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# Accepted Manuscript

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

Hannah L. Jarvis, PhD, Alex N. Bennett, PhD FRCP, Martin Twiste, PhD, Rhodri D. Phillip, FRCP, John Etherington, FRCP OBE, Richard Baker, PhD



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

Hannah L Jarvis, PhD<sup>1,2#</sup>

Alex N Bennett, PhD FRCP<sup>3,4,5</sup>

Martin Twiste, PhD<sup>2,4</sup>

Rhodri D Phillip, FRCP<sup>3</sup>

John Etherington, FRCP OBE<sup>3</sup>

Richard Baker, PhD<sup>1</sup>

<sup>1</sup> Department of Exercise and Sport Science, Manchester Metropolitan University, Crewe Campus, CW1 5DU

<sup>2</sup> School of Health Sciences, University of Salford, Salford, M6 6PU, UK

<sup>3</sup> Defence Medical Rehabilitation Centre, Headley Court, Epsom, Surrey, KT18 6JW, UK

<sup>4</sup> United National Institute for Prosthetics & Orthotics Development (UNIPOD), University of Salford, Salford, M6 6PU, UK

<sup>5</sup> Leeds Institute of Rheumatic and Musculoskeletal Medicine, University of Leeds

<sup>6</sup> National Heart and Lung Institute, Faculty of Medicine, Imperial College London

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#Corresponding author:

Dr Hannah Jarvis

Address: Department of Exercise and Sport Science, Manchester Metropolitan University,  
Crewe Campus, CW1 5DU

Email: h.l.jarvis@salford.ac.uk

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### **Conflicts of Interest**

The authors declare that there are no conflicts of interest

ACCEPTED MANUSCRIPT

1 **Temporal spatial and metabolic measures of walking in highly functional individuals**  
2 **with lower limb amputations**

3 **Abstract**

4 *Objective*

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

9

10 *Design*

11 Cross-sectional

12

13 *Setting*

14 Multi-disciplinary comprehensive rehabilitation centre

15

16 *Participants*

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

21

22 *Interventions*

23 Not applicable

24

25 *Main Outcomes and Measures*

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

28

29 *Results*

30 The individuals with amputation were all male, with a mean age 29 years (SD = 4) and mean  
31 New Injury Severity Score of 31 (SD = 16). Walking speed, stride length, step length and  
32 cadence of individuals with a unilateral trans-tibial or trans-femoral amputation was  
33 comparable to controls, and only for individuals with a bilateral trans-femoral amputation  
34 was walking speed significantly slower (1.12m/s,  $p = 0.025$ ) and cadence reduced (96  
35 steps/min,  $p = 0.026$ ). Oxygen cost for individuals with a unilateral trans-tibial amputation  
36 (0.15 ml/kg/m) was the same as for controls (0.15 ml/kg/m), and significantly increased by  
37 20% (0.18ml/kg/m,  $p = 0.023$ ) for unilateral trans-femoral and by 60% (0.24 ml/kg/m,  $p <$   
38 0.001) for bilateral trans-femoral individuals with amputation.

39

40 *Conclusion*

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

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

53

#### 54 **Keywords**

55 Amputation, rehabilitation, gait

56

#### 57 **List of abbreviations**

58 IED Improvised Explosive Device

59 NISS New Injury Severity Score

60 RTA Road Traffic Accident

61 NHS National Health Service

62 KD Knee disarticulation

63 BKD Bilateral knee disarticulation

64 TT Trans-tibial



65 IED Improvised explosive device

66 GSW Gunshot wound

67 TF Trans-femoral

68 LPPR Low profile reflex rotate

69 TSB Total surface bearing

70 IC Ischial containment

71 IBS Ischial bearing socket

72 DEB Distal end bearing

73

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

76 **Introduction**

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

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

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

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

115 Age of individuals is generally well-reported and the studies showing particularly low levels  
116 of energy expenditure tend to be on younger cohorts. <sup>(1, 3)</sup> Other individual characteristics,  
117 which might affect walking ability such as general health and motivation, are generally not  
118 well reported (although ability and willingness to participate in formal studies suggests a  
119 certain baseline for both). Another potentially important factor that is generally not  
120 particularly well reported or standardised is the rehabilitation programme. This, supported by  
121 the observation that many of the lowest energy costs of walking in individuals with

