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## **TITLE**

Standing posture and balance modalities in unilateral transfemoral and transtibial amputees

## **Authors full names and affiliations**

Anis Toumi<sup>a,b</sup>, Émilie Simoneau-Buessinger<sup>a</sup>, Jennifer Bassement<sup>a</sup>, Franck Barbier<sup>a</sup>, Christophe Gillet<sup>a</sup>, Paul Allard<sup>c</sup>, Sébastien Leteneur<sup>a</sup>

<sup>a</sup> Laboratoire d'Automatique de Mécanique et d'Informatique industrielles et Humaines, UMR CNRS 8201, Université Polytechnique Hauts-de-France, Valenciennes, France

<sup>b</sup> Centre de Rééducation Fonctionnelle La Rougeville, 59880 Saint-Saulve, France

<sup>c</sup> School of Kinesiology, Faculty of medicine, University of Montreal, C.P. 6128, Succursale Centre-ville, Montreal, Quebec H3C 3J7, Canada

## **Corresponding author**

Dr Anis Toumi, PhD  
anis.toumi@live.com

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**ABSTRACT**

*Introduction.* Lower limb amputation impairs postural performance that could be characterized by biomechanical parameters. This study is to investigate postural performance of persons with transfemoral and transtibial amputation compared to controls without amputation.

*Methods.* Eight transtibial, nine transfemoral and twelve able-bodied males participated in this study. Lower limb joints, pelvis and trunk angles were obtained from an optoelectronic motion analysis system to evaluate body posture parameters. The mean, range and speed of the center of pressure (CoP) in both antero-posterior and medio-lateral axes as well as the ellipse area covered by 90% of CoP and free moment were calculated using a single force-plate.

*Results and discussion.* Differences in body posture were only noted between the non-amputee and the transtibial groups. Transtibial amputees leaned more forwardly their trunk by 3.5° compared to able-bodied ( $p=0.028$ ). The mean CoP position in transfemoral amputees was closer to the non-amputated side than transtibial amputees ( $p=0.034$ ) and as compared to the dominant side in non-amputees ( $p=0.042$ ). Factor analysis revealed three postural performance modalities. Non-amputees postural performance was characterized solely by body posture parameters. Transfemoral amputees exclusively favored a modality associated with standing balance parameters, whereas transtibial amputees exhibited a mixed modality comprising a combination of postural and balance parameters.

*Conclusion.* These findings support that the level of amputation is characterized by postural performance modalities different from non-amputees. Clinicians could apply this knowledge as part of their routine rehabilitation program to enhance postural and standing balance assessments in unilateral transfemoral and transtibial amputees.

25 *Clinical Relevance*

26

27 • Rehabilitation programs focused on postural balance should be specific for persons with

28 lower limb amputation based on the level of amputation

29 • Trunk plays a key role to identify the postural modalities in persons with transtibial

30 amputation

31 • Both optoelectronic motion analysis system and force plate are recommended to improve

32 the assessment of postural performance of persons with amputation

33

## 34 INTRODUCTION

35 Upright postural body alignment and standing balance have long been a subject of interest in  
36 lower limb amputees (Ferne and Holliday, 1978). Postural assessment (Gaunaud et al., 2011)  
37 and balance training (Buckley et al., 2002) are part of the clinician's routine evaluation to reduce  
38 the risk of chronic conditions associated with impairment of body structures and functions.  
39 However, balance control strategies in lower limb of different level of amputation are  
40 contradictory, and a comprehensive analysis is lacking (Ku et al., 2014).

41 Transtibial amputees adjust their prosthetic alignment by balancing the upper part of the body  
42 over the center of pressure (CoP) of the prosthetic foot (Blumentritt et al., 1999). This could be  
43 attributed to differences in leg length, pelvic inclination and hip extension between their intact  
44 and amputated limbs (Gaunaud et al., 2011). Standing imbalance was reported to be greater in  
45 transtibial amputees compared to transfemoral amputees (Ferne and Holliday, 1978) and  
46 generally amputees display greater postural sway than non-amputees (JG Buckley et al., 2002).  
47 Though Hermodsson et al. (Hermodsson et al., 1994) concluded that balance deficits were  
48 greater in a group of vascular amputees compared to trauma transtibial amputees, little was  
49 reported on their non-amputee control group. In contrast, no significant difference in standing  
50 balance was reported between transtibial amputees and non-amputees (Vittas et al., 1986). These  
51 divergent observations could be associated with stump length and patients' confidence level (Ku  
52 et al., 2014), but also with body posture adjustments concomitant to standing balance.

