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2
3 Alternative measures of toe trajectory more accurately predict the probability of tripping than
4 minimum toe clearance

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28

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33 **Abstract**

34

35 Tripping is responsible for a large percentage of falls. Minimum toe clearance (MTC) during the
36 swing phase of gait is commonly used to infer the probability of tripping (POT). However, there
37 is limited empirical evidence to support the relationship between these two variables, and other
38 measures of toe trajectory may better predict POT than MTC. The goals of this study were to: 1)
39 quantify the relationship between MTC and POT; and 2) explore alternative measures of toe
40 trajectory that may predict POT more accurately than MTC. POT was estimated by comparing
41 the distribution of tripping obstacles measured along heavily-used, paved sidewalks on a
42 university campus, to the toe trajectory of 40 young adults obtained while walking over an
43 obstacle-free walkway in a research laboratory. POT exhibited a curvilinear relationship with
44 MTC, and regression equations were established to predict POT from MTC. POT was more
45 accurately predicted when using virtual points on the bottom of the anterior edge of the shoe to
46 determine MTC, compared to using a physical marker located on top of the toes to determine
47 MTC. POT was also more accurately predicted when using a new measure of toe trajectory (the
48 area below 40mm and above the toe trajectory, normalized by the swing length), compared to
49 just MTC. These are the first empirical results supporting a direct, quantitative relationship
50 between MTC and POT. These results may improve the ability to identify risk factors that
51 influence POT, and aid in developing interventions to reduce POT.

52 **1. Introduction**

53 Tripping is responsible for 23-32% of falls among workers (Amandus et al., 2012; Lipscomb et
54 al., 2006), and 35-53% of falls among older adults (Berg et al., 1997; Blake et al., 1988).

55 Tripping occurs when foot motion during the swing phase of gait is impeded by an obstacle or an
56 abrupt change in elevation of the walking surface. Researchers commonly use minimum toe
57 clearance (MTC) during swing to infer the probability of tripping (POT) (Barrett et al., 2010;
58 Garman et al., 2015; Schulz, 2011; Thies et al., 2015). MTC is determined from the toe
59 trajectory during swing, and is the lowest height above the walking surface near mid-swing
60 (Winter, 1991). It is generally accepted that a decrease in mean/median MTC, or an increase in
61 MTC variability, infers an increase in POT due to less clearance over obstacles or abrupt changes
62 in elevation (Barrett et al., 2010; Begg et al., 2007).

63
64 Despite the general acceptance of MTC as a measure to infer POT, there is limited empirical
65 evidence to support this relationship. Only three studies to our knowledge have reported an
66 association between MTC and retrospectively reported falls (Gehlsen and Whaley, 1990;
67 Khandoker et al., 2008a; Khandoker et al., 2008b). While two of three of these studies reported
68 differences in mean/median MTC (Khandoker et al., 2008b) or MTC variability (Khandoker et
69 al., 2008a; Khandoker et al., 2008b) between fallers and non-fallers, no studies to our knowledge
70 have demonstrated a quantitative predictive relationship between MTC and POT. In fact, it
71 could be argued that MTC is limited in its ability to predict POT given that it only quantifies toe
72 height at one instant during swing, though a trip obstacle could be present at any point during
73 swing (Figure 1). A measure of toe trajectory that incorporates more of the swing phase toe
74 trajectory may predict POT more accurately than MTC.

75

76

Insert Figure 1 about here

77

78 The goals of this study were to: 1) quantify the relationship between MTC and POT; and 2)
79 explore alternative measures of toe trajectory that may predict POT more accurately than MTC.
80 Prior to addressing these goals, two intermediate steps were completed. First, we developed a
81 method to calculate POT so that its relationship with MTC could be determined, and for use as a
82 basis for comparison between alternative measures of toe trajectory. Second, we determined
83 how the choice of location on the shoe used to determine toe trajectory, and hence MTC,
84 influenced the accuracy of predicting POT. We hypothesized that: 1) the ability to predict POT
85 from MTC would differ based upon the location on the shoe that was used to determine the toe
86 trajectory; 2) measures of the toe trajectory that incorporated more of the swing phase would
87 better predict POT than just MTC.

88

89 **2. Methods**

90 To estimate POT, it was necessary to obtain a realistic distribution of tripping obstacles. We
91 measured the number and height of abrupt changes in elevation (not including intentional
92 changes in elevation such as a curb) along 2.1 km (2,695 steps by AGB) of heavily-used, paved
93 sidewalks on a university campus. These obstacles were measured using a 10-cm ruler
94 positioned horizontally on top of the obstacle, and a second ruler positioned vertically and
95 resting at the base of the obstacle. Obstacle height was then measured using the vertical ruler.
96 Only obstacles ≥ 6 mm in height were recorded to be consistent with ASTM F 1637 (ASTM,
97 2013), which is an accepted international safety standard specifying that abrupt changes in

98 walkway elevation less than 6 mm do not require remediation (implying an acceptably low
99 potential to cause a trip).

