aim of this descriptive exploratory study is to record the temporal spatial parameters and metabolic energy expenditure during walking of individuals with amputation, walking with advanced prostheses and following completion of comprehensive rehabilitation, to able-bodied controls.

Design

Cross-sectional

Setting

Multi-disciplinary comprehensive rehabilitation centre

Participants

Thirty severely injured United Kingdom military personnel with amputation and subsequent completion of their rehabilitation programme (10 unilateral trans-tibial, 10 unilateral trans-femoral, and 10 bilateral trans-femoral) were compared to (and of similar age, height and mass ($p > 0.537$) as) 10 able-bodied controls.

Interventions

Not applicable

Main Outcomes and Measures

Temporal spatial and metabolic energy expenditure data were captured during walking on level ground at self-selected speed.

Results

The individuals with amputation were all male, with a mean age 29 years (SD = 4) and mean New Injury Severity Score of 31 (SD = 16). Walking speed, stride length, step length and cadence of individuals with a unilateral trans-tibial or trans-femoral amputation was comparable to controls, and only for individuals with a bilateral trans-femoral amputation was walking speed significantly slower (1·12m/s, p = 0.025) and cadence reduced (96 steps/min, p = 0.026). Oxygen cost for individuals with a unilateral trans-tibial amputation (0·15 ml/kg/m) was the same as for controls (0·15 ml/kg/m), and significantly increased by 20% (0·18ml/kg/m, p = 0.023) for unilateral trans-femoral and by 60% (0·24 ml/kg/m, p < 0.001) for bilateral trans-femoral individuals with amputation.

Conclusion

The scientific literature reports a wide range of gait and metabolic energy expenditure across individuals with amputation. The results of this study indicate that the individuals with amputation have a gait pattern which is highly functional and efficient. This is comparable to

a small number of studies reporting similar outcomes for individuals with a unilateral trans-tibial amputation, but the results from this study are better than those on individuals with trans-femoral amputations reported elsewhere, despite comparison with populations wearing similar prosthetic componentry. Those studies that do report similar outcomes have included individuals who have been provided with a comprehensive rehabilitation programme. This suggests that such a programme may be as important as, or even more important than, prosthetic component selection in improving metabolic energy expenditure. The data are made available as a benchmark for what is achievable in the rehabilitation of some individuals with amputations, but agreeably may not be possible for all amputees to achieve.

Keywords

Amputation, rehabilitation, gait

List of abbreviations

IED Improvised Explosive Device

NISS New Injury Severity Score

RTA Road Traffic Accident

NHS National Health Service

KD Knee disarticulation

BKD Bilateral knee disarticulation

TT Trans-tibial

IED Improvised explosive device

GSW Gunshot wound

TF Trans-femoral

LPPR Low profile reflex rotate

TSB Total surface bearing

IC Ischial containment

IBS Ischial bearing socket

DEB Distal end bearing

Temporal spatial and metabolic measures of walking in highly functional individuals with amputations

Introduction

Provision of prostheses and rehabilitation care for individuals with amputation is becoming increasingly important. The changing nature of modern warfare, highlighted by recent conflicts in Afghanistan and Iraq, has resulted in many service members suffering severe and life threatening injuries, often resulting in traumatic amputation of one or more limbs. In civilian populations, the aftermaths of current or previous wars and road traffic and work-based accidents are still a major cause of traumatic amputation. Events such as the Paralympics and Invictus games have highlighted the high functionality of some individuals and thus have increased the expectations among both individuals with amputation (whatever the cause) and wider society for high quality prostheses and rehabilitation outcomes.

Understanding the outcomes that individuals who have had amputations can expect from their rehabilitation programme and prosthetics provision is thus becoming increasingly important. In the scientific literature, however, there is considerable variation in the results of studies which have set out to document how individuals with amputation walk. Some studies, for example, have measured individuals with a unilateral trans-tibial amputation as walking at the same speed, stride and step length and with similar metabolic energy expenditure compared to the able-bodied. [1-3] Other studies report substantial differences between individuals with a unilateral trans-tibial amputation and the able-bodied of up to 53%.[4] Individuals who have had a trans-femoral amputation also show considerable variability with reported metabolic energy expenditure from 33% and up to 73% [1, 4-8] of values for the able-bodied.

Such variability could arise from a number of sources with the most obvious being cause of amputation, prosthetics prescription, other characteristics of the individual, and the nature of the rehabilitation programme. Both Torburn et al. [9] and Barth et al. [10] have reported that walking patterns and metabolic energy expenditure are significantly greater in individuals who have had an amputation as a consequence of vascular disease rather than trauma. For practical reasons, however, most studies have recruited relatively young and healthy individuals. Most of these have had amputation as a result of trauma (with a much smaller number having had cancer or congenital absence or deformities). Given the relative consistency of cause of amputation across the reported studies, this is unlikely to explain the variability of results.

Over recent decades there have been considerable advances in prosthetic componentry with the development of micro-processor knees, dynamic elastic response feet, and powered ankle units. Although, individuals with amputation express a strong preference for these devices, studies making a direct comparison between conventional and new componentry have failed to find clinically significant reductions in metabolic energy expenditure. [4-6, 11-14] Several studies using essentially similar componentry have recorded quite different levels of metabolic expenditure, [4, 6, 8, 11] suggesting that the variability is not primarily related to componentry.

Age of individuals is generally well-reported and the studies showing particularly low levels of energy ependiture tend to be on younger cohorts. [1, 3] Other individual characteristics, which might affect walking ability such as general health and motivation, are generally not well reported (although ability and willingness to participate in formal studies suggests a certain baseline for both). Another potentially important factor that is generally not particularly well reported or standardised is the rehabilitation programme. This, supported by the observation that many of the lowest energy costs of walking in individuals with amputation are from the military who may have benefitted from particularly intensive rehabilitation programmes, focussed on achieving very high levels of function. [1, 3, 15]

In summary high walking efficiency amongst individuals who have had an amputation is likely to be observed amongst younger, more motivated individuals in good general health who have state of the art prosthetics prescriptions and who have benefitted from an intensive rehabilitation programme focussed on achieving high levels of functionality. The cohort of British servicemen, who have been injured in recent wars and have completed the rehabilitation programme at the Defence Medical Rehabilitation Centre (DMRC) Headley Court, have these characteristics. Functional and mental health outcomes indicate that they have "achieved levels of physical function comparable to healthy age-matched adults" and had "mental health outcomes indicative of preparedness of full integration back into society", even though their original injuries were severe. [16]

Reporting the temporal spatial and metabolic measures of walking outcomes of this group may thus provide a useful benchmark for future clinical practice both within this establishment and more widely. The aim of this descriptive exploratory study is thus to record temporal spatial parameters and metabolic energy expenditure during walking in UK military personnel with amputation at different levels who have completed the rehabilitation programme at DMRC Headley Court, and compare these to able-bodied asymptomatic controls.