53 Standing balance in transtibial and transfemoral amputees and comparisons with able-bodied  
54 individuals have been well documented (John Buckley et al., 2002; Ferne and Holliday, 1978;  
55 Nederhand et al., 2012; Sadeghisani et al., 2016; Vrieling et al., 2008). However, their upright  
56 body posture positioning other than prosthetic alignment (Kobayashi et al., 2014) has been

57 seldom addressed. In general, few have examined the interaction between body posture attitude  
58 and standing balance. Nault et al. (Nault et al., 2002) were among the first to report a strong  
59 interaction between body segment alignment angles and standing balance parameters, but for  
60 non-treated scoliotic girls. In amputees, global body posture was most often characterized by  
61 shift in the mean CoP position and its excursion towards the non-amputated side (Curtze et al.,  
62 2016; Hlavackova et al., 2011; Rougier and Bergeau, 2009). But no study, to our knowledge,  
63 has integrated trunk and lower-limb postural joint alignment with standing balance to estimate  
64 stance adjustment modalities in unilateral transtibial and transfemoral amputees. ~~The interaction~~  
65 ~~between body misalignment due to the amputation and postural disturbances could improve~~  
66 ~~balance assessments and decrease the risk of falling in unilateral lower limb amputees.~~ The  
67 objective of this study was to determine if unilateral lower limb amputees assume similar  
68 upright posture and standing balance to non-amputees and if the level of amputation  
69 (transfemoral and transtibial) affects these body balance modalities. ~~The interaction between~~  
70 ~~body misalignment due to the amputation and postural disturbances could improve balance~~  
71 ~~assessments and decrease the risk of falling in unilateral lower limb amputees.~~

72

## 73 **METHODS**

### 74 **Participants**

75 Males with transfemoral (N=9) and transtibial (N=8) amputation and male controls without  
76 amputation (N=12) were recruited. Persons with amputation were active according to the  
77 amputee activity survey (Day, 1981) (Table 1). The exclusion criteria for the amputees were the  
78 presence of ulceration on the plantar surface of the non-amputated foot and/or the use of  
79 antipsychotic drugs, antidepressants or tranquilizers. For the able-bodied subjects, the exclusion

80 criteria were any medical conditions that could affect mobility or balance, such as neurological  
81 or orthopedic disorders; the use of antipsychotic medications, antidepressants or tranquilizers.  
82 All participants gave their written informed consent to participate in the study. All procedures  
83 are conformed to the Declaration of Helsinki and were approved by the local Ethics Committee  
84 of [XXXX].

85 (Insert Table 1)