122 amputation are from the military who may have benefitted from particularly intensive  
123 rehabilitation programmes, focussed on achieving very high levels of function. <sup>(1, 3, 15)</sup>

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

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

141

## 142 **Materials and methods**

### 143 *Participants*

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

147 Thirty individuals with amputation (10 unilateral trans-tibial, 10 unilateral trans-femoral, and  
148 10 bilateral trans-femoral) were recruited from those available at the time of data collection  
149 between October 2013 and August 2014. This is comparable with other studies of similar  
150 design. <sup>(1, 4, 6, 17-20)</sup> Inclusion criteria were that they could walk continuously for at least twelve  
151 minutes and had been wearing the same prostheses for at least six months prior to testing.  
152 Prosthetics prescription, including design of socket and type of liner for each individual with  
153 amputation, is presented in Table 1. All bilateral trans-femoral and 3 unilateral trans-femoral  
154 individuals with amputation wore single-axis hydraulic micro-processor knee units such as  
155 the Genium or C-Leg (Otto Bock, Duderstadt, Germany), or Plié (Freedom Innovations,  
156 Enschede, The Netherlands). The remaining unilateral trans-femoral individuals with  
157 amputation were fitted with a KX06 (Blatchford, Basingstoke, UK) which is a hydraulic  
158 polycentric knee unit (without micro-processor control). Prosthetic feet varied considerably  
159 but were all dynamic elastic response feet. Individuals with amputation who had suffered  
160 from a traumatic brain injury were excluded. All individuals with amputation were  
161 undergoing their rehabilitation programme at DMRC Headley Court. The rehabilitation  
162 programme described in Appendix 1 incorporates the same key components for each patient  
163 and all were managed by the same rehabilitation team at DMRC Headley Court. This utilises  
164 a structured and similar programme for each patient, allowing for individual variation and  
165 needs. Inclusion criteria for controls stated that they must have been asymptomatic for at least  
166 six months prior to testing and without previous major joint or soft tissue surgery.

167 Demographic data were collected including age, body mass (inclusive of prosthesis mass),  
168 height, New Injury Severity Score (NISS) <sup>(21)</sup> duration of rehabilitation (total time spent at

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

### 172 *Outcome measures*

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

186

### 187 *Statistical analysis*

188 No formal hypotheses are being tested and tests of statistical significance are thus taken as  
189 indicative of the relative probability of false positives. No corrections have been applied for  
190 multiple comparisons but the likelihood of this is addressed in the Discussion. All data were  
191 checked for normality using the Kolmogorov Smirnov test. Between group differences across

192 the three levels of amputation and the controls were compared using a one-way ANOVA  
193 followed, if statistical significance ( $P < 0.05$ ) was found, by post-hoc analysis of each  
194 amputation level group against control using Least Significant Difference. Other data were  
195 compared using a Kruskal-Wallis test with post-hoc analysis between each group of  
196 individuals with amputation versus control, using individual Mann-Whitney tests. For  
197 between leg comparison (prosthetic versus intact (unilateral individuals with amputation) or  
198 right versus left (bilateral individuals with amputation and controls), parametric data were  
199 compared using an independent t-test and non-parametric data using a Mann-Whitney test.  
200 Statistical analysis was conducted using SPSS (Statistical Package for the Social Sciences)  
201 Version 20 (IBM Corporation, New York, USA).

202

### 203 **Results**

204 Individuals with amputation and controls were of a similar age, height, and mass (Table 1)  
205 ( $p > 0.537$  lowest p value for any comparison with controls). Injuries sustained during  
206 operations in Afghanistan or Iraq were the most common cause of amputation with 21 from  
207 improvised explosive devices (IED), 3 from mine, and one from a gunshot wound. Five  
208 required amputation after non-operational injuries, three following road traffic accident  
209 (RTA), and two from other crush injuries. Mean NISS for all individuals with amputation  
210 was 31 which increased with severity of limb loss with unilateral trans-tibial (95% CI 10-22),  
211 compared to unilateral trans-femoral (17-30,  $p = 0.060$ ), and bilateral trans-femoral (44-55,  $p$   
212  $< 0.001$ ). Individuals with a bilateral trans-femoral amputation required significantly longer  
213 inpatient rehabilitation (22 months,  $p < 0.001$ ) than those with a unilateral trans-tibial (5  
214 months,  $p < 0.001$ ), or unilateral trans-femoral amputation (6 months,  $p < 0.001$ ). Prosthetics  
215 prescription for each individual with amputation is presented in Table 1.