Materials and methods

Participants

This study was approved by the Ministry of Defence Research Ethics Committee and the University of Salford ethics panel. Informed verbal and written consent to take part in this study was obtained from each participant.

Thirty individuals with amputation (10 unilateral trans-tibial, 10 unilateral trans-femoral, and 10 bilateral trans-femoral) were recruited from those available at the time of data collection between October 2013 and August 2014. This is comparable with other studies of similar design. [1, 4, 6, 17-20] Inclusion criteria were that they could walk continuously for at least twelve minutes and had been wearing the same prostheses for at least six months prior to testing. Prosthetics prescription, including design of socket and type of liner for each individual with amputation, is presented in Table 1. All bilateral trans-femoral and 3 unilateral trans-femoral individuals with amputation wore single-axis hydraulic micro-processor knee units such as the Genium or C-Leg (Otto Bock, Duderstadt, Germany), or Plié (Freeedom Innovations, Enschede, The Netherlands). The remaining unilateral trans-femoral individuals with amputation were fitted with a KX06 (Blatchford, Basingstoke, UK) which is a hydraulic polycentric knee unit (without micro-processor control). Prosthetic feet varied considerably but were all dynamic elastic response feet. Individuals with amputation who had suffered from a traumatic brain injury were excluded. All individuals with amputation were undergoing their rehabilitation programme at DMRC Headley Court. The rehabilitation programme described in Appendix 1 incorporates the same key components for each patient and all were managed by the same rehabilitation team at DMRC Headley Court. This utilises a structured and similar programme for each patient, allowing for individual variation and needs. Inclusion criteria for controls stated that they must have been asymptomatic for at least six months prior to testing and without previous major joint or soft tissue surgery.

Demographic data were collected including age, body mass (inclusive of prosthesis mass), height, New Injury Severity Score (NISS) ,[21] duration of rehabilitation (total time spent at

DMRC Headley Court for comprehensive rehabilitation), time since injury, prosthetic foot and knee prescription, socket design and type of liner. An NISS of greater than 15 indicates major trauma and 75 is the theoretical maximum for someone who survives their injuries.

Outcome measures

Key data variables collected included walking speed, stride and step characteristics, and metabolic energy expenditure (oxygen consumption per unit time, and oxygen cost per unit distance). All data were collected simultaneously in the gait laboratory at DMRC Headley Court. Participants walked for five minutes at self-selected speed. An optoelectronic motion capture system (Vicon, Oxford, UK) with ten T-Series Vicon cameras and four strain-gauged force plates (AMTI, Watertown, MA, USA) embedded within a ten metre walkway was used to capture three-dimensional kinematics and kinetics following the protocol detailed in Appendix 1. This allowed the calculation of temporal and spatial parameters. Metabolic energy expenditure measurements were captured using a Metamax (Cortex Biophysik GmbH, Leipzig, Germany) via indirect calorimetry. All data were normalised to body mass with prosthesis to allow comparison with previous studies. An average of the rate of oxygen consumption (ml/kg/min) was calculated over the last minute of data capture for each participant, and this is divided by walking speed to calculate oxygen cost (ml/kg/m).

Statistical analysis

No formal hypotheses are being tested and tests of statistical significance are thus taken as indicative of the relative probability of false positives. No corrections have been applied for multiple comparisons but the likelihood of this is addressed in the Discussion. All data were checked for normality using the Kolmogorov Smirnov test. Between group differences across the three levels of amputation and the controls were compared using a one-way ANOVA followed, if statistical significance (P<0.05) was found, by post-hoc analysis of each amputation level group against control using Least Significant Difference. Other data were compared using a Kruskall-Wallis test with post-hoc analysis between each group of individuals with amputation versus control, using individual Mann-Whitney tests. For between leg comparison (prosthetic versus intact (unilateral individuals with amputation) or right versus left (bilateral individuals with amputation and controls), parametric data were compared using an independent t-test and non-parametric data using a Mann-Whitney test. Statistical analysis was conducted using SPSS (Statistical Package for the Social Sciences) Version 20 (IBM Corporation, New York, USA).

Results

Individuals with amputation and controls were of a similar age, height, and mass (Table 1) (p>0.537 lowest p value for any comparison with controls). Injuries sustained during operations in Afghanistan or Iraq were the most common cause of amputation with 21 from improvised explosive devices (IED), 3 from mine, and one from a gunshot wound. Five required amputation after non-operational injuries, three following road traffic accident (RTA), and two from other crush injuries. Mean NISS for all individuals with amputation was 31 which increased with severity of limb loss with unilateral trans-tibial (95% CI 10-22), compared to unilateral trans-femoral (17-30, p 0.060), and bilateral trans-femoral (44-55, p <0.001. Individuals with a bilateral trans-femoral amputation required significantly longer inpatient rehabilitation (22 months, p < 0·001) than those with a unilateral trans-tibial (5 months, p < 0.001), or unilateral trans-femoral amputation (6 months, p <0.001). Prosthetics prescription for each individual with amputation is presented in Table 1.

Walking speed, stride length, and cadence of individuals with a unilateral trans-tibial or trans-femoral amputation was comparable to control ($p>0.340$). 95% confidence intervals for walking speed of individuals with a unilateral trans-tibial (1·28-1·44 m/s) or unilateral trans-femoral amputation (1·08-1·36 m/s) overlapped considerably that of the controls (1·25-1·33 m/s). Only for individuals with a bilateral trans-femoral amputation was walking speed significantly slower (1·00-1·24 m/s, p 0·030), andcadence reduced (89-103 steps per minute, p 0.026) whilst stride length was similar to control (p 0.206, Table 2). For between limb comparison, stance time was significantly longer for the intact limb (62- 66%) than the prosthetic limb (60- 62%, p 0.010) for the unilateral trans-tibial group. No other differences were reported between limbs for other groups.