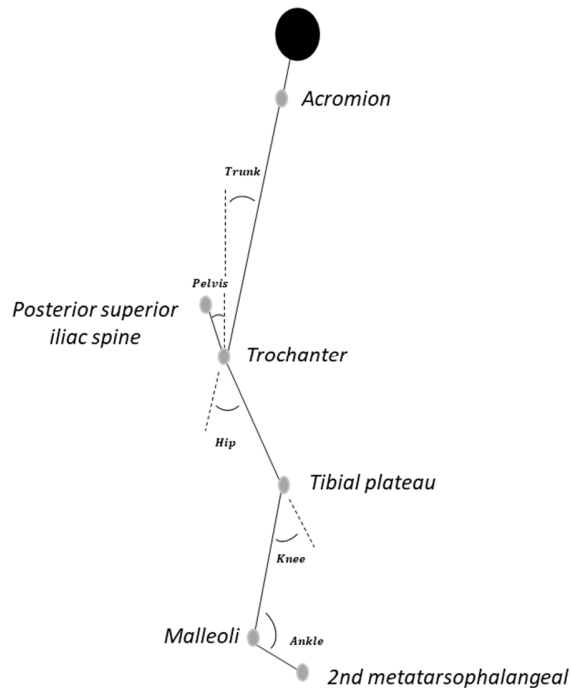
### 86 **Experimental protocol**

87 A 10 camera optoelectronic motion analysis system (Vicon 612, Oxford Metrics, UK), filmed the  
88 standing posture at a sampling frequency of 100 Hz. An eight-segment body model based on the  
89 International Society of Biomechanics joint coordinate standards (Wu, 2002) used to calculate  
90 body segment joint angles. . The postural balance task was performed with the participant  
91 standing upright on a force plate (Kistler, Switzerland) barefooted to avoid influences of  
92 footwear on balance. The upper limbs were at each side of the trunk. Three trials of one minute  
93 were performed, separated by a 2-minute resting period. The force plate signals were recorded at  
94 1000 Hz and filtered by a 10 Hz low-pass filter (2nd order Butterworth filter).

### 95 **Data analysis**

96 The mean natural trunk inclination was defined as the angle sustained by the line joining the  
97 midpoint between the greater trochanters and that of the acromions with respect to the vertical as  
98 shown in Figure 1. For the pelvis, hip, knee and ankle, the inclination was calculated in the  
99 sagittal plane only. The average pelvis inclination corresponded to the angle sustained by the line  
100 joining the midpoint between the greater trochanters and that of the posterior superior iliac spine  
101 with respect to the vertical. All joint angles were averaged for all three trials and for the  
102 dominant (D) and non-dominant (ND) sides of able-bodied individuals, and for the amputated

103 (A) and non-amputated (NA) sides for all amputees. For the sagittal plane, positive joint angles  
104 indicate a flexed position. Furthermore, positive angles on the frontal plane indicated a lateral  
105 bending to the right for able-bodied subjects or to the non-amputated side for the amputees. The  
106 right side was the dominant side (Chapman et al., 1987) for all the able-bodied participants.



107  
108 The CoP was calculated from force plate data. ~~Positive antero-posterior (AP) and medio-lateral~~  
109 ~~(ML) values indicated that the CoP position was located forward and to the left side,~~  
110 ~~respectively. Positive values corresponded to the non-dominant side for able-bodied individuals~~  
111 ~~and the amputated side for amputees. According to the coordinate system of the force plate~~  
112 ~~located at the center of the plate, positive antero-posterior (AP) values indicated that the CoP~~  
113 ~~position was located frontwards, the higher the value, the greater trunk leaned forwardly.~~  
114 ~~Negative medio-lateral (ML) values indicated that the CoP position was closer to the non-~~  
115 ~~amputated side for persons with amputation showing asymmetry in body weight distribution. For~~



116 able-bodied individuals, negative ML values indicated that the CoP position was closer to the  
117 dominant side.

118

119 The mean CoP positions, range and speed were calculated on the AP and ML axes. The CoP area  
120 corresponded to the ellipse that covered 90 % of the CoP excursion surface area. Finally, the root  
121 mean square of the free moment ( $T_z$  RMS) was also calculated from force plate data to quantify  
122 the rotational oscillation associated with postural balance (Dalleau et al., 2011, 2007).

### 123 **Statistical analysis**

124 Differences in outcomes between the two groups of unilateral lower limb amputees and non-  
125 amputees were tested by one-way ANOVAs on the postural and balance parameters. A Scheffé's  
126 post-hoc test was used because of the unequal group sizes. A  $p$ -value of 0.05 or less was  
127 considered as statistically significant. Factorial analysis was applied to identify the correlated  
128 body posture and standing balance variables. This approach was previously used by Sadeghi et  
129 al. (Sadeghi et al., 2000) to estimate the contribution of lower limb muscle power to gait. The  
130 variables with a factor loading of 0.7 or above were considered as significant. Statistical analyses  
131 were performed using Statistical Package for Social Sciences (SPSS) version 24/25 (IBM,  
132 Amrook, NY, USA).