100

101 To estimate POT, it was also necessary to obtain toe trajectory data during gait. These data were
102 obtained inside our research lab, rather than outdoors over the same sidewalk from which we
103 measured obstacle heights, due to equipment limitations and difficulty determining toe height
104 outdoors. Further, changes in gait due to visible obstacles (Begg et al., 2007; Schulz, 2011) and
105 experiencing a trip (Pavol et al., 1999; Schulz, 2011) would limit applicability to natural gait
106 without a recognized threat of a trip, which was the focus of this study.

107

108 Subjects involved in gait testing included 40 young adults (18-30 years; 20 men) without any
109 self-reported conditions that affected their gait. The lab study was approved by the local
110 Institutional Review Board, and all subjects provided informed consent prior to participating.
111 Subjects wore the same model of low-top walking shoe (Levi's® Jeffrey Denim) with a flat sole
112 and low rocker angle (Figure 2). Before gait testing began, subjects stood in the middle of the
113 walkway, near where MTC was subsequently measured, and lightly touched the bottom of the
114 anterior edge of the right shoe to the ground. The lowest vertical coordinate among the virtual
115 markers on the right shoe during this trial established the level of the walkway surface. Ten gait
116 trials were then completed during which subjects walked at a self-selected speed along a 10 m
117 laboratory walkway. Reflective markers were attached bilaterally over the lateral malleoli, and
118 on both shoes at the heel, toe, and lateral aspect (Figure 2). Marker positions were sampled at
119 100 Hz using an 8-camera motion capture system (Qualisys AB, Göteborg, Sweden), and low-
120 pass filtered at 10 Hz (second-order Butterworth filter). One swing phase (i.e., toe off to heel

121 strike, identified using the method of (Zeni et al., 2008)) from each foot was isolated from each
122 trial for analysis. Only one swing phase from each foot was analyzed from each trial because our
123 walkway was not perfectly level (variations on the order of 1 cm over the entire 10 m), and we
124 only wanted to determine MTC near the “toe-tap” that we used to define floor level. Virtual
125 markers along the bottom of the anterior edge of the shoe (Figure 2) were defined within a shoe-
126 fixed coordinate system (Startzell and Cavanagh, 1999). All data processing and computations
127 for calculating POT (described below) were performed using custom-written software in Matlab
128 (Mathworks, Inc., Natick, MA).

129

130 Insert Figure 2 about here

131

132 Three methods were used to generate three separate sagittal plane toe trajectories during swing.
133 Investigating three methods allowed us to evaluate the potential trade-off between sophistication
134 during data collection/processing, and the accuracy of POT predictions. The first toe trajectory
135 was of the physical toe marker, and was considered the least sophisticated method of
136 determining toe trajectory. The second toe trajectory was of the *single* anterior-most virtual
137 marker on the shoe that was preselected before data collection, and was considered a moderate
138 level of sophistication because it required using a shoe-fixed coordinate system to predict the
139 position of a single virtual marker on the shoe. The third toe trajectory was of the *instantaneous*
140 anterior-most virtual marker on the shoe within each sampled frame of marker data, and was
141 considered the highest level of sophistication because it required using a shoe-fixed coordinate
142 system to predict the position of multiple virtual markers, and the need to determine the anterior-
143 most of these virtual marker at each instant. MTC was defined as the minimum height of the

144 trajectory after the first maximum in toe height (Nagano et al., 2011), and was identified using
145 zero-crossings of the first derivative of the vertical coordinate of the trajectory. MTC was
146 determined from each of the three trajectories, and yielded $MTC_{Physical}$, MTC_{Pre} , and $MTC_{Instant}$,
147 respectively (Figure 3). Prior work has also used multiple locations on the shoe/sole to
148 determine MTC (Thies et al., 2011). Unlike this prior study, our method only considered
149 locations on, and therefore obstacles impacting, the “leading edge” of the shoe. We did not
150 consider a trip to have occurred when an obstacle would have contacted the bottom sole of the
151 shoe. While contact with the bottom of the sole can interrupt foot motion and result in a trip, we
152 elected to not consider them due to greater difficulty in predicting the extent to which swing foot
153 motion would be altered by the largely tangential contact between an obstacle and the bottom
154 surface of the shoe.

