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6 The effects of walking speed on minimum toe clearance and on the temporal
7 relationship between minimum clearance and peak swing foot velocity in unilateral
8 trans-tibial amputees.

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19

20 Abstract

21 *Background:* Minimum toe clearance is a critical gait event because it coincides with
22 peak forward velocity of the swing-foot, and thus there is an increased risk of tripping
23 and falling. Trans-tibial amputees have increased risk of tripping compared to able-
24 bodied individuals. Assessment of toe clearance during gait is thus clinically
25 relevant. In able-bodied gait, minimum toe clearance increases with faster walking
26 speeds and it is widely reported there is synchronicity between when peak swing-
27 foot velocity and minimum toe clearance occur. There are no such studies involving
28 lower-limb amputees.

29 *Objectives:* To determine the effects of walking speed on minimum toe clearance
30 and on the temporal relationship between clearance and peak swing foot velocity in
31 unilateral trans-tibial amputees.

32 *Study Design:* Cross-sectional.

33 *Methods:* Ten trans-tibial participants walked at slow, customary and fast speeds.
34 Minimum toe clearance and the timings of minimum toe clearance and peak swing-
35 foot velocity were determined and compared between intact- and prosthetic-sides.

36 *Results:* Minimum toe clearance was reduced on the prosthetic-side and, unlike on
37 the intact-side, did not increase with walking speed increases. Peak swing-foot
38 velocity consistently occurred (~ 0.014 s) after point of minimum toe clearance on
39 both limbs across all walking speeds, but there was no significant difference in the
40 toe-ground clearance between the two events.

41 *Conclusions and Clinical Relevance:*

42 The lack of increase in minimum toe clearance on the prosthetic-side at higher
43 walking speeds may potentially increase risk of tripping. Findings also indicate that
44 determining the instant of peak swing-foot velocity will also consistently identify
45 when/where minimum toe clearance occurs.

46 **Keywords:** Unilateral trans-tibial amputee, Gait, Gait events, Toe clearance,
47 Walking speed

48

49 Background

50 Minimum toe clearance (MTC) during overground walking is defined as the local
51 minimum in separation between the ground and the toes region of the forwards
52 swinging foot. The risk of tripping, which is the predominant cause of falls during
53 ambulation,¹ is highest at the point of MTC.² This results from a combination of the
54 proximity of the swing-foot to the ground, the high velocity of the swinging foot and
55 the forward-travelling centre of mass being in front of the base of support.³ Swing-
56 foot velocity will increase with increasing walking speed and previous research has
57 shown MTC increases at faster walking speeds⁴ increasing safety margins between
58 the foot and the floor. The instant of peak forwards velocity of the swinging foot
59 (PFV) has been reported to coincide with MTC³ although empirical data to support
60 this assertion were not presented. Numerous published studies allude to this
61 previous study^{2, 5, 6} but, as with the original study, they do not present supporting
62 data. No previous studies have investigated whether the relationship between PFV
63 and MTC is affected by changes in walking speed. Nor have they investigated
64 whether the relationship between PFV and MTC in unilateral trans-tibial amputee
65 (UTA) gait is the same as it is in able-bodied gait or whether instead UTAs display
66 differing temporal relationships between PFV and MTC on the intact- and prosthetic-
67 limbs.

68 UTAs have been shown to have a higher risk of falls than age-matched, able-bodied
69 controls.^{7, 8} This increased risk may partly be due to having lower MTC on the
70 prosthetic- compared to intact-side⁹⁻¹¹ and/or exhibiting increased MTC variability on
71 both the intact- and prosthetic-limbs.¹⁰ UTAs have altered gait kinematics and
72 kinetics (when compared to able-bodied individuals) due to the mechanical
73 constraints imposed on them by their prosthesis.¹²⁻¹⁴ These constraints result in

74 reduced walking speeds and increased inter-limb asymmetry compared to able-
75 bodied individuals.¹⁵ Furthermore, the compensatory intact-limb stance-phase power
76 generation at the hip and ankle increase with increases in speed.¹⁶ As a result of
77 such asymmetries and/or compensatory biomechanical adaptations the synchronicity
78 between PFV and MTC reported (assumed) in able-bodied gait may not be present
79 in UTAs.