### 133 **RESULTS**

134 Table 2 presents the postural body alignment results for all three groups. The only statistical  
135 differences were noted between the non-amputees and the transtibial groups. The transtibial  
136 amputees had a tendency to lean more forward with their trunk by  $3.5^\circ$  than the non-amputees ( $p$   
137 =0.028), and this was associated with an increase in dorsiflexion of the non-amputated ankle by

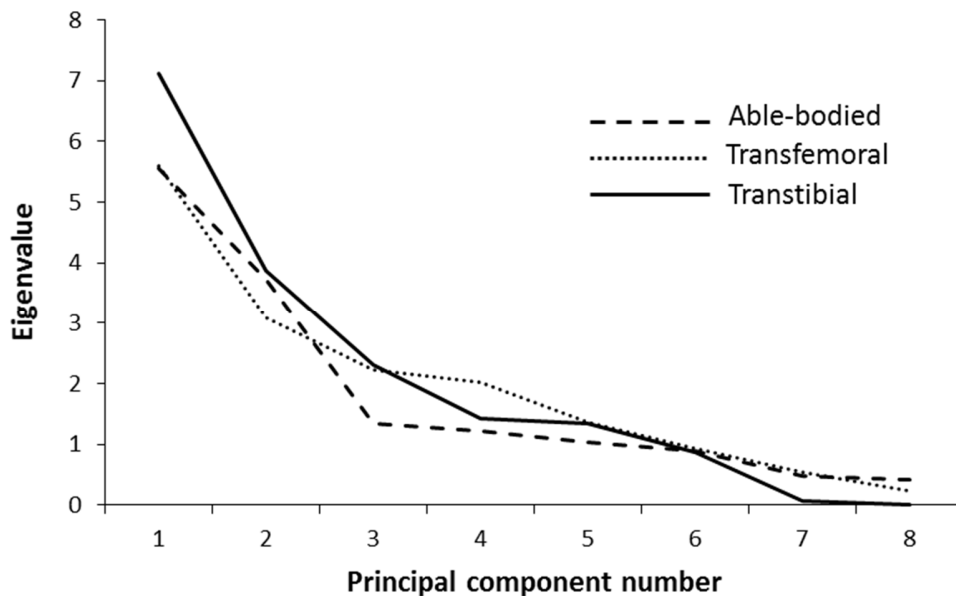
138 3° ( $p = 0.047$ ). The transfemoral amputees standing postural values varied substantially with  
139 respect to the other groups, but not enough to be statistically significant from the others.

140 (Insert Table 2)

141 The standing balance parameters for all three groups are shown in Table 3. The ML CoP was  
142 closer to the non-amputated side in the transfemoral group than in the transtibial amputees ( $p$   
143  $= 0.034$ ). The ML CoP in transfemoral group was shifted by 27 mm to the non-amputated side  
144 compared to the dominant side in able-bodied groups ( $p = 0.042$ ). Furthermore, the CoP was  
145 further anterior in the transtibial amputees than both transfemoral ( $p = 0.050$ ) and able-bodied ( $p$   
146  $= 0.002$ ) groups. This could be the result of a combined small trunk extension with a slight lateral  
147 flexed trunk, though not significantly greater than the other groups. Both amputee groups  
148 displayed a greater ML range ( $p = 0.005$ ) and sway area ( $p = 0.025$ ) than the non-amputee  
149 subjects; however, the latter groups were not statistically different from each other. This could  
150 reflect the ability of the amputees to maintain balance while leaning on their intact limb.

151 (Insert Table 3)

152 Figure 2 represents the evolution of the eigenvalues of the first 8 principal components (PC) for  
153 each group. Generally, all three curves follow a similar pattern. Factorial analysis indicated that  
154 the first 5 PCs have an eigenvalue above 1 explaining at least 86% of the total variance.  
155 However, there is a sharp decrease in the eigenvalues after the first two PCs. The latter accounts  
156 for 62%, 65% and 54% of the variance for the non-amputee, the transfemoral amputees and the  
157 transtibial amputees respectively.



158

159

160 Table 4 depicts the first and the second PCs for each group. Based on the postural and balance  
 161 parameters having a loading factor of 0.7 or above, three upright standing modalities were  
 162 observed. Using the first PC which accounts for about 40% of the variance, the able-bodied  
 163 group relies solely on body posture alignment parameters. Both trunk and all the lower limb  
 164 joints are used to maintain upright stance. The transfemoral amputees favor exclusively a  
 165 standing balance modality based on neuro-muscular control expressed by the range of their ML  
 166 CoP excursion and free moment RMS to control their mean CoP position. The transtibial  
 167 amputees exhibited a mixed standing modality comprising a synergy between postural and  
 168 balance actions. Pelvis flexion, hip and knee angles of the amputated leg interact with the CoP  
 169 speed in both ML and AP directions to regulate upright standing and balance.