155
156 Insert Figure 3 about here
157

158 POT was determined for each swing phase using the toe trajectory of the instantaneous anterior-
159 most virtual marker. We chose to use this trajectory, rather than the other two trajectories,
160 because it was felt that it most closely matched how trips actually occur (an obstacle impacting
161 the instantaneous anterior-most point on the shoe). First, the swing phase was segmented into 1
162 mm increments in the anterior-posterior direction. At each 1 mm increment, the distribution of
163 obstacle heights was compared to the toe trajectory height, and the total number of trips that
164 would have occurred was determined (a trip was assumed to have occurred if the obstacle height
165 exceeded the vertical component of the toe trajectory). This process was repeated at each 1 mm
166 increment throughout the trajectory. Second, POT was calculated as the quotient of the total

167 number of trips and the total number of comparisons. From this, POT was the percentage of
168 swing phases that would have resulted in a trip, given the distribution of obstacles that we
169 measured over 2,695 steps. Scatterplots were generated between the three MTC values and POT
170 to visualize these relationships. Transformations were explored in an attempt to find linear
171 relationships between MTC and POT that most accurately predicted POT (as inferred by the
172 smallest standard error of estimate: SEE), while also favoring models and transformations that
173 resulted in reasonably uniform residuals.

174
175 Sixteen alternative measures of toe trajectory were also explored and compared in their ability to
176 predict POT. These alternative measures were developed based upon intuition and a desire to
177 include more of toe trajectory, and are listed and illustrated in the online supplementary material.
178 The measure that exhibited the smallest SEE with reasonably uniform residuals was the area
179 below a 40mm “threshold” and above the toe trajectory, normalized by the length (i.e. distance)
180 of swing (Figure 4). This area represents the mean distance of the toe trajectory below 40 mm
181 (MD40). All of these alternative measures used the toe trajectory of the instantaneous anterior-
182 most virtual marker. As with MTC, transformations were explored for each alternative measure
183 to find the linear relationship that best predicted POT (smallest SEE) with reasonably uniform
184 residuals.

185

186 Insert Figure 4 about here.

187

188 **3. Results**

189 Thirty-five obstacles ranging in height from 6 to 29 mm were measured from the sidewalk, with
190 a median (interquartile range) of 11 (11) mm (Figure 5). POT for each swing phase ranged from
191 0.2-0.8%, indicating that a trip is expected to occur once every 125-500 steps during natural gait
192 (e.g., without any expectation of a trip) and given the measured distribution of obstacles. All
193 three MTC values exhibited a curvilinear relationship with POT (Figure 6), and a cube-root
194 transformation of POT resulted in the lowest SEE for the linear relationships we explored.
195 Among the three MTC values, $MTC_{Instant}$ exhibited the lowest SEE (0.046%), while $MTC_{Physical}$
196 exhibited the highest SEE (0.085%) when predicting POT. $MTC_{Instant}$ across all subjects and all
197 trials had a mean \pm standard deviation of 12.8 ± 6.9 mm with a skewness of 0.81, and a median
198 (interquartile range) of 11.7 (8.3) mm. Among the 16 alternative measures explored, MD40
199 most accurately predicted POT based upon a SEE of 0.029%, which was 37% lower than
200 $MTC_{Instant}$, and the lowest of all alternative measures that exhibited reasonably uniform residuals
201 (Figure 7 and supplementary material).

202

203 Insert Figure 5 about here

204 Insert Figure 6 about here

205 Insert Figure 7 about here

206

207 **4. Discussion**

208

209 The first goal of this study was to quantify the relationship between MTC and POT. Prior to
210 addressing this goal, we determined how the choice of location on the shoe used to determine toe
211 trajectory, and hence MTC, influenced the accuracy of predicting POT. We hypothesized that

212 the ability to predict POT from MTC would differ based upon the location on the shoe that was
213 used. Clear differences were evident (Figure 6), and the toe trajectory (and MTC) derived from
214 the instantaneous anterior-most virtual marker exhibited the best accuracy when predicting POT.
215 However, this method also required the highest level of sophistication during data collection and
216 processing, given the need to predict the position of multiple (20 in this study) virtual markers on
217 the shoe, and to determine the most anterior marker at each frame of analysis. Using the
218 preselected single anterior-most virtual marker on the shoe only increased SEE from 0.046%
219 POT to 0.054% POT, and may thus be more efficient (needing only predictions of the position of
220 a single virtual marker on the shoe). Both methods that used virtual markers along the bottom of
221 the anterior edge of the shoe, however, more accurately predicted POT than using a physical
222 marker placed above the toes. This was likely due to the fact that MTC_{Pre} and $MTC_{Instant}$
223 represent points on the shoe that are the most anterior and inferior on the shoe, and therefore
224 most likely to impact a tripping obstacle. $MTC_{Physical}$ does not predict POT as accurately as these
225 other two methods because the geometric relationship between this marker and the most anterior
226 and inferior point on the shoe (most likely to impact a tripping obstacle), while constant in a
227 shoe-fixed coordinate system, is variable in a global coordinate system, and depends upon the
228 angles of joints in both the swing and stance lower limbs (Winter, 1992).