Oxygen uptake data were not available from three participants with amputation, two unilateral trans-tibial and one unilateral trans-femoral, due to two not wanting to wear a gas mask and a failed calibration for the other. The mean rate of oxygen consumption increased with increasing amputation level but the difference compared with control subjects was only statistically significant for the bilateral trans-femoral group (43% greater, $p = 0.001$). Oxygen cost for individuals with a unilateral trans-tibial amputation (0·13-0·16 ml/kg/m) was the same as for controls (0·14-0·16 ml/kg/m), and significantly increased by 20% (0·16-0·20 ml/kg/m, $p = 0.023$) for individuals with a unilateral trans-femoral and by 60% (0·20-0·27 ml/kg/m, $p < 0.001$) for individuals with a bilateral trans-femoral amputation (Table 2).

Discussion

The ultimate aim when managing the rehabilitation of an individual with amputation is to achieve good functional outcomes. Self-selected walking speed, metabolic oxygen cost, and gait pattern are all strong indicators of this. The results of this study indicate that the individuals with amputation in this study have a functional and efficient gait pattern.

Individuals with amputation in this study walked at a similar speed or faster (Figure 1), with a longer stride length, more symmetrical step length, and narrower stride width than in comparable studies [4, 6, 8, 12, 18, 19, 22, 23] of groups with similar age, mass and activity level using similar prosthetic components. Individuals with a unilateral trans-tibial amputation had the same oxygen cost of walking as the controls which has only been observed in two other studies [3, 24] (Figure 2). The oxygen cost of walking for individuals with unilateral trans-femoral amputation in this study was only 24% greater than that of the controls. In comparison, the oxygen cost of walking for individuals with this level of amputation in other studies [1, 4, 6-8, 11, 25, 26] ranges from 25% (0·20 ml/kg/m)[6] to 50% (0·30 ml/kg/m) [25] greater than that of controls (Figure 2). The oxygen cost of walking for individuals with a bilateral trans-femoral amputation in this study is 25% less than the only other reported cohort study, and individuals with amputation in this study walked significantly faster.[19] In summary, the data indicate that individuals with amputation in this study perform at least as well as and in many **cases** better than those described in the literature in terms of gait function (temporal spatial parameters) and efficiency (metabolic energy expenditure).

Differences to previous studies are unlikely to be a consequence of the prosthetics prescription which is similar to previous studies in terms of the characteristics that are likely to affect level walking in a straight line at self-selected speed. The primary developments in prosthetics design over the period covered by these studies have focussed on allowing adaptability in individuals with amputation to walk at different speeds and to cope with sloped or uneven surfaces. Such developments are only likely to have a minor effect on studies of walking in laboratory conditions at self-selected speed on a flat surface.

The individuals with amputation cohorts also differ somewhat. As a consequence of either intentional or unintentional recruitment bias, most studies have been on relatively healthy individuals with amputation resulting from localised trauma or cancer. The extent of injuries other than amputation is poorly described in previous studies. The majority of individuals with amputation in this study have had major life-threatening trauma (as indicated by the NISS scores) and have sustained a range of other injuries (e.g. gastro-intestinal, genital) and there is no reason to suspect that other cohorts have walked less well because their concomitant injuries were more severe.

The positive outcomes found in this study may result from a variety of factors, including other patient characteristics and the rehabilitation programme. This is a particularly highly motivated cohort in that many of whom engage in endurance sport (including rowing the Atlantic and walking across Greenland!). The rehabilitation programme is also likely to be influential, but poor specification of this in the literature makes detailed comparison difficult. The length of the military rehabilitation programme that individuals with amputation in this study have completed is probably of similar length to that in others who report similarly positive results. [1, 3, 15] Its intensity and focus on the highest levels of functional outcome is likely to be greater than that of civilian programmes such as those proposed by the British Society of Rehabilitation Medicine, [27] the British Association of Chartered Physiotherapists in Amputee Rehabilitation [15] or the Dutch Evidence Based Guidelines For Amputation And Prosthetics Of The Lower Extremi*ty.* [28] Whilst these include recommendations that individuals are advised about, such as returning to sport and other hobbies, their main focus is on achieving competence in the activities of daily living. Given the apparent success of this programme, a fuller description is supplied in Appendix 2.

From this study, we propose that this dataset (more comprehensively documented in Appendix 3) could be used as a benchmark against which to compare other studies or clinical results from individuals with amputation. Nearly all studies compare the walking ability of individuals with amputation to that of the “normal” able-bodied, which is generally an unobtainable goal. Instead, comparing the walking ability to individuals with amputations, but who are rehabilitated to the highest functional level, may be more appropriate. However, considering the characteristics of each individual with amputation will always be important, as it may be equally unrealistic to compare outcomes from an elderly and unwell individual with an amputation due to vascular disease with the outcomes from the young otherwise healthy individuals with amputation due to trauma reported in this study. [9, 10]

Study Limitations

There are a number of limitations to this study. Different studies adopt different procedures for mass normalisation, principally in whether the mass of the prosthesis is included along with that of the individual. There are arguments for either approach but, perhaps more importantly, this is not always reported explicitly. All metabolic energy expenditure was normalised to body mass plus prosthesis which will lead to lower normalised values than studies normalising to body mass only, and this may account for some of the differences with previous studies. The aim of this study was to describe the cohorts studied rather than to detect differences between them, and the p-values were only intended to be indicative of the strength of results. It can be argued that, whilst many p-values are below 0.05, there is still a risk of false positives as a consequence of the multiple tests applied. The consistency of results across a range of outcome measures, however, suggests that this is unlikely. The generally narrow 95% confidence intervals on most important parameters suggest that the overall conclusions of the paper are still valid.