170 The second PC explains about 20% of the variance (Table 4). It is interesting to note that able-  
 171 bodied subjects essentially used a balance modality as a complementary mechanism to their  
 172 postural alignment adjustments observed in the first PC. Lateral trunk flexion, the smallest

173 significant loading factor, is their only postural parameter. The transfemoral amputees rely on the  
174 amputated ankle and neuro-muscular control using CoP speed in both directions as a secondary  
175 modality for postural adjustments. The transtibial amputees rely on their non-amputated knee,  
176 and lateral trunk flexion to maintain their mean ML CoP position.

177 (Insert Table 4)

## 178 **DISCUSSION**

179 The purpose of this study was to analyze postural performance from a combination of both body  
180 posture and standing balance parameters in unilateral lower limb amputees in comparison to non-  
181 amputee able-bodied controls. This study highlights three postural modalities specific for each  
182 group. Though the transfemoral amputees displayed slightly similar body posture alignment than  
183 non-amputees, this was achieved by a greater loading on their non-amputated side combined  
184 with a backward CoP shift. The transtibial amputees had more anterior trunk flexion and  
185 dorsiflexion on the non-amputated side than the other groups. The transfemoral group tended to  
186 have a greater trunk flexion compared to able-bodied ( $2.7^\circ$ ,  $0.2^\circ$  respectively). A possible  
187 explanation for these results on trunk flexion could be related to a secondary adaptation post-  
188 amputation in body posture alignment (Goujon-Pillet et al., 2008). The trunk has an important  
189 impact on human motion due to its mass (Leteneur et al., 2013).

190 To maintain their respective standing stance, both amputee groups had to significantly increase  
191 their range of CoP in the ML direction combined with a greater sway area (Ku et al., 2014).  
192 These observations underline the need to include the functions of a subtalar joint in foot  
193 prosthesis designs (Allard et al., 1995) to maintain standing stability and improve recovery after  
194 foot placement errors during gait (Segal and Klute, 2014).

195 Generally, lower limb amputees load put more body weight on their non-amputated limb  
196 (Hlavackova et al., 2011; Rougier and Bergeau, 2009; Vrieling et al., 2008) as reported in this  
197 study. Buckley et al. (JG Buckley et al., 2002) identified the importance of the ankle in lower  
198 limb amputees to maintain balance during body movements in the sagittal plane to modulate  
199 ground reaction forces (Damavandi et al., 2009; Gillet et al., 2003). Experienced unilateral  
200 amputees with a high activity level compensate for the loss of an ankle by increasing body  
201 movements and loading in the non-amputated limb (Vrieling et al., 2008). However, Nederhand  
202 et al. (Nederhand et al., 2012) reported a non-significant loading asymmetry in favor of the non-  
203 amputated leg.

204 Not only body posture was affected by the amputation level but decrease standing balance ability  
205 was also observed in amputees (John Buckley et al., 2002; Isakov et al., 1992). Some  
206 disagreement exists whether this difficulty lies in controlling the AP (John Buckley et al., 2002)  
207 or ML CoP sway as was observed in this study. Some report that transtibial amputees lack ankle  
208 control in their prosthetic limb leading to a lateral foot and ankle strategy (Curtze et al., 2016;  
209 Vrieling et al., 2008). In general, the non-amputee ankle compensates the lack of a foot and ankle  
210 strategy offered by the prosthetic limb (Curtze et al., 2012; Ku et al., 2014). These studies which  
211 involved either transfemoral or transtibial amputees or both groups support that body posture as  
212 well as standing balance are affected by the level of amputation. However, their relative  
213 contributions within each amputee group and even in non-amputees themselves remains  
214 unknown.