229

230 The second goal of this study was to explore alternative measures of toe trajectory that may
231 predict POT more accurately than MTC. We hypothesized that measures of toe trajectory that
232 incorporated more of the swing phase would better predict POT than just MTC. Supporting this
233 hypothesis, MD40 predicted POT more accurately than MTC or any other alternative measure.
234 The improved ability of MD40 at predicting POT, which includes the possibility of a trip

235 occurring at any point within swing, was likely due to: 1) including more of the swing phase than
236 just MTC; and 2) not including portions of the toe trajectory when its height is above 40 mm;
237 such portions are inconsequential to POT because no obstacles were above 40 mm in the
238 distribution of obstacles used to calculate POT. The area below a 30mm threshold and above the
239 toe trajectory, normalized by the length of swing (i.e. MD30) exhibited a smaller SEE than
240 MD40, but the residuals were not uniform indicating an undesirable variation in accuracy of
241 prediction within the range of MTC investigated. Interestingly, the area under 40 mm and *under*
242 the toe trajectory did not predict POT as accurately at MD40 (SEE = 0.076%; see supplementary
243 material). This was likely because this area was larger than that in MD40, and was therefore less
244 sensitive to small changes in toe trajectory below 40 mm than the area below 40 mm and above
245 the toe trajectory. Future work involving different distributions of tripping obstacles may need
246 to adjust this 40 mm threshold.

247

248 To accomplish the goals of this study, it was necessary to develop a method to calculate POT to
249 serve as a basis of comparison for MTC and the alternative measures. Our method involved
250 several assumptions and limitations. First, toe trajectory data used to estimate POT were
251 obtained without the threat of an actual tripping obstacle. As such, the POT reported here is
252 most relevant for gait when tripping obstacles are unexpected and unseen. This implicit
253 assumption is also common among studies that use MTC to infer POT. Second, POT was
254 estimated by assuming that the tripping obstacle was equally likely to appear at any anterior-
255 posterior location (within a 1 mm increment) throughout the swing phase. Given the lack of
256 relevant quantitative data indicating otherwise, we considered this a reasonable assumption.
257 Third, we only used the anterior-posterior trajectory of the swing foot, and assume any obstacle

258 would exist within this plane. Fourth, POT values, and the regression models that predict POT
259 from MTC, are specific to the distribution of obstacle heights used to estimate POT. Fifth, we
260 only explored linear relationships between alternative measures and POT (transformed or not
261 transformed) for simplicity, but acknowledge that additional non-linear terms in the regression
262 equation may provide small improvements in accuracy. Sixth, the POT values reported here
263 were for young adults walking over a level surface at a self-selected speed. Care should thus be
264 used when generalizing beyond these conditions and subjects. However, the methods reported
265 here should generalize to other subject populations.

266

267 A logical alternative to our method of calculating POT would be to determine the number of
268 steps and trips while subjects walked along the same outdoors sidewalk over which obstacles
269 were measured. However, this seemingly straightforward approach involves substantial
270 experimental limitations. First, normal variations in ground surface along the outdoor sidewalk
271 (e.g. varying pitch and texture of walking surface) would make it difficult to quantify the height
272 of the toe trajectory accurately. Second, gait is altered after experiencing a trip (Pavol et al.,
273 1999; Schulz, 2011). So if/when a subject experienced a trip, their results could no longer be
274 generalized to typical (unexpected) trips. Third, gait is altered when tripping obstacles are
275 visible (Begg et al., 2007; Schulz, 2011). So after a subject sighted an obstacle (the timing of
276 which could differ between subjects), their results could no longer be generalized to unexpected
277 trips. We thus used an approach that combined an obstacle-free walking surface without the
278 threat of a trip, and a distribution of measured obstacles measured elsewhere, to provide a more
279 robust method and results that are expected to better generalize to unexpected trips.

280

281 Best and Begg (2008) measured the toe trajectory of a subject walking on a treadmill and used
282 statistical modeling to predict POT from MTC for a single swing phase, *assuming a tripping*
283 *obstacle was present at the same location as MTC* (Best and Begg, 2008). At an obstacle height
284 of 1.2 cm (closest value reported by these authors to the mean $MTC_{Instant}$ of 1.28 cm found here),
285 they predicted a trip to occur every 1.24 steps, or during 80.6% of steps. This method of
286 calculating POT (assuming a tripping obstacle to be present at the same location as MTC)
287 differed from our method, in that the POT we report represented the percentage of steps with
288 identical toe trajectory that would have resulted in a trip over 2,695 steps (2.1 km of sidewalk),
289 given the distribution of tripping obstacles measured (including steps with no obstacle). Our
290 method also accounts for the possibility of a tripping obstacle to be presented at any point over
291 the swing phase, not just at MTC. While both approaches to estimating POT are valuable, the
292 current one incorporates the prevalence of tripping obstacles, and may thereby represent a more
293 ecologically-valid estimation. When predicting POT from $MTC_{Instant} = 1.2$ cm, our method
294 predicts a trip to occur during 0.21% of steps, or one trip every 476 steps. We are able to make a
295 reasonable comparison between the POT reported from both studies if we multiply the 80.6% of
296 steps reported by Best and Begg (2008) by the percentage of 2,695 steps that involved a tripping
297 obstacle greater than 1.2 cm (13 steps out of 2,695 steps = 0.48%). This predicts a trip to occur
298 during 0.39% of steps, or one trip every 256 steps, which is a POT of the same order of
299 magnitude as that reported here. Some level of convergent validity is thus apparent between the
300 two rather distinct approaches. Ultimately, a higher level of predictive validity for the methods
301 developed here will require investigating the association between POT/MD40 and the frequency
302 of tripping during everyday life.
303