80 The primary aim of the present study was to determine the effects of changes in
81 walking speed on intact- and prosthetic- limb MTC in UTAs during overground
82 ambulation. A secondary aim was to establish whether PFV was synchronous with
83 MTC for the intact- and prosthetic- limbs and if the level of synchronicity was affected
84 by changes in walking speed.

85

86 Methods

87 Ten physically active male UTAs (mean \pm SD age; 48 ± 11.7 years, mass; 86 ± 17.7
88 kg, height; 1.78 ± 0.06 m) took part, each giving written informed consent prior to
89 their involvement. All had undergone amputation at least two years prior to
90 participation (mean 10.8 ± 12.4 years, range 2 to 43 years) and all had used their
91 current prosthesis for at least six months (mean 1.6 ± 1.2 years). All participants
92 habitually used an *Esprit* foot (Chas. A. Blatchford and Sons Ltd., Basingstoke,
93 UK). The study was conducted in accordance with the tenets of the Declaration of
94 Helsinki and approval was gained from the Institutional Committee for Ethics in
95 Research.

96

97 Kinematic and ground reaction force (GRF) data were recorded at 100 Hz and 400
98 Hz respectively using an eight camera motion capture system (Vicon MX, Oxford,
99 UK) and two force platforms (surface area, 508 mm x 464 mm, AMTI, MA, USA)
100 while participants completed overground walking trails along a flat and level, 8 m
101 walkway. The force platforms were situated side-by-side approximately half way
102 along the walkway, i.e. approximately 4 m from where participants initiated gait to
103 begin the trial. Trials were completed at three different speed levels: customary,
104 'slow' and 'fast'. Due to the methodological limitations associated with speed-
105 controlled studies and the difficulty in generalising findings from such studies to the
106 natural environment¹⁷ we decided not to control walking speed. Instead participants
107 were instructed to walk "at their normal walking speed", "slowly" and "as fast as
108 comfortably possible". Participants completed trials at each speed until 20 'clean'
109 contacts with either force platform had been made with each foot (20 trials x 3
110 speeds x 2 limbs = 120 PFV/MTC events). A 'clean' contact was defined as one
111 where the entire foot was placed onto a force platform without any visible targeting or
112 change in step length or cadence. Only MTC events which occurred while the
113 contralateral foot was in contact with one of the force platforms were used in
114 subsequent analyses. We focussed our analysis on gait cycles occurring over the
115 platform as this ensured participants were walking at a steady state walking speed
116 when MTC was determined. This was important because of the analysis of speed
117 effects.

118 During data collection, participants wore their own flat-soled shoes and 'lycra' shorts.
119 Spherical, retro-reflective markers were placed bilaterally over the acromion
120 processes, iliac crests, greater trochanters, medial and lateral femoral condyles,
121 medial and lateral malleoli, heel, medial and lateral aspect of the mid-foot, first and

122 fifth metatarsal heads and above the second toe (and corresponding locations on the
123 prosthetic-limb). Markers were also placed on the sternal notch, xiphoid process, C7
124 and T8 vertebrae. A headband was used to mount 4 head markers, and plate-
125 mounted 4-marker clusters were worn on the thighs and shanks, whilst a skin-
126 mounted 4-marker cluster was attached about the sacrum. Following 'subject'
127 calibration the acromion, knee and ankle markers were removed.

128 Labelling and gap filling of marker trajectories were undertaken within Workstation
129 software (Vicon, Oxford, UK). The resultant C3D files were then exported to Visual
130 3D motion analysis software (C-Motion, Germantown, MD, USA), where a nine
131 segment 6DoF model of each participant¹⁸ was constructed. More details regarding
132 the data collection and processing methodology can be found in our earlier report.¹⁹
133 Virtual landmarks were created at the antero-inferior endpoint of both shoes (shoe-
134 tip) and embedded within the local coordinate system of each foot.^{10, 20} Kinematic
135 and GRF data were filtered using a fourth order, zero-lag Butterworth filter with a 6
136 Hz cut-off. Initial contact (IC) and toe-off (TO) were defined as the instants the
137 vertical component of GRF first went above or below 20 N respectively. Due to
138 equipment failure there were no GRF data recorded for two participants therefore for
139 these IC and TO were defined using kinematic data: IC was defined as the instant of
140 contralateral limb peak hip extension²¹ and TO as the instant of peak posterior
141 displacement of the ipsilateral toe marker relative to the pelvis.²² Swing phase was
142 defined from the instant of TO until ipsilateral IC.