215 This study was able to determine the relative contributions of body postural alignment and  
216 standing balance in unilateral transfemoral and transtibial amputees and in non-amputees. To our  
217 knowledge, no one has yet addressed this interaction in unilateral lower limb amputees. This

218 could be explained in part by the fact that the balance contribution of each leg was not strongly  
219 coupled to weight-bearing in each leg in lower limb amputees (Nederhand et al., 2012).  
220 Furthermore, many studies based their understanding of standing balance modalities in relation  
221 to the amputated or non-amputated limb sides rather than to assess the relationships among sets  
222 of interrelated variables. In this study, the first and highest PC underlines the dominance of  
223 postural parameters in maintaining standing balance in adult non-amputees. The lack of  
224 interaction between body parameters and their relation to standing stability was previously  
225 reported in able-bodied girls (Nault et al., 2002) and in adult amputees (Nederhand et al., 2012).  
226 However, transfemoral amputees essentially favor a standing balance modality. This could be  
227 attributed in part to lesser joint mobility on the prosthetic side. The transtibial amputees who  
228 displayed a mixed body postural and balance modality take advantage of the intact knee on the  
229 prosthetic side to maintain standing balance. These relationships between postural modalities and  
230 the level of amputation could partly be explained by the reduction in the active joint degrees of  
231 freedom due to the amputation level, and the more proximal the amputation is, the greater the  
232 need to rely on a standing balance modality.

233 Postural assessment is a common application in clinics which aim to detect and reduce the risk of  
234 chronic conditions associated with poor posture attitudes (Vrieling et al., 2008). Clinicians could  
235 also include challenging balance disturbances as part of their routine rehabilitation program for  
236 unilateral transfemoral amputees where balance is largely impaired (Ku et al., 2014). These  
237 observations could be of interest in improving unilateral lower limb amputees' postural balance  
238 and be useful in assisting prosthetic alignment, in monitoring of patients with lower limb  
239 amputation (Rougier and Bergeau, 2009).

240 While this work has provided insight into the interaction between body posture and standing  
241 balance in unilateral amputees, the results need to be interpreted with caution. The pattern of  
242 balance modalities was evaluated in upright quiet stance only. Different interactions between the  
243 level of amputation and balance modalities could be expected during perturbed balance or gait  
244 (Sadeghisani et al., 2016). Other activities of daily living could also rely on different balance  
245 modalities for successful postural control (Barnett et al., 2013). ~~The use of two force plates could~~  
246 ~~be beneficial in isolating the control and balance actions of the amputated and non-amputated~~  
247 ~~limbs in unilateral amputees (Curtze et al., 2012) in relation to balance modalities (Sadeghi et al.,~~  
248 ~~2001).~~ Results of this present study suggest that postural reeducation programs should improve  
249 both postural and standing balance in persons with lower limb amputation. Future longitudinal  
250 investigations are needed to determine the control and balance actions of the amputated and non-  
251 amputated limbs in unilateral amputees (Curtze et al., 2012) in relation to balance modalities  
252 (Sadeghi et al., 2001) by the use of two force plates. Moreover, the participants of this study  
253 were males, which makes the generalization of these findings to females limited. Further studies  
254 are needed in males and females with amputation to ascertain sex-related differences in postural  
255 performance. A further study could assess the benefits of training programs on the ankle and  
256 Achilles tendon in improving balance. Recent research has investigated how Achilles tendon  
257 mechanical properties change in persons with lower limb amputation (Toumi et al., 2020) and  
258 that contribute to postural performance (Onambele et al., 2006).

259 Finally, longitudinal studies are required to assess the impact of individual rehabilitation  
260 program on postural performance of persons with lower limb amputation including the  
261 interaction between body posture and standing balance parameters.

262

263 **CONCLUSION**

264 ~~Factorial analysis highlighted the interaction between body posture and standing balance~~  
265 ~~parameters in unilateral transfemoral and transtibial amputees and able bodied. The non amputee~~  
266 ~~group relied primarily on standing erect while maintaining balance as secondary adjustments.~~  
267 ~~The transfemoral amputees' stance depended on balance control first and secondly by ankle~~  
268 ~~adjustments on the non amputated side. The transtibial amputees exhibited a mixed modality of~~  
269 ~~simultaneously maintaining upright stance and standing balance. It appears that active joint~~  
270 ~~degrees of freedom reduction due to amputation level increases the need for a balance modality~~  
271 ~~in unilateral amputees. These finding support the concept of individualizing rehabilitation~~  
272 ~~programs according to the level of amputation.~~ **This study highlights that the level of amputation**  
273 **in persons with unilateral lower limb amputation needs to be considered as a clinical factor in**  
274 **postural balance rehabilitation. It is about adaptation of all techniques used by clinicians during**  
275 **rehabilitation program. These findings support the concept of individualizing rehabilitation**  
276 **programs according to the level of amputation.** We believe that the knowledge translation of  
277 these results will positively impact clinical care in unilateral lower limb amputees.