Conclusions

The findings from this study indicate that individuals with unilateral trans-tibial amputation can achieve a similar metabolic cost of walking to able-bodied individuals, and the cost of walking for individuals with uni- and bilateral trans-femoral amputations is lower than in previous reports. The overall outcome of care for individuals with amputation may be influenced by a variety of other factors, including age, fitness, and motivation, and the present results indicate the added importance of participation in an advanced rehabilitation programme. The programme provided by the authors is one example of advanced rehabilitation for individuals with amputations that can produce highly functional outcomes and excellent economy.

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Acknowledgments

Mr Mark Thoburn and Miss Gillian Conway were instrumental in supporting the logistics of data collection, giving advice on prosthetic componentry and obtaining clinical data.

Funding

Funding was provided by Defence Medical Services.

Figure legends

Figure 1. Comparison of walking speed (mean and standard deviation) in individuals with a unilateral trans-tibial and trans-femoral amputation during walking reported by this study and others.[3-5, 7, 8, 12, 14, 20, 23, 24, 26] Missing error bars indicate that the standard deviation was not provided in source. Solid black line indicates control. In all studies except Schmalz et al [4] speeds were identified from over ground walking. All study cohorts are comprised either entirely or predominantly of individuals who had amputations as a consequence of trauma. All study cohorts wore elastic response feet and micro-processor knee joints except some individuals with amputation in.[1, 26]

Figure 2. Comparison of oxygen cost (mean and standard deviation) in individuals with a unilateral trans-tibial and trans-femoral amputation during walking reported by this study and others. [1, 3-8, 12, 20, 24, 26, 29] Self-selected walking speed for individuals with amputation except [1] but similar speed to all other investigations. Missing error bars indicate that the standard deviation was not provided in source. Normalisation to body mass and prosthesis used by this study, while used normalisation to just body weight [3, 5-8, 20] for [1, 4, 12, 24, 26] methods of normalisation not defined. All studies included individuals who had sustained a traumatic amputation. All study cohorts wore elastic response feet and micro-processor knee joints except.[1, 26]

Table 1: Characteristics of participants

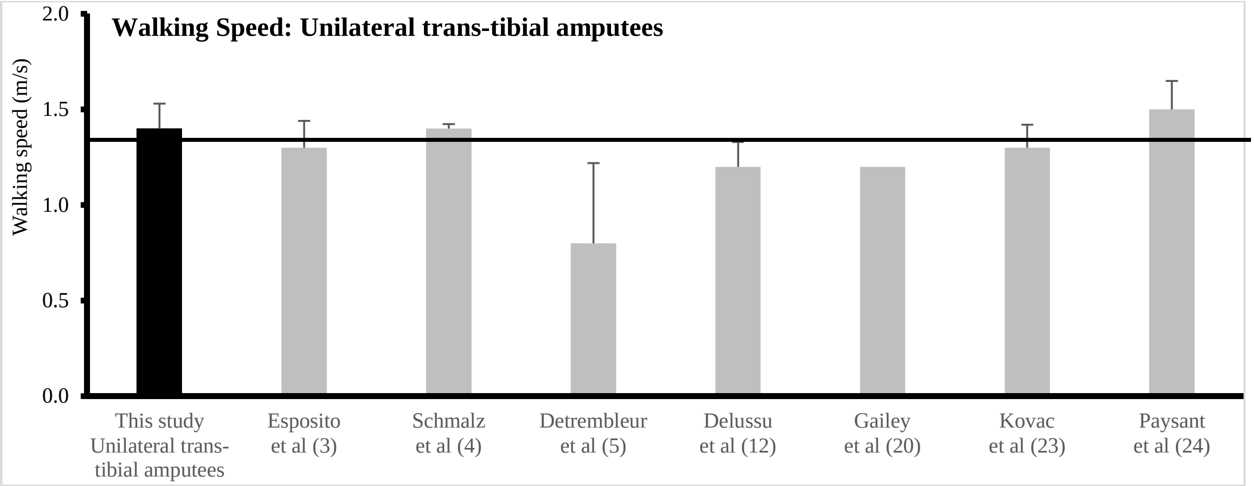
Group	Age (years)	Mass (kg)	Height (m)	NISS	Cause of amp.	Duration of rehab. (months)	Time from injury (months)	Socket type	Socket liner	Torque Adaptor	Prosthetic foot	Prosthetic knee
Unilateral trans-tibial	23	78·2	1·81	N/A	Crush	3·6	12	TSB	Iceross sport pin	Yes	Echelon VT	N/A
	29	88·5	1·86	17	IED	11·8	61	PTB	none	No	VSP	N/A
	24	119·6	1·86	12	IED	4·2	8	PTB	No	No	Variflex XC	N/A
	28	84·9	1·86	29	IED	13·4	33	PTB	cushion	Yes	Echelon VT	N/A
	32	94·1	1·85	12	Mine	2·1	69	TSB	Iceross pin	No	Reflex Shock	N/A
	28	89·5	1·75	17	IED	5·7	19	TSB	Iceross synergy	No	Echelon VT	N/A
	28	84·5	1·80	17	IED	4·9	20	PTB	Pin	No	Reflex Shock	N/A
	35	103·7	1·80	5	IED	5·9	19	TSB	Pin	Yes	Echelon VT	N/A
	26	87·8	1·90	21	IED	6·3	20	TSB	Pin	Yes	Echelon VT	N/A
	24	66·5	1·74	N/A	Crush	6·0	7	TSB	Pin	No	Variflex XC	N/A
Mean (SD)	28 (4)	90 (14)	1·82 (0·05)	16 (7)		5 (3)	27 (22)					
Unilateral trans-femoral	32	88·8	1·69	24	IED	4·5	39	IBS	Seal in liner	No	Axtion	C-LEG
	29[KD]	85·3	1·78	22	RTA	6·8	8	DEB	Seal in	No	Variflex xc	KX06
	35	83·5	1·81	43	Mine	5·2	32	IC	Seal in	No	Reflex shock	KX06
	26[KD]	98·6	1·89	18	IED	4·8	44	DEB	Seal in	No	LPRR	Plie
	27[KD]	94·3	1·80	16	GSW	4·9	26	DEB	No	No	Variflex xc	KX06
	27	89·9	1·75	18	IED	6·9	71	IBS	No	No	LPRR	KX06
	30[KD]	83·8	1·87	29	IED	3·5	23	DEB	No	Yes	Elite VT	KX06
	27	96·9	1·87	18	Mine	6·7	98	n/n	Seal in	No	Triton HD	X3
	27	80·3	1·75	34	RTA	11·4	22	DEB	Guardian	No	Echelon	KX06
	35	81·1	1·71	16	RTA	3·8	29	IBS	Seal in	No	Variflex xc	KX06
Mean (SD)	29 (3)	89 (6)	1·81 (0·06)	24 (9)		6 (2)	39 (27)					
Bilateral trans-femoral	29	86·7	1·91	36	IED	6·7	32	IC (r) DEB (l)	Seal in (r) Alpha cushion (l)	No	Low profile triton	Genium
	24	85·5	1·85	59	IED	7·8	33	Quad	Seal in	No	Axtion	C-leg
	28	68·1	1·67	57	IED	12·3	40	n/n	Seal in	No	Axtion	C-leg
	28[TF/TT]	88·8	1·85	50	IED	17·2	27	TSB (l) IC (r)	Seal in (r) Activa (l)	Yes (l)	Triton shock +LPRR	Genium
	29	72·9	1·83	41	IED	13·4	46	IC	Seal in	No	LPRR	Genium
	34	78·9	1·75	57	IED	12·5	39	IC	Seal in	No	LPRR	Genium
	37[BKD]	88·7	1·89	41	IED	15·9	28	DEB	No	No	LPRR	Genium
	29	90·4	1·81	48	IED	10·9	24	IBS	Seal in	No	LPRR	Genium
	27	136·2	1·82	50	IED	17·7	32	DEB	Seal in (r) Sock fit (l)	No	LPRR	Genium
	25	70·7	1·76	54	IED	22·1	43	IC	Seal in	Yes	Triton shock	Genium
Mean (SD)	29 (4)	90 (20)	1·82 (0·07)	49 (8)		24 (5)	35 (7)					
Control Mean (SD)	30 (6)	78 (8)	1·84 (0·07)									