143 The following parameters were determined: The instants of intact- and prosthetic-
144 limb PFV; the instants of intact- and prosthetic- limb MTC; toe-ground clearance at
145 intact- and prosthetic- limb PFV and MTC. The instant of PFV was defined as the
146 point of maximal velocity in the direction of travel (A/P) of the foot-segment centre of

147 mass during swing; and was determined automatically within Visual 3D. The instant
148 of MTC was defined as the point of the local minimum of the vertical component in
149 shoe-tip trajectory during mid-swing; and was determined manually by examining the
150 shoe-tip trajectory of each trial (see Figure 1). We used this 'manual' approach to
151 ensure the local minima in toe-ground clearance that occur at or just after TO would
152 not be identified in error; which might have been the case if we had determined MTC
153 automatically. Toe-ground clearance values at PFV and MTC were determined as
154 the height of shoe-tip above the ground at each event.

155

156 Statistical analysis

157 A "Limits of Agreement" (LOA) analysis²³ and 95 % confidence intervals established
158 agreement between the instants of when PFV and MTC events occurred. This
159 analysis determined the mean positive or negative temporal difference (bias)
160 between the timings of the two events (agreement) and also the period of time
161 before or after MTC in which 95 % of PFV events occurred (precision/repeatability).
162 The normality (or otherwise) of the data was determined using a Shapiro-Wilk test.
163 Toe-ground clearances were compared using repeated measures ANOVA with limb
164 (prosthetic, intact), event, (PFV, MTC) and speed level (slow, customary, fast) as
165 between factors. Post hoc analyses were conducted using a Tukey HSD test. The
166 alpha level was set at 0.05.

167

168 Results

169 Mean walking speeds for the slow, customary and fast levels were $0.93 \pm 0.12 \text{ ms}^{-1}$,
170 $1.13 \pm 0.17 \text{ ms}^{-1}$, and $1.36 \pm 0.27 \text{ ms}^{-1}$ respectively (range $0.73 - 1.77 \text{ ms}^{-1}$).

171 In total 1200 PFV and 1200 MTC events (600 each, for intact- and prosthetic-limbs)
172 were analysed. Data were normally distributed ($p > 0.05$).

173

174 *Speed-related alterations in minimum toe clearance*

175 Minimum toe clearance was significantly affected by walking speed ($p = 0.011$) so
176 that clearances at the fast speed were significantly higher than those at the slow
177 speed ($p = 0.010$); though a speed-by-limb interaction ($p = 0.004$) indicated that only
178 the speed-related increases on the intact-limb were significant (table 1). There were
179 no significant differences in the toe-ground clearance values at MTC and PFV across
180 all speeds ($p = 0.38$). Minimum toe clearance was significantly lower ($p < 0.001$) on
181 the prosthetic-limb and post-hoc analysis indicated that differences between limbs
182 were significant at all speeds (slow; $1.11 \pm 0.69 \text{ cm}$, customary; $1.09 \pm 0.68 \text{ cm}$, fast;
183 $1.10 \pm 0.64 \text{ cm}$) compared to the intact-limb (slow; $2.28 \pm 0.87 \text{ cm}$, customary; $2.52 \pm$
184 0.90 cm , fast; $2.57 \pm 0.85 \text{ cm}$).

185

186 *Synchronicity in PFV and MTC*

187 The agreement (synchronicity) between the timing of PFV and MTC at each walking
188 speed level, and the average agreement across all speeds, are shown for the intact
189 and prosthetic limbs in Table 1. On the intact-limb, PFV occurred $0.015 \pm 0.011 \text{ s}$
190 after MTC, and the 95 % LOA between PFV and MTC was $- 0.037 \text{ s}$ to $+ 0.006 \text{ s}$. On

191 the prosthetic-limb, PFV occurred 0.012 ± 0.010 s after MTC, and the 95 % LOA
192 between PFV and MTC was -0.033 s to $+0.008$ s.

