Original Article

Effects of Speed and Visual-Target Distance on Toe Trajectory During the Swing Phase of Treadmill Walking

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Abstract

Toe trajectory during swing phase is a precise motor control task that can provide insights into the sensorimotor control of the legs. The purpose of this study was to determine changes in vertical toe trajectory during treadmill walking due to changes in walking speed and target distance. For each trial, subjects walked on a treadmill at one of five speeds while performing a dynamic visual acuity task at either a “far” or “near” target distance (five speeds $\times$ two targets distances = ten trials). Toe clearance decreased with increasing speed, and the vertical toe peak just before heel strike increased with increasing speed, regardless of target distance. The vertical toe peak just after toe-off was lower during near-target visual acuity tasks than during far-target tasks, but was not affected by speed. The ankle of the swing leg appeared to be the main joint angle that significantly affected all three toe trajectory events. The foot angle of the swing leg significantly affected toe clearance and the toe peak just before heel strike. These results will be used to enhance the analysis of lower limb kinematics during the sensorimotor treadmill testing, where differing speeds and/or visual target distances may be used.

Introduction

Toe trajectory during the swing phase of locomotion has been recognized as a precise motor control task involving multiple joints and muscles on both the stance and swing limbs [1], thereby giving a global view of the control task [2] and the accuracy of sensory-to-motor transformations of the limbs [3]. The study of toe trajectory (more specifically toe clearance) is often utilized in the determination of propensity to trip while walking [1, 4] or when stepping over an obstacle [3, 5]. Subjects with abnormal gait may exhibit altered toe trajectories – thereby increasing their chances of tripping – despite attempting to compensate with novel motor-control strategies in the legs [6].

Speed of Treadmill Walking

This laboratory has developed a sensorimotor testing protocol for the assessment of locomotor control before and after a given adaptation, such as exposure to the microgravity environment during space flight [7]. During the test, subjects walk on a motorized treadmill at 1.8 m/sec (4.0 mph) while performing a visual acuity test at two different target distances (see Methods section). In initial trials immediately following an adaptation, some subjects may not be able to keep up with the 1.8 m/sec treadmill speed. If this is the case, then those trials are conducted at a slower speed that the subject can maintain.

However, the slower walking speed can not be ignored in the kinematic analyses; otherwise, significant differences seen pre- to post-adaptation may be mistakenly attributed to the adaptation, instead of to the slower gait speed. It has been reported that as walking speed increases, subjects exhibit increases in stride length [8-10], stride frequency [8], hip flexion and total excursion [9, 11], ankle plantarflexion [9], and vertical head excursion [9, 11]. Andriacchi et al. [12] showed that differences in gait patterns in ACL-deficient patients versus normal subjects were more due to slower gait speeds than the pathology. Similarly, Elble et al. [4] reported that the elderly subjects in their study tended to walk slower than the younger subjects, which accounted for most of the "age-related" differences normally attributed to the elderly. Changes in toe clearance with walking speed has been studied, but with mixed results [2, 4, 10, 11, 13].

Visual Target Distance

During normal, "everyday" walking, people fix their gaze on "far" targets (those greater than 2 m from the eyes). This lab's sensorimotor testing protocol requires the subjects to perform a visual acuity test at two distinct target distances while walking to assess the adaptation of the subject's gaze control system, including vestibulo-ocular reflex (VOR) function. The VOR is required to maintain a stable image on the retina, thus eliminating visual "blur" during head and body motion. Angular VOR is employed during far-target fixation, and linear VOR is used during near-target fixation [8, 14].

Visual-fixation distance has been shown to affect head and trunk motion during treadmill walking [8, 15], and differences in the visual task have been shown to affect lower body gait parameters [16]. The effects of visual target distance on toe trajectory have not been specifically addressed. The purpose of this study was to determine changes in vertical toe trajectory during treadmill walking due to changes in walking speed and target distance.

Methods and Materials

Setup: Six male and six female subjects (height = 172.0 ± 9.74 cm.; age: 33 ± 8.0 years; weight: 71.1 ± 14.94 kg.) gave informed consent and participated in this study. Subjects were free from neurovestibular or sensorimotor impairment and prior major musculo-skeletal injury. The NASA Lyndon B. Johnson Space Center (NASA-JSC) Committee for the Protection of Human Subjects reviewed and approved this protocol.