Table 1: [KD] knee disarticulation (rather than true trans-femoral amputation). [BKD] bilateral knee disarticulation. [TF/TT] trans-femoral and trans-tibial amputation (rather than bilateral trans-femoral). LPRR: low profile reflex rotate, RTA: road traffic accident, IED: improvised explosive device, Crush: crush injury, GSW: gunshot wound, PTB: patella tendon bearing, TSB: total surface bearing, IC: ischial containment, IBS: ischial bearing socket, DEB: distal end bearing, N/A: Not applicable. The duration of rehabilitation listed in Table 1 represents the time spent attending a rehabilitation programme at xxxx xxxxxxx xxxxx, whilst time from injury represents the time from injury to when the person attending data collection for the study

Table 2: Comparison of temporal and spatial parameters, and oxygen consumption and cost between individuals with amputation and control groups.

Parameter	Unilateral trans-tibial		Unilateral trans-femoral		Bilateral trans-femoral		Control	
	Intact	Prosthetic	Intact	Prosthetic	Right	Left	Right	Left
Walking Speed (m/s) p=0.015	1·36 *+5%* (1·28- 1·44) p=0.340		1·22 *-5%* (1·08- 1·36) p=0.340		1·12 *-13%* (1·00- 1·24) p=0.025		1·29 (1·25- 1·33)	
Stride Length (m) p=0.575	1·46 *-1%* (1·38- 1·54) p=0.893		1·42 *-3%* (1·28- 1·57) p=0.538		1·37 *-7%* (1·27- 1·47) p=0.206		1·47 (1·40- 1·54)	
Stride Width (m) p=<0.0001	0·13 *+9%* (0·11- 0·15) p=0.517		0·18* *+54%* (0·15- 0·22) p=<0.0001		0·22 *+84%* (0·21- 0·24) p=<0.0001		0·12 (0·11- 0·13)	
Cadence (steps/min) p=0.005	112 *+6%* (107- 117) p=0.124		103 *-3%* (97- 109) p=0.521		96 *-8%* (89- 103) p=0.026		106 (101- 110)	
Step Length (m)	0·73 *-1%* (0·69- 0·78)	0·73 *+0%* (0·68- 0·77)	0·72 *-3%* (0·63- 0·80)	0·71 *-3%* (0·64- 0·78)	0·69 *+8%* (0·63- 0·74)	0·69 *+7%* (0·63- 0·75)	0·74 (0·70- 0·78)	0·73 (0·69- 0·77)
	p=0.834		p=0.875		p=0.907		p=0.800	
Stance Time (% cycle)	63·8 *+1%* (62·1- 65·5)	60·9 *-3%* (60.0- 61.8)	64·0 *+1%* (61·0- 67·0)	62·3 -1% (60·7- 63·9)	64·0 *+2%* (61·0- 67·0)	62·3 *+0%* (60·7- 63·9)	63·1 (61·8- 64·.4)	62·9 (61·2- 64·6)
	p=0.010		p=0.336		p=0.983		p=0.853	
O_2 Consumption (ml/kg/min) p=0.004	12·3 *+9%* (11·0- 13·7) p=0.456		13·3 *+17%* (11·4- 15·2) p=0.138		16·2 *+43%* (13·6- 18·8) p=<0.0001		11·3 (10·8- 11·9)	
O_2 Cost (ml/kg/m) p=<0.0001	0·15 *+0%* (0·13- 0·16) p=0.987		0·18 *+20%* (0·16- 0·20) p=0.023		0·24 *+60%* (0·22- 0·27) p=<0.0001		0·15 (0·14- 0·16)	

Table 2: p-values in first column are for ANOVA across all four groups where $p<0 \cdot 05$. All entries given as the mean with percentage difference relative to data from control group and then 95% confidence interval in parenthesis. [a] asterisks are results of post-hoc comparisons. * statistically significant difference from control ($p < 0 \cdot 05$). ** statistically significant difference between prosthetic and intact lower limbs ($p < 0 \cdot 05$).