304 **5. Conclusion**

305 This study called into question the implicitly-assumed association between MTC and POT held
306 in prior research. A method was developed to calculate POT during gait, and was used to
307 determine the direct, quantitative relationship between MTC and POT. More accurate ways to
308 predict POT from toe trajectory were also investigated. POT was more accurately predicted
309 when using virtual points on the bottom of the anterior edge of the shoe to determine MTC,
310 compared to using a physical marker located on top of the toes to determine MTC. POT was
311 also more accurately predicted when using a new measure of toe trajectory, compared to just
312 MTC. Results from this work may help improve the accuracy of predictions of POT from toe
313 trajectory, which can allow researchers and clinicians to better appreciate the clinical
314 significance of alterations in MTC on POT. It may also improve the ability to identify risk
315 factors that influence POT, and help develop interventions to reduce POT.

316

317 **Conflict of interest statement**

318 The authors have no conflicts of interest to report.

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323

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397 Figure Captions

398 Figure 1. Three sample toe trajectories during the swing phase of gait, illustrating variability
399 between swing trajectories during phases other than the point of MTC. Intuitively, these three
400 trajectories should be associated with different probabilities of tripping, since a tripping obstacle
401 with a height greater than the toe trajectory could be present at any point between toe-off and
402 heel-strike. However, because all three trajectories exhibit the same MTC, all three would be
403 considered to have the same probability of tripping.

404
405 Figure 2. Photograph of the shoes worn by subjects showing the placement of physical markers
406 and virtual markers. The positions of the virtual markers were defined within a shoe-fixed
407 coordinate system defined using the three physical markers shown.

408
409 Figure 3. Sample comparison of the three methods of determining toe trajectory during swing,
410 and the corresponding minimum toe clearance (MTC) for each. MTC_{Phys} and MTC_{Pre} are the
411 trajectories of an individual physical marker and virtual marker on the shoe as described in the
412 text. $MTC_{Instant}$ is the resulting trajectory when using, from each from of the marker data, the
413 coordinate of the most anterior virtual marker.

414
415 Figure 4. Schematic illustrating the calculation of the alternative measures that best predicted
416 the probability of tripping. The alternative measure was calculated as the area below 40 mm and
417 above the toe trajectory, divided by swing length, and is abbreviated as MD40.

418
419 Figure 5. Distribution of tripping obstacles (abrupt changes in elevation) measured along 2,695
420 steps (i.e. 2.1 km) of heavily-used, paved sidewalks on a university campus. Obstacles with
421 heights less than 6 mm were not included.

422
423 Figure 6. Scatterplots illustrating a curvilinear relationship between minimum toe clearance
424 (MTC) and the probability of tripping (POT) (upper row), and regression lines used to predict the
425 cube root of POT from MTC (lower row). When using these regression equations, MTC should
426 be in units of mm, and the solution should be cubed to calculate POT (the percentage of swing
427 phases that would have resulted in a trip, given the distribution of obstacles that we measured).
428 The three columns illustrate differences in the accuracy of predictions when using MTC values
429 derived from the three toe trajectories.

430
431 Figure 7. Scatterplot illustrating the relationship between MD40 (area below 40 mm and above
432 toe trajectory, divided by swing length) and the probability of tripping (POT), including a
433 regression line with necessary transform to achieve a linear relationship and lowest standard
434 error of the estimate.

Figure 1
[Click here to download Figure: F1 - Motivation plot.eps](#)