To ensure that the results of this study would be directly applicable to other studies in this laboratory, this protocol emulated that of our current sensorimotor assessment test. Subjects wore lab-supplied shoes (Converse, North Andover, MA) with footswitches (Motion Lab Systems, Baton Rouge, LA) taped to the heel and toe areas of the soles. The footswitch data (sampled at 1000 Hz) was used to determine heel strike and toe-off events in the time-series data. Retroreflective markers (25 mm dia.) were affixed to landmarks on the subject to define the local anatomical coordinate system for each body segment. The marker positions were: bilateral posterior superior iliac spines and the sacrum (pelvis); greater trochanter, lateral femoral condyle, and anterior midpoint of the thigh (thigh); lateral fibular head, lateral malleolus and tibial crest (shank); lateral aspect of the calcaneus, fifth metatarsal head and superior aspect of the shoe (foot). An actual toe marker was not used in this marker set in favor of a “virtual” toe marker (see description below). The virtual toe marker – generated at the position of the distal tip of the 2nd toe of the right foot/shoe – allowed for tracking of the point on the shoe that would most likely contact the walking surface.

Protocol: A six-camera motion capture system (Motion Analysis, Santa Rosa, CA) recorded the three-dimensional (3D) positions of the markers at a rate of 60 Hz. Accuracy, repeatability and resolution of our system in the split-volume setup were all determined to be approximately 0.1 mm [17]. Before the walking trials, a static trial was recorded with the subject standing motionless in the middle of the calibration volume.

This trial was used for calculating the transformation matrices between each segment's local coordinate system and the lab's global coordinate system (+X = forward along the long axis of the treadmill belt; +Y = "left," perpendicular to the x-axis in the plane of the belt; +Z = vertically "up").

For the walking trials, subjects walked on a motorized, instrumented treadmill (Gaitway, Kistler Instrument Corp., Amherst, NY) at one of five speeds (0.9, 1.1, 1.3, 1.6, 1.8 m/sec) while performing a dynamic visual acuity task at either a "far" target or a "near" target distance (4 m and 0.5m, respectively) (Figure 1). Each subject performed ten 60-second trials – one for each speed-target combination. Trial order was determined within a balanced-block design, and subjects were randomly assigned to one of the twelve orders.

Visual task: The dynamic visual acuity (DVA) test, designed to assess gaze control performance during walking, was utilized to provide a consistent task demand (for a detailed description of the test, see [14]). Once the subject attained a steady pace at the start of a trial, Landholt-C optotypes in one of four orientations appeared on the display screen for 150 msec (Figure 1). The subject was instructed to verbally identify the position of the "gap" in the optotype (up, down, left, right). The response was recorded by the operator via a numeric keypad, which was connected to a laptop computer running LabVIEW software (National Instruments, Austin, TX) that both displayed the optotype and logged the responses. Once the response was recorded, the next optotype immediately flashed on the screen. The successive optotypes would become smaller as the subject gave correct answers, and larger after wrong answers. The number of optotypes shown during a trial depended on the subject's rate of response.

Kinematic Analysis: Footswitch and 3D marker position data were exported and analyzed using in-house software developed in Matlab (R2006a, Mathworks, Natick, MA). Footswitch data were used for the determination of the heel strike events and subsequent time normalization of the time-series motion data. Euler angles for the pelvis, hip, thigh, knee, shank, ankle and foot were computed from the motion data. A "virtual marker" representing the right toe was generated at the position of the distal tip of the 2nd toe of the right foot, using the three foot markers and the segment's local coordinate system. For the walking trials, the virtual toe marker's vertical (z) position was reported relative to its height during the quiet stance trial.

The analysis of the vertical toe trajectory during swing phase concentrated on three main events (Figure 2): (a) Toe clearance (TCl) was the lowest vertical height of the toe during swing phase; (b) First toe peak just after toe-off (Toemax1) was the first maximum, which occurs before the foot swings forward; (c) Second toe peak just before heel strike (Toemax2) occurred as the foot prepared for the next step. TCl, Toemax1, and Toemax2 were determined for each stride along with corresponding lower body frontal angles (pelvis roll, and ab/adduction of the right and left hips) and sagittal angles (right foot, right and left ankles, right and left knees, and right and left hips) when the three events occurred.