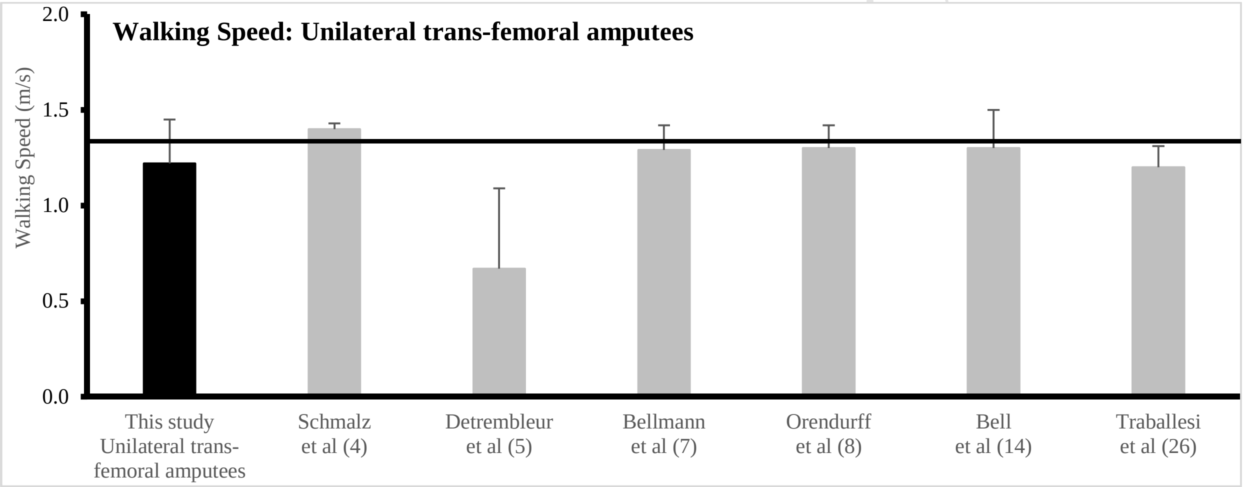


Figure 1. Comparison of walking speed (mean and standard deviation) in individuals with a unilateral trans-tibial or trans-femoral amputation during walking reported by this study and others.[3-5, 7, 8, 12, 14, 20, 23, 24, 26] Missing error bars indicate that the standard deviation was not provided by source. Solid black line indicates control. In all studies except Schmalz et al [4] speeds were identified from over ground walking. All study cohorts are comprised either entirely or predominantly of individuals who had amputations as a consequence of trauma. All study cohorts wore elastic response feet and micro-processor knee joints except some individuals with amputation.[1, 26]

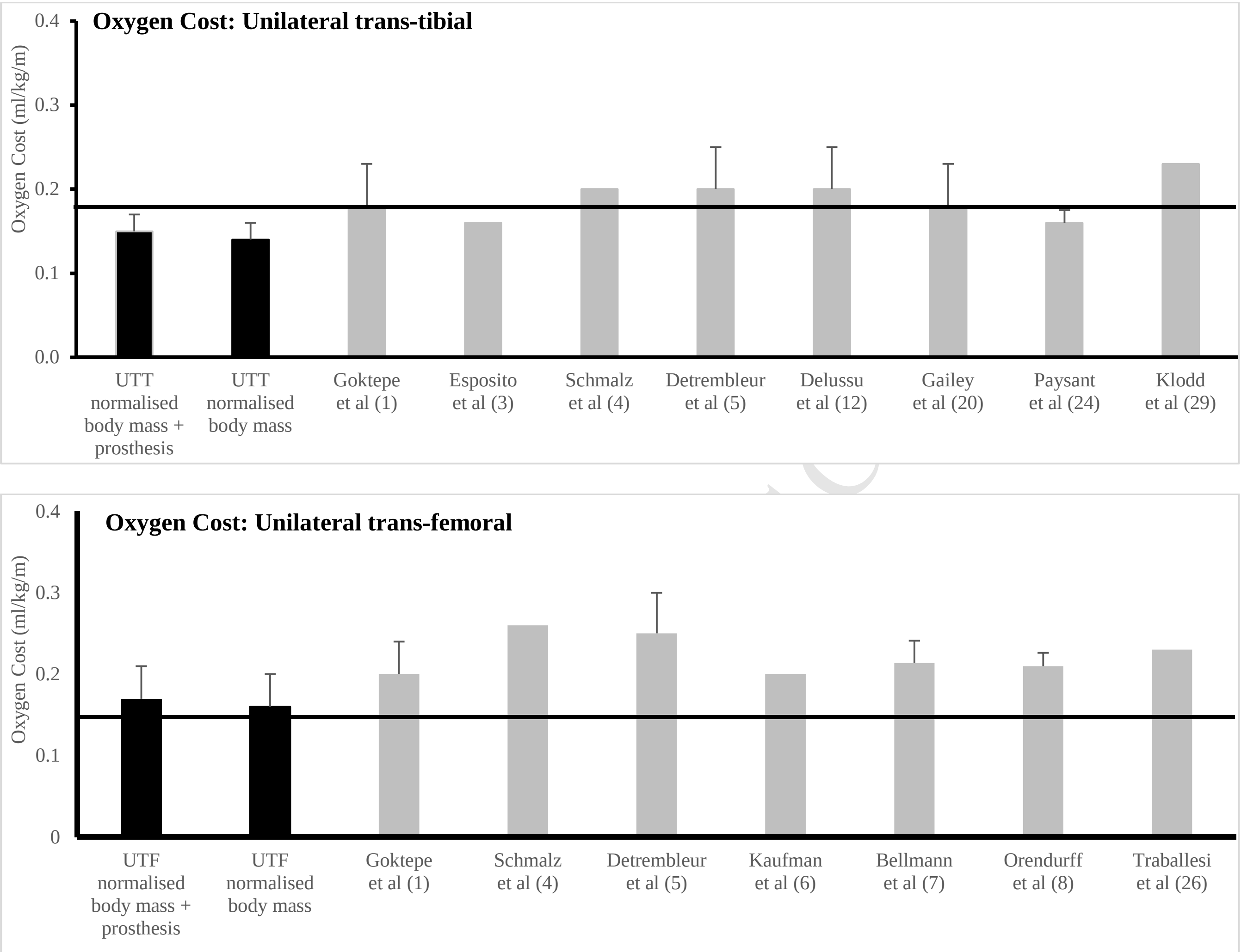


Figure 2. Comparison of oxygen cost (mean and standard deviation) in individuals with a unilateral trans-tibial or trans-femoral amputation during walking reported by this study and others. [1, 3-8, 12, 20, 24, 26, 29] UTT: individuals with a unilateral trans-tibial amputation, UTF: individuals with a unilateral trans-femoral amputation. Self-selected walking speed for individuals with amputation except [1] but similar speed to all other investigations. Missing error bars indicate that the standard deviation was not provided in source. Normalisation to body mass and prosthesis (UTT/UTF normalised Body Mass +prosthesis) used by this study, while used normalisation to just body weight in this study (UTT/UTF normalised Body Mass) and used by, [3, 5-8, 20] whilst for [1, 4, 12, 24, 26] methods of normalisation not defined. All