216 Walking speed, stride length, and cadence of individuals with a unilateral trans-tibial or trans-  
217 femoral amputation was comparable to control ( $p > 0.340$ ). 95% confidence intervals for  
218 walking speed of individuals with a unilateral trans-tibial (1.28-1.44 m/s) or unilateral trans-  
219 femoral amputation (1.08-1.36 m/s) overlapped considerably that of the controls (1.25-1.33  
220 m/s). Only for individuals with a bilateral trans-femoral amputation was walking speed  
221 significantly slower (1.00-1.24 m/s,  $p = 0.030$ ), and cadence reduced (89-103 steps per minute,  
222  $p = 0.026$ ) whilst stride length was similar to control ( $p = 0.206$ , Table 2). For between limb  
223 comparison, stance time was significantly longer for the intact limb (62- 66%) than the  
224 prosthetic limb (60- 62%,  $p = 0.010$ ) for the unilateral trans-tibial group. No other differences  
225 were reported between limbs for other groups.

226 Oxygen uptake data were not available from three participants with amputation, two  
227 unilateral trans-tibial and one unilateral trans-femoral, due to two not wanting to wear a gas  
228 mask and a failed calibration for the other. The mean rate of oxygen consumption increased  
229 with increasing amputation level but the difference compared with control subjects was only  
230 statistically significant for the bilateral trans-femoral group (43% greater,  $p = 0.001$ ). Oxygen  
231 cost for individuals with a unilateral trans-tibial amputation (0.13-0.16 ml/kg/m) was the  
232 same as for controls (0.14-0.16 ml/kg/m), and significantly increased by 20% (0.16-0.20  
233 ml/kg/m,  $p = 0.023$ ) for individuals with a unilateral trans-femoral and by 60% (0.20-0.27  
234 ml/kg/m,  $p < 0.001$ ) for individuals with a bilateral trans-femoral amputation (Table 2).

235

## 236 Discussion

237 The ultimate aim when managing the rehabilitation of an individual with amputation is to  
238 achieve good functional outcomes. Self-selected walking speed, metabolic oxygen cost, and



239 gait pattern are all strong indicators of this. The results of this study indicate that the  
240 individuals with amputation in this study have a functional and efficient gait pattern.

241 Individuals with amputation in this study walked at a similar speed or faster (Figure 1), with a  
242 longer stride length, more symmetrical step length, and narrower stride width than in  
243 comparable studies<sup>(4, 6, 8, 12, 18, 19, 22, 23)</sup> of groups with similar age, mass and activity level  
244 using similar prosthetic components. Individuals with a unilateral trans-tibial amputation had  
245 the same oxygen cost of walking as the controls which has only been observed in two other  
246 studies<sup>(3, 24)</sup> (Figure 2). The oxygen cost of walking for individuals with unilateral trans-  
247 femoral amputation in this study was only 24% greater than that of the controls. In  
248 comparison, the oxygen cost of walking for individuals with this level of amputation in other  
249 studies<sup>(1, 4, 6-8, 11, 25, 26)</sup> ranges from 25% (0.20 ml/kg/m)<sup>(6)</sup> to 50% (0.30 ml/kg/m)<sup>(25)</sup> greater  
250 than that of controls (Figure 2). The oxygen cost of walking for individuals with a bilateral  
251 trans-femoral amputation in this study is 25% less than the only other reported cohort study,  
252 and individuals with amputation in this study walked significantly faster.<sup>(19)</sup> In summary, the  
253 data indicate that individuals with amputation in this study perform at least as well as and in  
254 many **cases** better than those described in the literature in terms of gait function (temporal  
255 spatial parameters) and efficiency (metabolic energy expenditure).