Joint angles of the left leg for each of the toe trajectory events could not be directly calculated, since no markers are placed on the left leg in our sensorimotor protocol. Therefore joint angles of the left leg were estimated using angle data from the right leg phase-shifted by one step. When a toe event was determined, its point in the gait cycle was recorded (%GCt). Assuming the subjects walked with a symmetric gait

[18], it was inferred that joint angles (θ) on the left leg at %GCt were the same as the corresponding joint angles of the right leg that occurred exactly one step (50%GC) earlier in the stride.

$$\theta_{LEFT}(\%GCt) = \theta_{RIGHT}(\%GCt - 50\%GC)$$

Statistical Methods: No significant effects of gender nor trial order were found, so all data was pooled into a single data set. Means and standard deviations over strides of all toe-trajectory measures (TTM) were calculated for each subject and experimental condition, resulting in a data set of 120 observations (12 subjects, 5 speeds, 2 target distances). The sample means and standard deviations were therefore used as dependent variables in the fitting of a random effects regression model with between and within-subject normally distributed errors thus allowing for the repeated measures design. Regression coefficients and associated standard errors were then used to make inference on the effects of speed and target distance.

Since control of the toe of the swing foot depends on the joint angles in both the swing and stance legs [1], we performed a secondary analysis, where we attempted to identify which of the ten lower leg joint angles computed in the kinematic analysis were the main drivers affecting the three toe trajectory measures. We did this by first fitting thirty random-effects regression models using each toe trajectory measure as the dependent variable and each of ten leg angles as a single covariate, in turn. Each regression model produced a slope estimate, standard error and p-value for the test of zero slope. Using Holm's method [19] for controlling the family-wise error rate to 0.05, we then identified significant angle vs. toe trajectory measure combinations as those whose regression slope p-values were less than the adjusted threshold (approximately 0.0026). All analysis was done with Stata statistical software (Release 9; Stata Corp LP; College Station, TX).

Results

Average TCl significantly *decreased* with increasing treadmill walking speed (slope = -4.3 mm/(m/sec); $p<0.01$), but was not affected by visual target distance (Figure 3). The secondary analysis revealed that the angles of the foot, ankle, and knee of the swing leg and the estimated knee angle of the stance leg had a significant effect on TCl (Table 1).

Average toe peak just after toe-off (Toemax1) was apparently not affected by speed, but it did decrease significantly ($p < 0.01$) when subjects performed the DVA task at the near-target distance compared to far-target (Figure 4). In the secondary analysis, only the swing ankle angle significantly affected Toemax1 (Table 2). The swing foot angle *may* also have been a factor affecting Toemax1, but its contribution was not technically significant, with its adjusted p-value ($P = 0.0035$) just over the Holm threshold.

The toe peak just prior to heel strike (Toemax2) *increased* significantly with increasing speed ($p < 0.01$), with a slope of 59.1 mm/(m/sec) across the range of speeds. It was not affected by target distance (Figure 5). The angles of the swing foot, swing ankle, swing hip (flex/ext) and the pelvis (roll) and the estimated angles of the stance ankle and stance hip (flex/ext) all significantly affected Toemax2 (Table 3). However, the foot and ankle angles of the swing leg seemed to be the greatest contributors, as reflected in their z-scores (i.e., regression coefficients divided by standard errors).

No significant interactions of speed and target distance were observed for any of the toe trajectory measures.

Discussion:

Visual Target Distance: Visual-target viewing distance affects head-trunk coordination during walking [8, 15]. Since the entire body works in concert to maintain stable gaze during walking [7, 8, 16], it should follow that lower limb kinematics – and therefore toe trajectory – would be affected as well. However in this study, only the first peak after toe-off (Toemax1) was affected by visual target distance. Toemax1, which occurs at the point of maximum heel elevation, is the "preparation" before the foot and leg swing forward for the next step. The toe must attain enough initial height such that as the leg swings forward in an energy-efficient, pendular motion, it will have sufficient clearance near mid-swing [13]. There was little mention of Toemax1 in past studies of toe trajectory [1, 10, 13]. However, the only results presented were from Osaki et al., who found a linear relationship between Toemax1 and the toe's peak velocity preceding Toemax1. A justification for the reduction in Toemax1 for the near-target condition is currently under investigation.

In the overground walking protocols that examined toe trajectory, no mention was made as to where each subject was looking or asked to look during the trials. It is reasonable to assume that subjects in these studies fixed their gaze on a non-specific "far" target – such as the end of the walkway or the region ahead of them on a track. It has been reported that there were no significant differences in the ground reaction forces when subjects visually "targeted" a force plate on a walkway and when they did not [20, 21]. However, performing a task during walking has been shown to affect body kinematics, either during manual pointing tasks [22] or visual tasks [15, 16]. For instance, subjects walking on a treadmill exhibit an 11% increase in knee flexion just after heel strike while reading 5-digit numbers on a computer screen positioned 4 meters away as opposed to simply staring at a dot at the same distance [16]. Therefore some of the differences in results between this study and others cited may be due to the task involvement, which would invoke walking strategies to maintain a stable gaze.