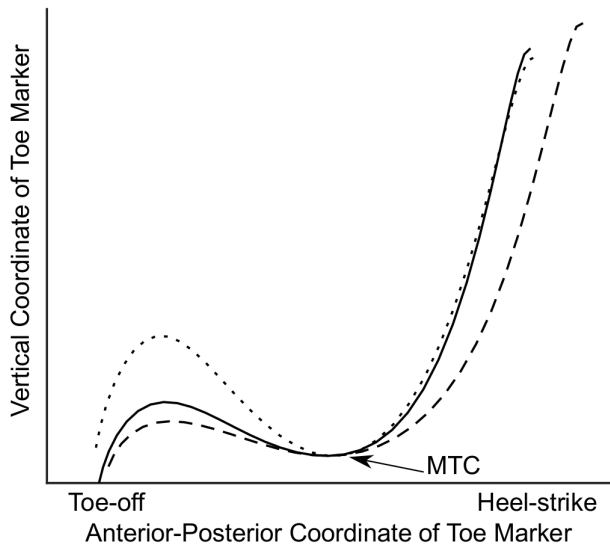


Figure 2
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Figure 3
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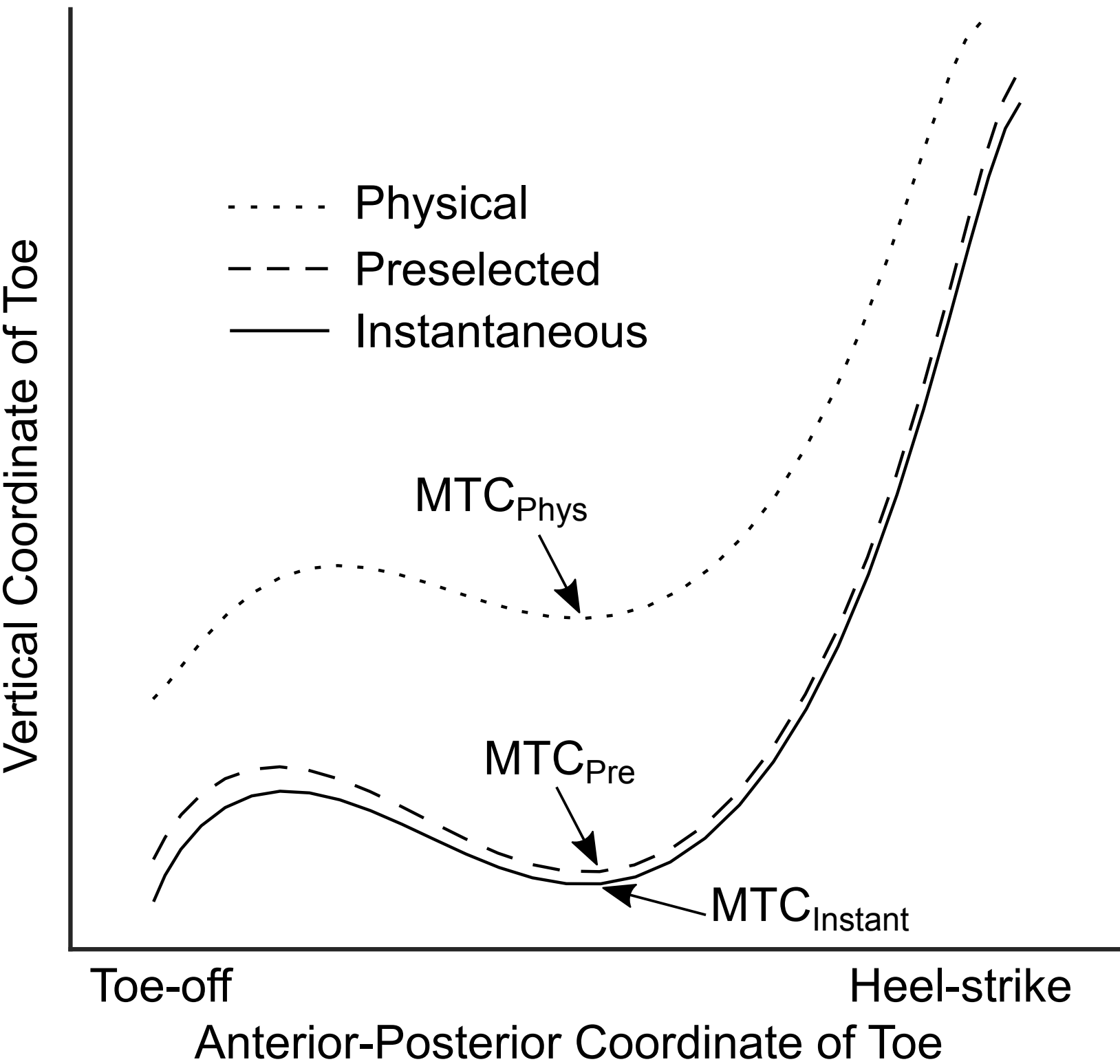


Figure 4
[Click here to download Figure: F4 - Metric Illustration.eps](#)

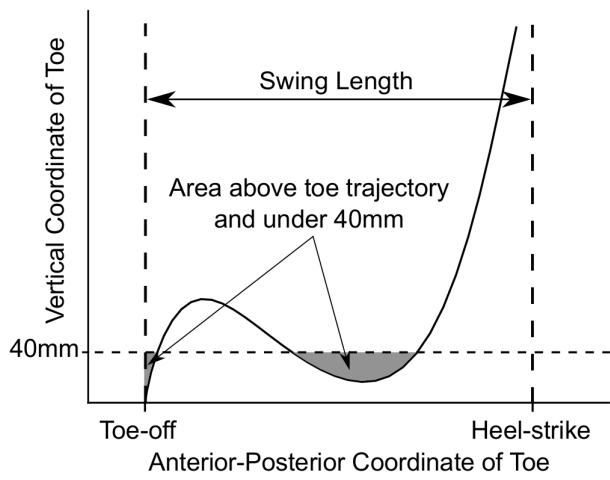


Figure 5
[Click here to download Figure: F5 - Obstacle Histogram.eps](#)