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

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

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

286 From this study, we propose that this dataset (more comprehensively documented in  
287 Appendix 3) could be used as a benchmark against which to compare other studies or clinical

288 results from individuals with amputation. Nearly all studies compare the walking ability of  
289 individuals with amputation to that of the “normal” able-bodied, which is generally an  
290 unobtainable goal. Instead, comparing the walking ability to individuals with amputations,  
291 but who are rehabilitated to the highest functional level, may be more appropriate. However,  
292 considering the characteristics of each individual with amputation will always be important,  
293 as it may be equally unrealistic to compare outcomes from an elderly and unwell individual  
294 with an amputation due to vascular disease with the outcomes from the young otherwise  
295 healthy individuals with amputation due to trauma reported in this study. <sup>(9, 10)</sup>

296

### 297 **Study Limitations**

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

311

**312 Conclusions**

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

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404

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408

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**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. <sup>(3-5, 7, 8, 12, 14, 20, 23, 24, 26)</sup> 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 <sup>(4)</sup> 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. <sup>(1, 26)</sup>

**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. <sup>(1, 3-8, 12, 20, 24, 26, 29)</sup> Self-selected walking speed for individuals with amputation except <sup>(1)</sup> 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 <sup>(3, 5-8, 20)</sup> for <sup>(1, 4, 12, 24, 26)</sup> 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. <sup>(1, 26)</sup>



Table 1: <sup>KD</sup> knee disarticulation (rather than true trans-femoral amputation). <sup>BKD</sup> bilateral knee disarticulation. <sup>TF/TT</sup> 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 xxxxxxxx xxxxx, whilst time from injury represents the time from injury to when the person attending data collection for the study

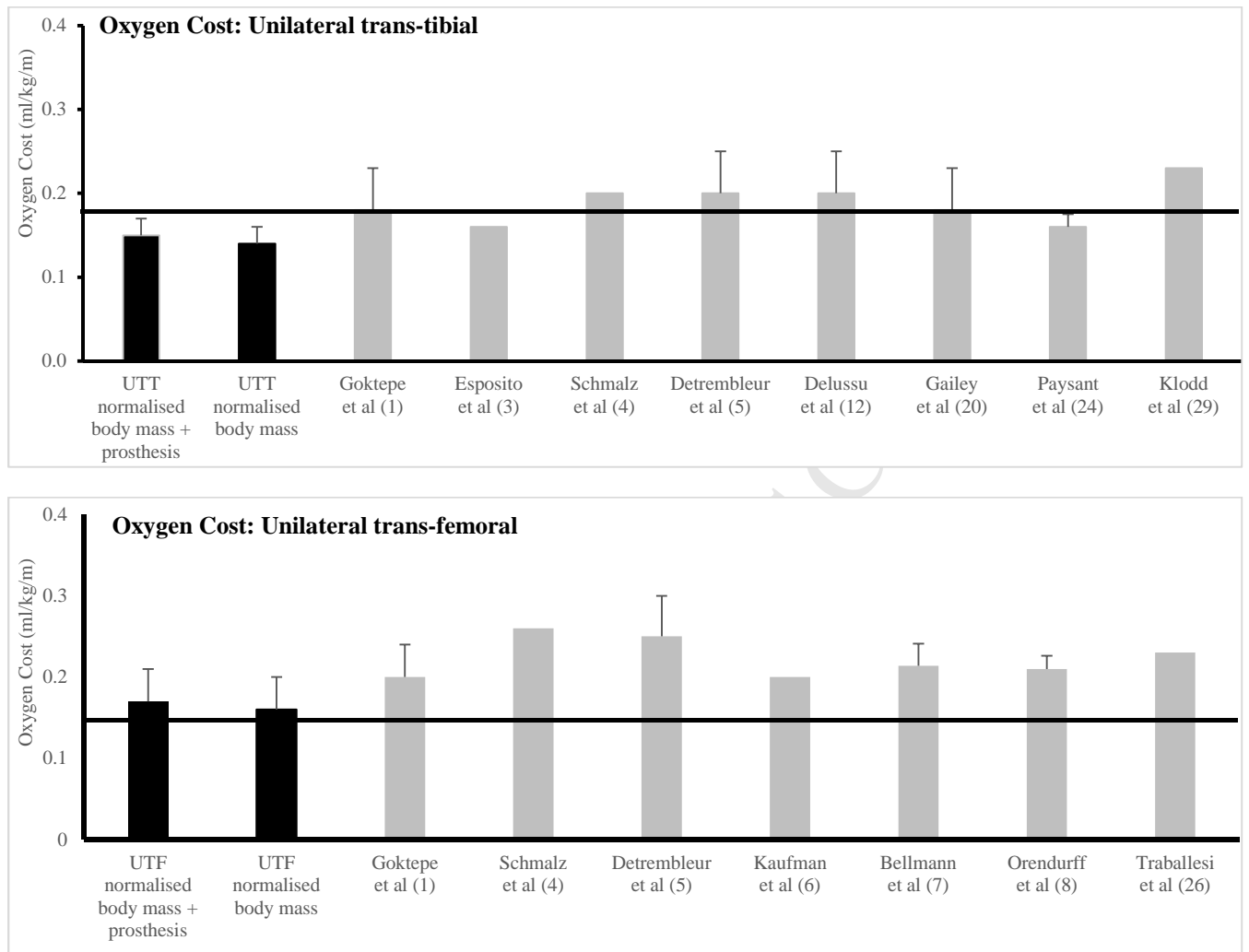
**Table 2:** Comparison of temporal and spatial parameters, and oxygen consumption and cost between individuals with amputation and control groups.