Speed: In this study, we found that as speed increased, TCl significantly *decreased*, and Toemax2 significantly *increased*. Others have reported non-significant trends in TCl with changes in overground walking speed – both decreasing [2] and increasing [4, 11, 13]. The significant increase for Toemax2 with speed matched that reported by others [4, 10, 11, 13]. Table 4 summarizes the slopes of TCl and Toemax2 versus speed as calculated from each author's respective tables of results. The overground studies yielded the steepest absolute slopes for TCl, especially those testing elderly subjects. Interestingly, this study had the least steep slope for TCl and yet the steepest slope for Toemax2.

It should be noted that in Osaki et al. [10], the subjects walked on a treadmill and fixed their gaze on a dot positioned 1 meter from their eyes (a "near" target). Like this study, they found increases in Toemax2 with speed, however, they found no change in TCl across speeds. Straight comparisons with their results, however, could not be made, since Osaki et al. based their "toe" trajectory results on the motion of a marker on the 5th metatarsal head, and they normalized all linear measurements to leg length and speed measurements to Froude number. Furthermore, no data tables were presented, so slopes for TCl vs. speed or Toemax2 vs. speed could not be calculated.

Standard deviations (SD) for TCl within trials were consistent across subjects for each of the five tested speeds (Table 5). Our SD values at treadmill speeds of 0.9 m/sec (2.0 mph) and 1.1 m/sec (2.5 mph) compared well with those reported by Dingwell et al. [23] who tested subjects walking on a treadmill at 1 m/sec (2.3mph) – although they tracked motion of the 5th metatarsal head of the left foot, instead of a toe marker. Of the overground walking studies, most reported SD's almost twice as great as ours, with those published by Mills and Barrett [24] being the exception. Toemax2 SD's in this study decreased with increasing speed (Table 5), yet in the overground protocols, SD's appeared to *increase* with speed. These differences in the trends and magnitudes of SD between treadmill and overground conditions can be expected. Overground walking allows for greater variances in both speed and direction and is much more forgiving with regards to stability. In contrast, the tolerances for maintaining gait on a treadmill are much lower, given that the walking speed is driven by the belt [25].

There is disagreement in the literature as to whether overground and treadmill walking are analogous, which would allow for direct comparison of results. Often in these studies, most measures were found to be similar between the two conditions, yet there were always a few significantly different exceptions. Murray et al. [26] reported no significant differences in the toe's vertical pathway between treadmill and overground walking across speeds, and there was consistent variability of repeated measures between the two conditions. However, they did note significantly shorter step lengths and increased cadences for treadmill walking. For the most part, ground reaction forces during treadmill and overground walking at the same speed were comparable [27, 28]. Yet significant differences were found in the vertical reaction forces in mid- to late-stance [27], and in maximum fore-aft and minimum medial-lateral reaction forces [28]. Riley et al. also found significant changes in hip, knee and pelvis joint angles, but all changes were within normal variability of the respective parameters from their analysis.

The ankle of the swing leg appeared to be the main joint angle that significantly affected all three events. The foot angle significantly affected TCl and Toemax2, yet it *may* also have affected Toemax1, but it was not shown to be significant in this study. Winter [1] reported additional contributions from stance leg ankle flexion and hip abduction angles on TCl. However in this study, significant effects by these two angles were not observed. Kinematics of the foot has been cited as the main focus of lower limb control for walking [10, 29] and obstacle avoidance [30]. Osaki et al. [10], specifically, developed a second-order mathematical model for predicting changes in toe dynamics, where the main control parameter was the foot, which was shown to behave like an undamped pendulum during swing phase.

The fact that the ankle and foot are major contributors in controlling toe trajectory infers that those whose walking shows evidence of greater variability in foot or leg orientation – whether it be due to age, pathology or adaptation – may be at a higher risk of tripping. For instance, astronauts returning from long-duration space flight exhibit greater ankle and knee variability [25], which in turn could adversely affect TCl, since the knee angles of both the stance and swing legs and the ankle angle of the swing leg are the greatest contributors to TCl.