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355 **Tables**

356

357 **Table 1.** Physical characteristics of the participants of the three groups <sup>a</sup>

	<b>Able-bodied subjects (n=12)</b>	<b>Transfemoral amputees (n=9)</b>	<b>Transtibial amputees (n=8)</b>	<b><i>P</i>-value</b>
<b>Age (years)</b>	53.7 ± 21.5	59.2 ± 7.9	47.6 ± 20.4	0.43
<b>Height (m)</b>	1.77 ± 0.09	1.72 ± 0.06	1.74 ± 0.07	0.36
<b>Body mass (kg)</b>	78.0 ± 10.1	66.6 ± 11.7	71.0 ± 8.9	0.03
<b>Adjusted BMI (with prosthetic) (kg/m<sup>2</sup>)</b>	N/A	22.1 ± 4.0	23.0 ± 3.3	0.97
<b>Underlying cause of amputation</b>	N/A	Vascular n=6 Trauma n=3	Vascular n=3 Trauma n=5	N/A
<b>Time since amputation (months)</b>	N/A	135 ± 214	84 ± 159	0.59
<b>Amputee activity score <sup>b</sup></b>	N/A	10±12	14±12	N/A

358 <sup>a</sup>Mean ± SD, <sup>b</sup> Thresholds scores used in classifying the level of activity using amputee activity  
359 survey are inactive (-70 to -40), restricted (-40 to -10), average (-9 to +9), high (+10 to +29),  
360 and very high (+30 to +50)

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366 **Table2.** Body posture parameters: joint angles for the able-bodied subjects, transfemoral and  
 367 transtibial amputees. Data are reported as means  $\pm$  standard deviation for the dominant, the non-  
 368 dominant, the amputated and the non-amputated sides respectively  
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	Able-bodied		Transfemoral		Transtibial	
	Dominant	Non-dominant	Non-amputated	Amputated	Non-amputated	Amputated
<b>Ankle (°)</b>	5.4 $\pm$ 0.7*	6.2 $\pm$ 0.7	7.4 $\pm$ 0.8	7.9 $\pm$ 0.8	8.4 $\pm$ 0.9*	5.5 $\pm$ 0.8
<b>Knee (°)</b>	2.8 $\pm$ 0.9	2.5 $\pm$ 0.7	0.5 $\pm$ 1.1	0.9 $\pm$ 0.9	-0.5 $\pm$ 1.1	2.9 $\pm$ 0.9
<b>Hip (°)</b>	-1.4 $\pm$ 0.8	-1.4 $\pm$ 0.9	-1.6 $\pm$ 0.9	1.6 $\pm$ 1.1	-0.4 $\pm$ 1.0	0.3 $\pm$ 1.1
<b>Pelvis (flexion) (°)</b>	-13.4 $\pm$ 2.1		-8.7 $\pm$ 2.5		-9.2 $\pm$ 2.5	
<b>Trunk (flexion) (°)</b>	0.2 $\pm$ 0.8*		2.7 $\pm$ 0.9		3.7 $\pm$ 1.0*	
<b>Trunk (lateral flexion) (°)</b>	0.1 $\pm$ 0.5		0.8 $\pm$ 0.5		0.3 $\pm$ 0.6	

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 371 \* indicates a  $p < 0.05$  between the able-bodied and the transtibial groups

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384 **Table 3.** Standing balance parameters for the able-bodied subjects, transfemoral and transtibial