Parameter	Unilateral trans-tibial		Unilateral trans-femoral		Bilateral trans-femoral		Control	
	Intact	Prosthetic	Intact	Prosthetic	Right	Left	Right	Left
Walking Speed (m/s)	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)	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)	0.13 +9% (0.11- 0.15) p=<0.0001		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)	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) p=0.834	0.72 -3% (0.63- 0.80)	0.71 -3% (0.64- 0.78) p=0.875	0.69 +8% (0.63- 0.74)	0.69 +7% (0.63- 0.75) p=0.907	0.74 (0.70- 0.78)	0.73 (0.69- 0.77) p=0.800
Stance Time (% cycle)	63.8 +1% (62.1- 65.5)	60.9 -3% (60.0- 61.8) p=0.010	64.0 +1% (61.0- 67.0)	62.3 -1% (60.7- 63.9) p=0.336	64.0 +2% (61.0- 67.0)	62.3 +0% (60.7- 63.9) p=0.983	63.1 (61.8- 64.4)	62.9 (61.2- 64.6) p=0.853
O <sub>2</sub> Consumption (ml/kg/min)	12.3 +9% (11.0- 13.7) p=0.004		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 <sub>2</sub> Cost (ml/kg/m)	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  $p < 0.05$ . All entries given as the mean with percentage difference relative to data from control group and then 95% confidence interval in parenthesis. <sup>a</sup> asterisks are results of post-hoc comparisons. \* statistically significant difference from control ( $p < 0.05$ ). \*\* statistically significant difference between prosthetic and intact lower limbs ( $p < 0.05$ ).



**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.<sup>(3-5, 7, 8, 12, 14, 20, 23, 24, 26)</sup> 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<sup>(4)</sup> 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.<sup>(1, 26)</sup>



**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. <sup>(1, 3-8, 12, 20, 24, 26, 29)</sup> 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 <sup>(1)</sup> 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, <sup>(3, 5-8, 20)</sup> whilst for <sup>(1, 4, 12, 24, 26)</sup> 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.<sup>(1, 26)</sup>

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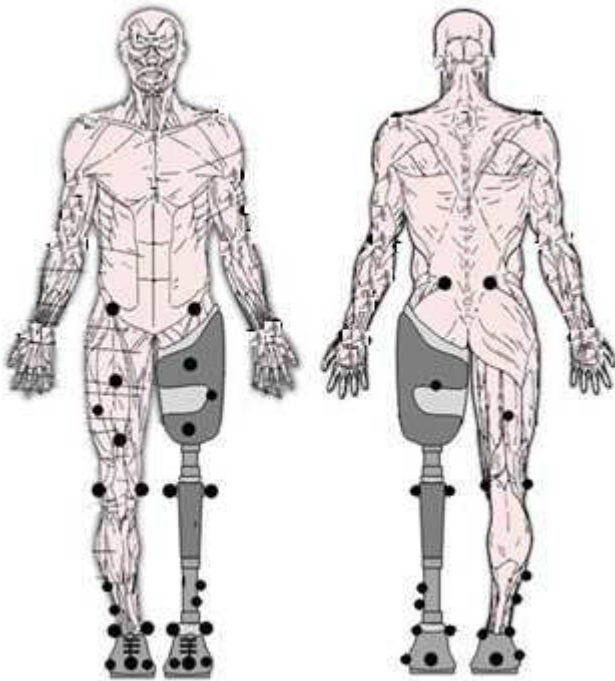
## Appendices