193

194 INSERT TABLE 1

195 INSERT FIGURE 1

196

197 Discussion

198 The aim of the present study was to determine how alterations in walking speed
199 affected MTC in UTAs during overground ambulation. A secondary aim was to
200 establish whether alterations in walking speed affected the temporal relationship
201 between PFV and MTC. The results indicate that MTC increased at higher walking
202 speeds on the intact-limb but was unaffected by changes in speed on the prosthetic-
203 limb. Furthermore, irrespective of limb, there was a small and consistent temporal
204 difference (bias) between when PFV and MTC occurred that was unaffected by
205 walking speed. Finally, the results also indicate that MTC was significantly reduced
206 on the prosthetic- compared to the intact-limb across all speeds.

207 The increase in intact-side toe clearance with increasing walking speed is similar to
208 the speed related increases reported in the able-bodied.⁴ It has been reported
209 previously that some degree of inter-limb asymmetry in toe clearance occurs in older
210 able-bodied adults.²⁶ The authors noted that the inter-limb asymmetry in toe
211 clearance was associated with step time asymmetry, i.e. the limb with the shorter
212 step time and higher swing-foot velocity had higher toe-ground clearance. They
213 suggested that increased safety margins required at faster swing-foot speeds may

214 be driving the asymmetry. Such speed-accuracy considerations cannot explain toe
215 clearance inter-limb asymmetries in UTAs who typically present spatially longer
216 steps on the prosthetic-limb than on the intact-limb as well as higher swing-foot
217 velocities on the prosthetic-side (as highlighted in Figure 1). If speed-accuracy
218 considerations were the primary driver of such differences it would be expected that
219 higher clearances would occur on the prosthetic-side at all walking speeds. The
220 finding (in the present study) that toe-ground clearance on the prosthetic-side did not
221 increase with speed but did on the intact-side indicates that step time/length
222 asymmetry is not the driver of UTA toe clearance asymmetries. The fact that toe-
223 ground clearance increased with speed on the intact-side but not on the prosthetic-
224 side suggests some level of active, central motor control of the swinging foot was
225 present on the intact-limb and absent on the prosthetic-limb. In the present study the
226 magnitude of speed-related changes in toe-ground clearance were around 2 – 3 mm.
227 Only minimal dorsiflexion (~ 1 degree) would be required to affect such changes. It
228 would seem apparent therefore that the active control on the intact-limb occurred at
229 the ankle; which would explain why such control was not evident on the prosthetic-
230 side.

231 The mean temporal difference between when PFV and when MTC occurred was
232 small - approximately 0.014 ± 0.01 s across both limbs and across all speeds. PFV
233 occurred consistently after MTC; indeed only 7 of 1200 PFV events occurred prior to
234 the corresponding MTC event. In other words the temporal relationship between PFV
235 and MTC was unaffected by changes in walking speeds and was the same for both
236 the prosthetic- and intact-sides. This invariance suggests that swing phase inter-
237 segmental coordination is the same for both limbs. It also suggests that during swing
238 the lower limbs act as simple mechanical pendulums, and thus toe-ground clearance

239 is, at least partially, a result of how the entire limb swings about the hip rather than
240 being solely/largely controlled by swing-limb ankle and/or knee flexion. Hence, as
241 well as its relevance to trips and falls, analysis of MTC metrics also provides insights
242 into underlying neural control strategies and coordination patterns.

243 In the study by Winter³ it was highlighted that PFV and MTC were synchronous.
244 However, no empirical data were presented to support this contention, and in
245 addition the sampling rate of the kinematic analysis was not detailed. It is reasonable
246 to infer that the video-based methodology used to collect the kinematic data in
247 Winter's³ study would have been sampled at a lower rate (likely ~ 30 Hz) than that
248 used in the present study. The lower temporal resolution may well have given the
249 appearance of absolute synchronicity (no temporal difference) between PFV and
250 MTC. The present study, which used a sampling rate of 100 Hz, demonstrated that,
251 MTC occurs, on average, slightly (i.e. just over one sampling frame) before PFV.
252 This small but consistent temporal offset between PFV and MTC likely explains the
253 slight (non-significant) difference in toe-ground clearance between each event (Table
254 1). It is important to emphasise that the temporal relationship between PFV and MTC
255 (PFV consistently occurring after MTC) was invariant across limbs and across
256 walking speeds. Furthermore, although there was no significant difference in the toe-
257 ground clearance values at PFV and MTC, toe-ground clearance was on average 1
258 – 2 mm higher at PFV than at MTC. We thus suggest that when adopting the
259 approach of using PFV to identify the instance of when minimum toe clearance
260 occurs, an off-set of + 0.014 s should be applied. That is, once instant of PFV is
261 identified, the toe-ground clearance value 0.14 seconds sooner in swing should be
262 determined as the point of minimum toe clearance.