	<b>Able-bodied</b>	<b>Transfemoral</b>	<b>Transtibial</b>
<b>CoP AP (mm)</b>	60.9 ± 13.0 <sup>†</sup>	44.6 ± 11.7 <sup>†‡</sup>	63.3 ± 17.3 <sup>‡</sup>
<b>CoP ML (mm)</b>	-10.5 ± 11.3 <sup>†</sup>	-38 ± 23.5 <sup>†‡</sup>	-18.5 ± 9.0 <sup>‡</sup>
<b>Range AP (mm)</b>	28.0 ± 7.0	42.4 ± 14.6	39.4 ± 16.7
<b>Range ML (mm)</b>	19.0 ± 10.7 <sup>*</sup>	47.5 ± 20.2 <sup>*</sup>	45.3 ± 16.8 <sup>*</sup>

385 amputees. means ± standard deviation

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<b>Speed AP (mm/s)</b>	2.7 ± 0.7	3.4 ± 1.6	3.3 ± 1.5
<b>Speed ML (mm/s)</b>	1.1 ± 0.5	1.7 ± 0.7	1.7 ± 0.6
<b>Area (mm<sup>2</sup>)</b>	143.8 ± 76.4 *	771.4 ± 122.9 *	636.6 ± 130.3 *
<b>Tz RMS (Nm/kg)</b>	0.009 ± 0.033	0.106 ± 0.038	0.022 ± 0.040

387 \* indicates a  $p < 0.05$  between able-bodied and both amputee groups

388 † indicates a  $p < 0.05$  between transfemoral and able-bodied groups

389 ‡ indicates a  $p < 0.05$  between transfemoral and transtibial groups

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396 **Table 4.** Loading factors of the first and second principal components (PC1/PC2) of the able-  
 397 bodied subjects, transfemoral and transtibial amputees. Bold text indicates loading factors above  
 398 0.7

	PC1/PC2	Able-bodied		Transfemoral		Transtibial	
		Dominant	Non-dominant	Non-amputated	Amputated	Non-amputated	Amputated
<b>Ankle</b>	PC1	<b>-0.708</b>	-0.035	-0.015	-0.048	0.176	0.055
	PC2	0.142	-0.180	0.217	<b>-0.842</b>	0.286	-0.237
<b>Knee</b>	PC1	<b>0.854</b>	0.592	-0.687	-0.063	-0.251	<b>-0.897</b>
	PC2	-0.082	0.255	0.101	-0.013	<b>-0.823</b>	-0.269
<b>Hip</b>	PC1	<b>0.908</b>	<b>0.885</b>	-0.339	0.277	0.038	<b>-0.702</b>



	PC2	-0.099	0.006	0.227	0.075	-0.513	-0.163
Pelvis flexion	PC1	0.095		0.163		<b>-0.882</b>	
	PC2	-0.339		0.517		0.147	
Trunk (flexion)	PC1	0.109		-0.115		0.160	
	PC2	-0.121		0.097		0.033	
Trunk (lateral flexion)	PC1	<b>0.927</b>		0.303		0.081	
	PC2	<b>0.760</b>		0.440		<b>0.895</b>	
CoP AP	PC1	-0.012		-0.213		0.215	
	PC2	-0.130		0.039		-0.215	
CoP ML	PC1	0.355		<b>-0.858</b>		0.112	
	PC2	-0.091		-0.092		<b>0.817</b>	
Range AP	PC1	-0.166		0.410		0.673	
	PC2	<b>0.829</b>		0.530		0.526	
Range ML	PC1	0.093		<b>0.775</b>		0.460	
	PC2	<b>0.913</b>		0.322		0.572	
Speed AP	PC1	-0.450		0.034		<b>0.865</b>	
	PC2	0.674		<b>0.865</b>		0.364	
Speed ML	PC1	-0.311		0.299		<b>0.748</b>	
	PC2	<b>0.789</b>		<b>0.783</b>		0.623	
Area	PC1	-0.102		0.500		0.381	
	PC2	<b>0.916</b>		0.601		0.471	

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<b>Tz</b>	PC1	0.568	<b>0.958</b>	-0.422
	PC2	0.588	0.120	-0.064

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400 **Captions to illustrations**

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402 **Figure. 1** Schematic representation of the trunk, pelvis, hip, knee and ankle and the  
403 corresponding trunk and joint sagittal angles.

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405 **Figure. 2** Eigenvalues of the first 8 principal component of the able-bodied subjects (AB), and  
406 the transfemoral (TF) and the transtibial (TT) amputees.