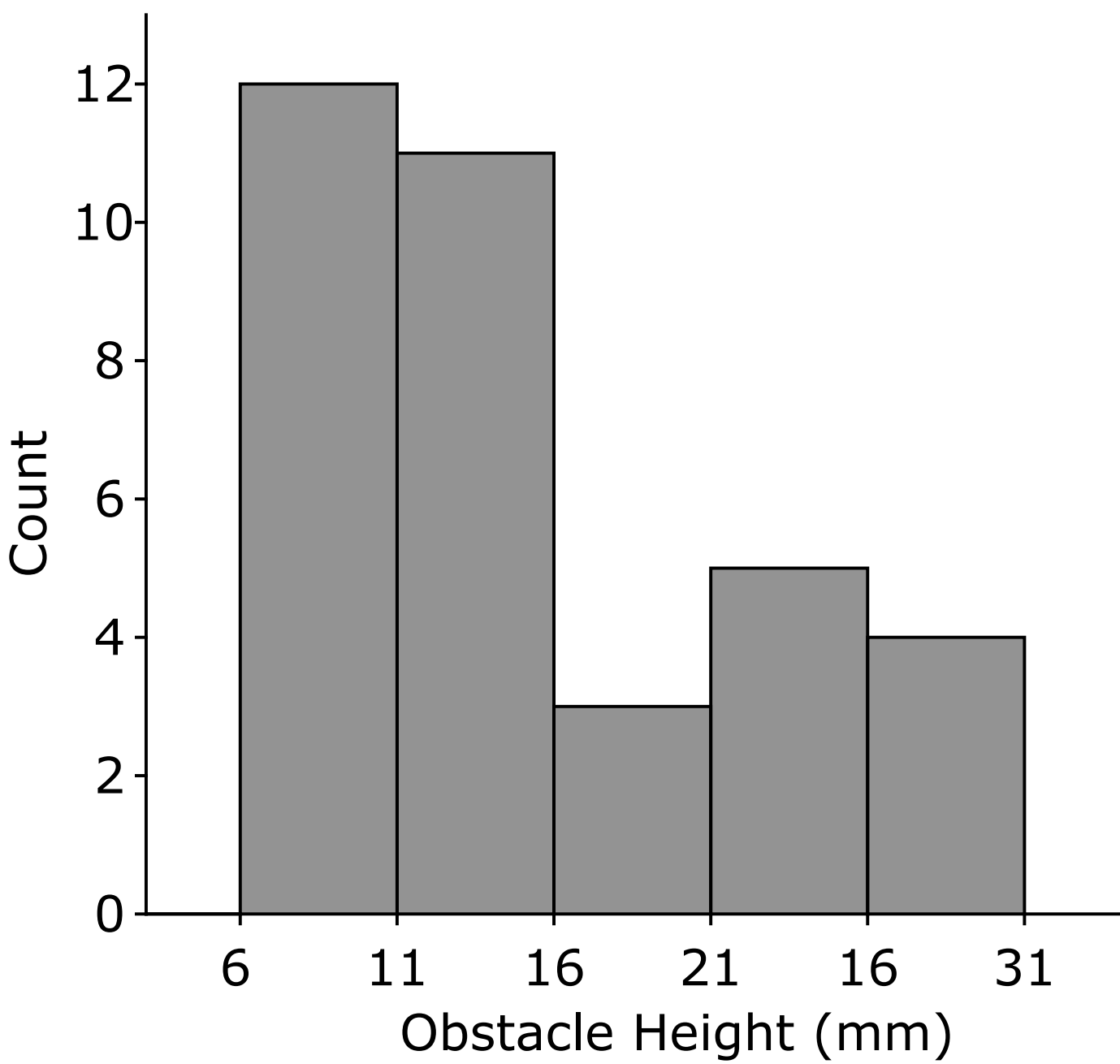


Figure 6
[Click here to download Figure: F6 - MTC Results.eps](#)