263

264 The significantly lower clearance on the prosthetic-side compared to the intact-side
265 corroborates previous findings.⁹⁻¹¹ In a current sister study, we argue that the
266 differences in MTC between the intact- and prosthetic-limb is mainly due to having
267 greater intact-limb MTC (compared to values reported in the literature for able-
268 bodied individuals) rather than the prosthetic-limb having reduced MTC.¹¹ Having
269 greater clearance on the intact-side is likely to be, at least to some extent, a result of
270 UTAs typically presenting reduced residual-knee flexion during the loading-response
271 of early stance,^{11, 24, 25} which would raise the height of the swing-limb hip. While
272 reduced stance-phase residual-knee flexion likely contributed, in the present study,
273 to the differences in MTC between sides it is important to note that prosthetic-limb
274 MTC (~1.1cm) is lower than that previously reported for able-bodied adults (1.8 - 1.9
275 cm),^{27,28} and is also slightly lower than what we report (in our sister study) for the
276 prosthetic-limb in a larger group of amputees (1.9 cm).¹¹ In the current study all
277 amputees used the same type of prosthetic foot (Esprit), whereas in our other
278 study¹¹ participants used a range of foot types. This suggests that the type of
279 prosthetic foot, and, perhaps more particularly, the way it is set-up will have a
280 bearing on prosthetic-limb MTC. Indeed, in our other study we show that prosthetic-
281 limb MTC is increased when participants switched from using their habitual
282 prosthetic foot to using a foot with a hydraulically articulating attachment that allowed
283 the foot to be relatively dorsiflexed at toe-off and throughout swing.¹¹

284

285 Conclusions

286 The lack of walking speed related toe-ground clearance changes on the prosthetic-
287 side may potentially increase UTAs' risk of tripping at faster walking speeds. The

288 lack of change on the prosthetic-side (but increase in toe clearance with speed on
289 the intact-side) also suggests that speed-related modulation of toe-ground clearance
290 for an intact-limb typically occurs at the ankle. The timing of when PFV occurred was
291 virtually synchronous with MTC. The consistent and minimal temporal difference
292 between the two events was invariant across speed levels and across limbs. This
293 temporal consistency suggests both lower-limbs act as simple mechanical
294 pendulums during swing. Finally, the consistent and minimal temporal differences
295 between events, regardless of speed and limb, indicates that identifying the instant
296 of peak swing-foot velocity could be implemented in automated processing
297 procedures to determine the point of minimum toe clearance.

298

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301 **Conflicting Interests:** The authors declare that there is no conflict of interest.

302

303

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386 Table 1. Mean (SD) walking speeds, temporal difference between PFV and MTC
 387 events, and toe-ground clearance at PFV and MTC.

Walking speed (ms ⁻¹)		Temporal difference* (s)	Range (s)	95% Levels of Agreement (s)	Toe clearance @ PFV (cm)	Toe clearance @ MTC (cm)
Overall	Intact	-0.015 (0.011)	-0.04 / +0.01	-0.037 / +0.006	2.65 (0.76)	2.46 (0.87)
	Pros	-0.012 (0.010)	-0.04 / +0.05	-0.033 / +0.008	1.21 (0.71)	1.10 (0.66)
Slow 0.93 (0.12)	Intact	-0.015 (0.011)	-0.05 / 0	-0.037 / +0.006	2.49 (0.78)	2.28 (0.87)
	Pros	-0.012 (0.010)	-0.04 / +0.03	-0.031 / +0.007	1.22 (0.73)	1.11 (0.69)
Customary 1.13 (0.17)	Intact	-0.015 (0.011)	-0.04 / 0	-0.038 / +0.007	2.70 (0.79)	2.52 (0.90)
	Pros	-0.011 (0.011)	-0.04 / +0.05	-0.033 / +0.010	1.20 (0.71)	1.09 (0.68)
Fast 1.36 (0.27)	Intact	-0.016 (0.010)	-0.04 / +0.01	-0.036 / +0.005	2.77 (0.74)	2.57 (0.85)
	Pros	-0.014 (0.011)	-0.04 / +0.02	-0.035 / +0.007	1.22 (0.74)	1.10 (0.64)