### 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.<sup>1</sup> 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, Natick, 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.<sup>2</sup>

**Appendix Table1: Marker placement for amputee and control participants**

Segment	Marker Placement
<b>Pelvis</b>	<ul style="list-style-type: none"> <li>• Markers were placed onto the right and left anterior superior iliac spine and right and left posterior superior iliac spine.</li> <li>• These were used to define and track this segment</li> </ul>
<b>Thigh</b>	<ul style="list-style-type: none"> <li>• 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</li> <li>• To define the thigh segment, the hip joint centre was created using recommendations by Harrington et al.<sup>3</sup> and a marker was placed onto the medial and lateral condyles of the femur or onto the knee joint centre of a prosthetic knee.</li> </ul>
<b>Shank</b>	<ul style="list-style-type: none"> <li>• To track the shank segment four 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.</li> <li>• 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 malleoli or the equivalent for the prosthetic foot</li> </ul>
<b>Foot</b>	<ul style="list-style-type: none"> <li>• 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 1<sup>st</sup>, 2<sup>nd</sup> and 5<sup>th</sup> metatarsal heads.</li> <li>• To define the foot segment, markers were placed onto the medial and lateral malleoli and metatarsal heads 1 and 5.</li> </ul>

**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 xxxxxxxx xxxxx.

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

eTable3: <sup>a</sup>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
<b>Walking speed (m/s)</b>	1.26	1.32	1.10	1.22	0.94	1.03	1.20	0.91	0.90	1.40
<b>Stride length (m)</b>	1.50	n/d <sup>a</sup>	1.21	1.49	1.33	1.18	1.53	1.17	1.36	1.55
<b>Stride width (m)</b>	0.22	n/d <sup>a</sup>	0.21	0.20	0.23	0.22	0.19	0.26	0.22	0.25
<b>Cadence (steps per minute)</b>	99	n/d <sup>a</sup>	109	98	85	104	94	93	79	109
<b>Right leg step length (m)</b>	0.76	n/d <sup>a</sup>	0.59	0.73	0.67	0.60	0.76	0.57	0.68	0.79
<b>Left leg step length (m)</b>	0.77	n/d <sup>a</sup>	0.62	0.76	0.66	0.58	0.77	0.60	0.68	0.75
<b>Right leg stance time (% of gait cycle)</b>	61	71	60	59	60	70	69	59	65	66
<b>Left leg stance time (% of gait cycle)</b>	64	59	64	63	65	59	59	62	62	66
<b>Oxygen consumption (ml/kg/min)</b>	15.5	20.8	14.6	14.6	12.1	15.7	13.2	15.9	13.3	26.1
<b>Oxygen cost (ml/kg/m)</b>	0.20	0.27	0.22	0.20	0.22	0.26	0.18	0.29	0.25	0.31

eTable4: <sup>a</sup>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
<b>Walking speed (m/s)</b>	1.33	1.30	1.31	1.20	1.32	1.23	1.31	1.39	1.30	1.30
<b>Stride length (m)</b>	1.45	1.45	1.32	1.48	1.38	1.46	1.53	1.52	1.39	1.72
<b>Stride width (m)</b>	0.12	0.15	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.11
<b>Cadence (steps per minute)</b>	110	107	119	97	115	101	103	110	112	91
<b>Right leg step length (m)</b>	0.73	0.74	0.65	0.81	0.69	0.70	0.75	0.74	0.71	0.87
<b>Left leg step length (m)</b>	0.72	0.72	0.67	0.67	0.69	0.76	0.78	0.78	0.68	0.85
<b>Right leg stance time (% of gait cycle)</b>	61	63	61	63	66	63	63	63	67	61
<b>Left leg stance time (% of gait cycle)</b>	61	63	61	62	66	62	62	69	63	60
<b>Oxygen consumption (ml/kg/min)</b>	10.9	11.5	11.0	11.2	11.9	13.0	11.9	11.3	9.3	11.3
<b>Oxygen cost (ml/kg/m)</b>	0.14	0.15	0.15	0.14	0.15	0.18	0.15	0.13	0.12	0.15