studies included individuals who had sustained a traumatic amputation. All study cohorts wore elastic response feet and micro-processor knee joints except.[1, 26]

Appendices

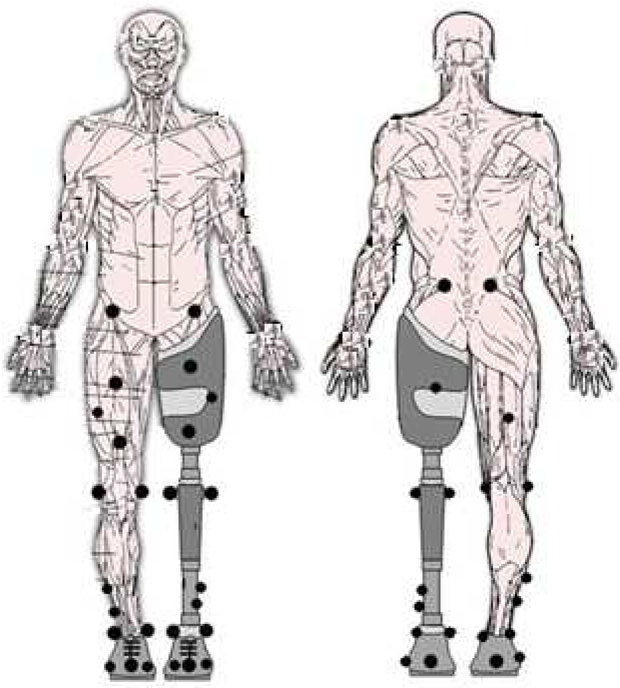
Appendix 1 Detailed data capture protocol

The motion capture system (Vicon, Oxford, UK) recorded the locations of retro-reflective markers attached to the skin or prosthesis for establishing anatomical coordinate systems of, and to track the movement of the pelvis, thigh, shank and foot segments during walking. The placement of these markers is described in Appendix Table 1, and demonstrated in Appendix Figure 1. Kinematic data were collected at 120Hz and ground reaction forces at 1200Hz. A static standing trial was recorded for each participant so to calculate the location of joint centres. All data were digitised within Vicon, and then exported for modelling and analysis within Visual 3D (C-Motion, Rochelle, USA). A model specific to the height and mass of each participant was created. The inertial parameters for each segment are based upon the recommendations from De Leva et al.[1] Joint kinematics were calculated for the pelvis, hip, knee and ankle using inverse dynamics. This allows specific constraints to be applied at the joints of the virtual model so to limit rotation and or translation. The pelvis permitted six degrees of freedom, but only sagittal, coronal and transverse plane rotation were permitted at all other joints. Gait events (initial contact, toe off and initial contact after swing phase) were defined from contact with the force plates. All data were normalised to 0-100% of the gait cycle and exported as an ASCII. MATLAB (Mathworks, Natrick, MA, USA) was used to extrapolate and export the required data to Microsoft Excel for calculation of the GPS as similar to described in Baker et al.[2]

Appendix Table1: Marker placement for amputee and control participants

Segment	Marker Placement
Pelvis	• Markers were placed onto the right and left anterior superior iliac spine and right and left posterior superior iliac spine. • These were used to define and track this segment
Thigh	• To track the thigh segment three markers were placed onto the mid-point of the anterior aspect of the thigh in a triangle cluster formation and another marker placed onto the mid-point of the posterior aspect of the thigh • To define the thigh segment, the hip joint centre was created using recommendations by Harrington et al.[3] and a marker was placed onto the medial and lateral condyles of the femur or onto the knee joint centre of a prosthetic knee.
Shank	• To track the shank segment tour markers were placed in a square cluster formation onto the lateral distal aspect of the shank, the socket for trans-tibial amputees or the prosthetic knee for trans-femoral amputees. • To define the shank segment, markers were placed onto the medial and lateral condyles of the femur or the knee joint centre of a prosthetic knee, and the medial and lateral malleloi or the equivalent for the prosthetic foot
Foot	• To track the foot segment a marker were placed on top of the shoe overlaying the mid-point of the posterior and lateral aspect of the calcaneus and on top of the 1st, 2nd and 5th metatarsal heads. • To define the foot segment, markers were placed onto the medial and lateral malleoli and metatarsal heads 1 and 5.

Appendix Figure 1: Marker placement for amputee and control participants



Appendix 2: Description of rehabilitation programme

The ethos of the rehabilitation programme starts with early rehabilitation, firstly, during the acute phase in hospital, and then, secondly, post-acute phase at xxxx xxxxxxx xxxxx. Rehabilitation at xxxx xxxxxxx xxxxx utilising periodic in-patient rehabilitation of between two to six weeks at a time, which is segmented with time at home before returning for more rehabilitation depending on what is suitable for the patient. Rehabilitation is inter-disciplinary with emphasis on managing the physical and psychological consequences of injury. Individual and group based sessions utilising physiotherapy, exercise therapy, prostheses fitting, and occupational theory are key for individuals with amputation to regain muscular strength, co-ordination and control post-injury so that they can learn to walk with their prostheses as soon as possible. The mental health team, which includes psychological support, social work and counselling, play an equally important role in helping many patients manage the psychological disturbances from war and injury. This includes coming to terms with the probable change in career due to medical discharge from military service post-injury, and the effect all of the above have on the patient's family. Rehabilitation continues until the inter-disciplinary team agree that optimum possible function has been achieved, mental health issues have been addressed, pain is controlled, and appropriate social and vocational plans are in place. Due to nature of their potential other injuries all rehabilitation is bespoke and guided by patient goal setting, with input from the inter-disciplinary team. Complications from those injuries can impact on the rehabilitation in different ways, be it returning to hospital for further surgeries or limiting their ultimate functional level – for example spinal injuries precluding running and impact work.