388 *All temporal differences were significant ($p < 0.001$).

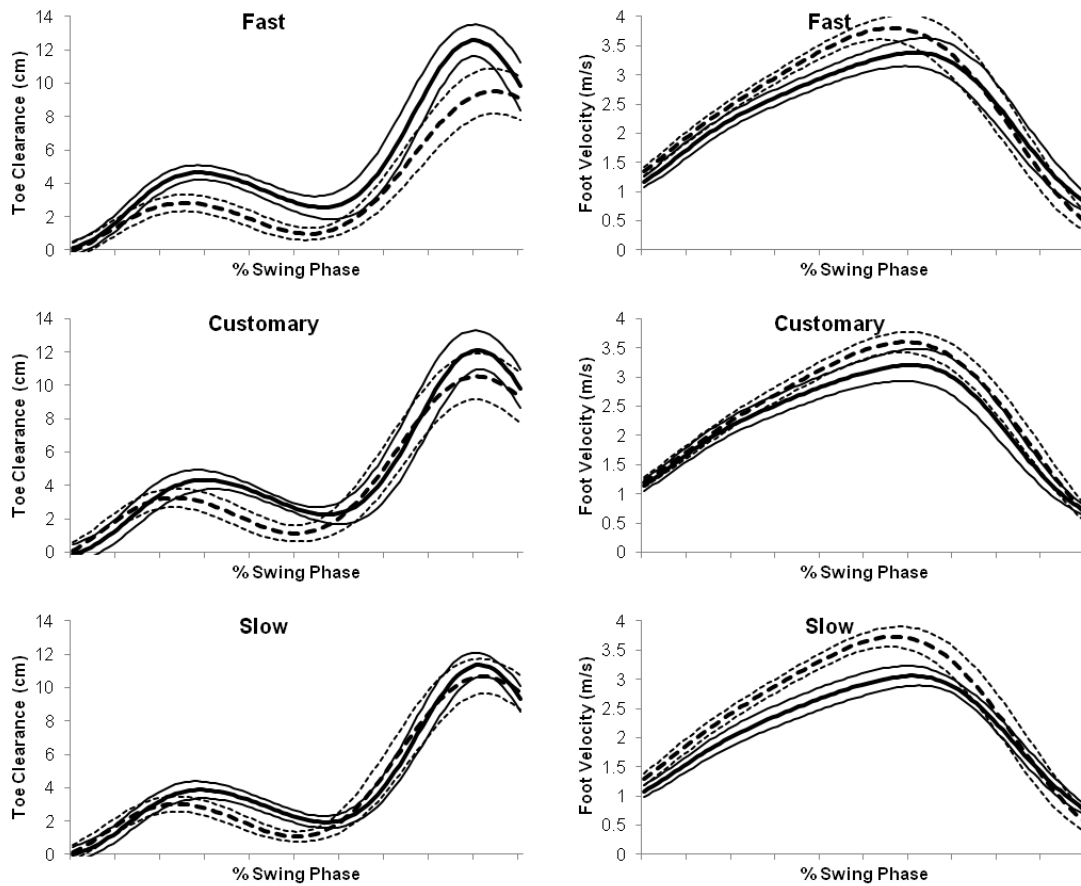
389 A negative temporal difference indicates PFV occurred after MTC.

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395 Figure 1. Ensemble Mean \pm SD swing phase vertical toe trajectory (left-hand column)
 396 and A/P foot velocity (right-hand column) for the intact- (solid lines) and prosthetic-
 397 (dashed lines) limbs for one participant at slow, customary and fast walking speeds.

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