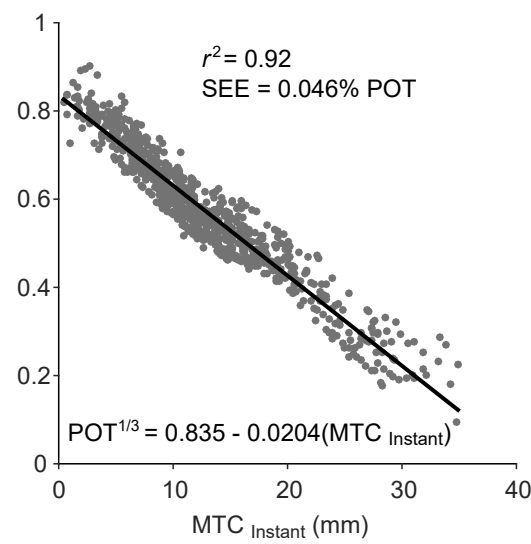
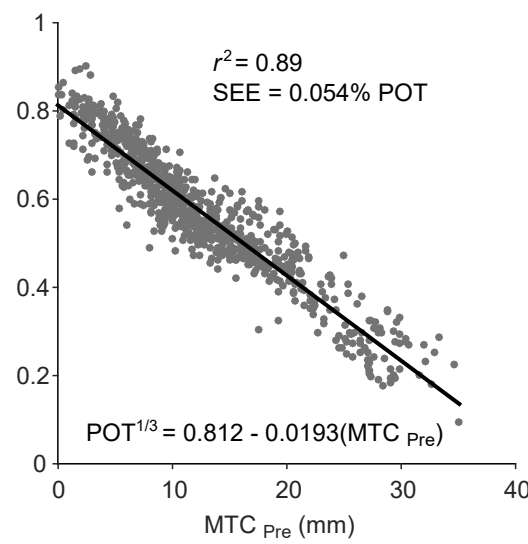
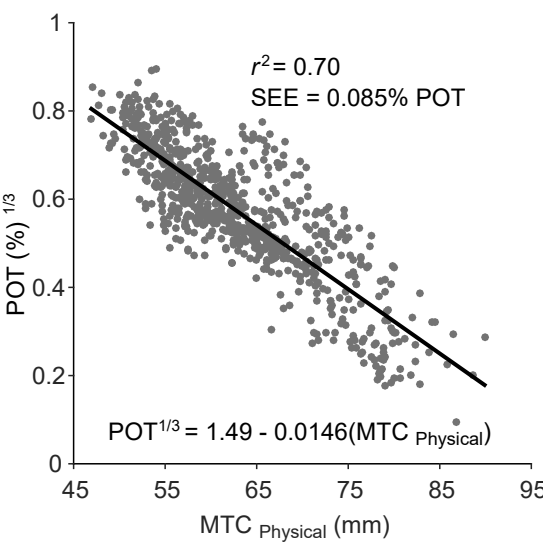
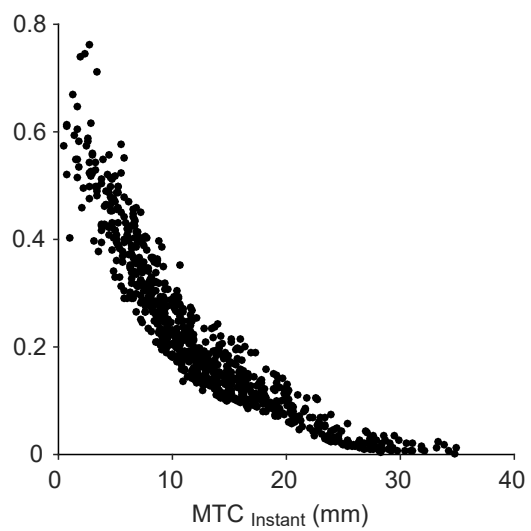
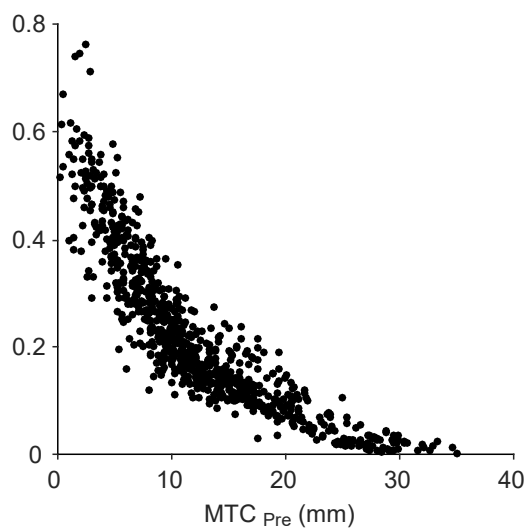
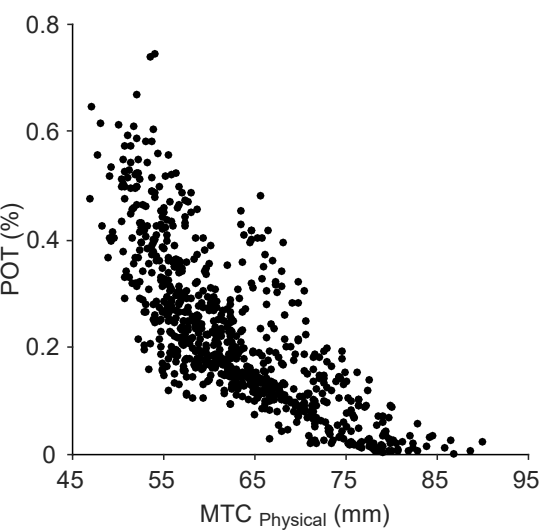


Figure 7

[Click here to download Figure: F7 - Other metrics results.eps](#)