Appendix 3: Benchmark data

Appendix 3 Table 1: Temporal spatial parameters, and oxygen consumption and oxygen cost for n=10 unilateral trans-tibial individuals with amputation

	1	2	3	4	5	6	7	8	9	10
Walking speed (m/s)	1.53	1.26	1.17	1.51	1.50	1.30	1.52	1.30	1.25	1.30
Stride length (m)	1.37	1.44	1.35	1.54	1.53	1.33	1.49	1.35	1.80	1.44
Stride width (m)	0.13	0.14	0.20	0.13	0.11	0.09	0.08	0.16	0.12	0.15
Cadence (steps per minute)	134	105	104	118	117	105	1043	109	112	116
Intact leg step length (m)	0.75	0.69	0.70	0.75	0.75	0.65	0.74	0.66	0.92	0.73
Prosthetic leg step length (m)	0.62	0.75	0.65	0.78	0.80	0.69	0.75	0.68	0.85	0.70
Intact leg stance time (% of gait cycle)	63	64	67	60	61	63	63	69	62	66
Prosthetic leg stance time (% of gait cycle)	59	62	62	59	61	60	62	59	62	63
Oxygen consumption (ml/kg/min)	13.8	10.5	10.0	14.6	10.63	11.2	14.9	13.2	n/d	n/d
Oxygen cost (ml/kg/m)	0.15	0.13	0.14	0.16	0.12	0.14	0.16	0.17	n/d	n/d

eTable2: [a]n/d: no data available

Appendix 3 Table 2: Temporal spatial parameters, oxygen consumption, and oxygen cost for n=10 individuals with a unilateral trans-femoral amputation

	1	2	3	4	5	6	7	8	9	10
Walking speed (m/s)	1.19	0.96	1.10	1.50	1.12	1.31	1.10	1.60	1.10	1.22
Stride length (m)	1.28	1.04	1.30	1.77	1.34	1.51	1.28	1.77	1.36	1.59
Stride width (m)	0.19	0.30	0.13	0.19	0.12	0.19	0.21	0.13	0.18	0.21
Cadence (steps per minute)	112	111	102	102	100	104	103	109	97	92
Intact leg step length (m)	0.68	0.50	0.65	0.95	0.72	0.69	0.63	0.93	0.67	0.74
Prosthetic leg step length (m)	0.60	0.53	0.65	0.82	0.65	0.82	0.65	0.84	0.69	0.85
Intact leg stance time (% of gait cycle)	61	71	60	59	60	70	69	59	65	66
Prosthetic leg stance time (% of gait cycle)	64	59	64	63	65	59	59	62	62	66
Oxygen consumption (ml/kg/min)	11.1	13.8	11.2	13.7	11.5	10.3	n/d[a]	18.3	12.3	17.7
Oxygen cost (ml/kg/m)	0.15	0.23	0.17	0.15	0.17	0.13	n/d[a]	0.18	0.20	0.24

eTable3: [a]n/d: no data available

Appendix 3 Table 3: Temporal spatial parameters, oxygen consumption, and oxygen cost for n=10 individuals with a bilateral trans-femoral amputation

	1	2	3	4	5	6	7	8	9	10
Walking speed (m/s)	1.26	1.32	1.10	1.22	0.94	1.03	1.20	0.91	0.90	1.40
Stride length (m)	1.50	n/d[a]	1.21	1.49	1.33	1.18	1.53	1.17	1.36	1.55
Stride width (m)	0.22	n/d[a]	0.21	0.20	0.23	0.22	0.19	0.26	0.22	0.25
Cadence (steps per minute)	99	n/d[a]	109	98	85	104	94	93	79	109
Right leg step length (m)	0.76	n/d[a]	0.59	0.73	0.67	0.60	0.76	0.57	0.68	0.79
Left leg step length (m)	0.77	n/d[a]	0.62	0.76	0.66	0.58	0.77	0.60	0.68	0.75
Right leg stance time (% of gait cycle)	61	71	60	59	60	70	69	59	65	66
Left leg stance time (% of gait cycle)	64	59	64	63	65	59	59	62	62	66
Oxygen consumption (ml/kg/min)	15.5	20.8	14.6	14.6	12.1	15.7	13.2	15.9	13.3	26.1
Oxygen cost (ml/kg/m)	0.20	0.27	0.22	0.20	0.22	0.26	0.18	0.29	0.25	0.31

eTable4: [a]n/d: no data available

Appendix 3 Table 4: Temporal spatial parameters, oxygen consumption, and oxygen cost for n=10 controls (able-bodied/asymptomatic)

	1	2	3	4	5	6	7	8	9	10
Walking speed (m/s)	1.33	1.30	1.31	1.20	1.32	1.23	1.31	1.39	1.30	1.30
Stride length (m)	1.45	1.45	1.32	1.48	1.38	1.46	1.53	1.52	1.39	1.72
Stride width (m)	0.12	0.15	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.11
Cadence (steps per minute)	110	107	119	97	115	101	103	110	112	91
Right leg step length (m)	0.73	0.74	0.65	0.81	0.69	0.70	0.75	0.74	0.71	0.87
Left leg step length (m)	0.72	0.72	0.67	0.67	0.69	0.76	0.78	0.78	0.68	0.85
Right leg stance time (% of gait cycle)	61	63	61	63	66	63	63	63	67	61
Left leg stance time (% of gait cycle)	61	63	61	62	66	62	62	69	63	60
Oxygen consumption (ml/kg/min)	10.9	11.5	11.0	11.2	11.9	13.0	11.9	11.3	9.3	11.3
Oxygen cost (ml/kg/m)	0.14	0.15	0.15	0.14	0.15	0.18	0.15	0.13	0.12	0.15