Limitations of this study may have included subjects' unfamiliarity with DVA testing (especially using a near target), hence making it a novel task that may have required some adjustment period. We employed a virtual marker at the toe position, instead of using an actual toe marker. This was done partly for a complete simulation of our sensorimotor protocol, where no toe marker is used. The virtual toe marker may not have been an exact duplication of the true toe position, although our kinematic results compared well with the other studies. Finally, the estimation of left leg joint angles at the toe trajectory events based on the right leg angles one step prior may not have been a perfect recreation of the true left leg angles due to our assumption of symmetrical gait. However, this did not affect the results, since the main leg angles contributing to all three events were on the swing leg (ankle and foot), not the stance leg.

Conclusions

While subjects walked on a treadmill while performing a dynamic visual acuity task, toe clearance decreased with increasing speed, and the vertical toe peak just before heel strike increased with increasing speed, regardless of target distance. The vertical toe peak just after toe-off was lower during near-target visual acuity tasks than during far-target tasks, but was not affected by speed. The ankle of the swing leg appeared to be the main joint angle that significantly affected all three events. The foot angle of the swing leg significantly affected toe clearance and the toe peak just before heel strike, yet it *may* also have affected the toe peak just after toe-off, but it was not shown to be significant in this study. These results will be used to enhance the analysis of lower limb kinematics during the sensorimotor treadmill testing following exposure to an adaptive environment, such as space flight.

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Table 1

Results of the linear, random-effects regression with Holm's correction for segment and joint angles at the instance of toe clearance. The "z" value is the number of standard errors that the slope is away from zero. $\mathbf{P_{adj}}$ is the Holm-corrected p-value threshold needed to achieve a family-wise Type-I error rate of 0.05.

Angle @ TCl	z	P>|z|	Padj
Foot (swing)	-6.92	< 0.001*	0.0019
Ankle (swing)	3.29	< 0.001*	0.0025
Knee (swing)	5.19	< 0.001*	0.0021
Hip flex/ext (swing)	-0.32	0.7502	0.0125
Hip abd/add (swing)	0.01	0.9884	0.0500
Pelvis roll	-1.81	0.0699	0.0031
Ankle (stance)	-1.35	0.1780	0.0036
Knee (stance)	3.48	< 0.001*	0.0024
Hip flex/ext (stance)	-1.67	0.0953	0.0033
Hip abd/add (stance)	0.36	0.7225	0.0100

Table 2

Results of the linear, random-effects regression with Holm's correction for segment and joint angles at the instance of Toemax1. The "z" value is the number of standard errors that the slope is away from zero. $\mathbf{P_{adj}}$ is the Holm-corrected p-value threshold needed to achieve a family-wise Type-I error rate of 0.05.

Angle @ Toemax1	z	P>|z|	Padj
Foot (swing)	-2.92	0.0035	0.0026
Ankle (swing)	4.73	< 0.001*	0.0022
Knee (swing)	-2.00	0.0456	0.0029
Hip flex/ext (swing)	1.29	0.1967	0.0042
Hip abd/add (swing)	0.57	0.5680	0.0071
Pelvis roll	-0.27	0.7905	0.0167
Ankle (stance)	0.38	0.7070	0.0083
Knee (stance)	1.33	0.1826	0.0038
Hip flex/ext (stance)	-0.89	0.3738	0.0050
Hip abd/add (stance)	1.03	0.3032	0.0045

Table 3

Results of the linear, random-effects regression with Holm's correction for segment and joint angles at the instance of Toemax2. The "z" value is the number of standard errors that the slope is away from zero. $\mathbf{P_{adj}}$ is the Holm-corrected p-value threshold needed to achieve a family-wise Type-I error rate of 0.05.

Angle @ Toemax2	z	P>|z|	Padj
Foot (swing)	-100.21	< 0.001*	0.0017
Ankle (swing)	22.45	< 0.001*	0.0017
Knee (swing)	2.76	0.0058	0.0028
Hip flex/ext (swing)	5.72	< 0.001*	0.0020
Hip abd/add (swing)	0.75	0.4555	0.0056
Pelvis roll	8.13	< 0.001*	0.0018
Ankle (stance)	-4.00	< 0.001*	0.0023
Knee (stance)	-0.18	0.8538	0.0250
Hip flex/ext (stance)	-6.18	< 0.001*	0.0019
Hip abd/add (stance)	-0.70	0.4826	0.0063

Table 4

Change in toe clearance (TCl) and toe peak just before heel strike (Toemax2) with speed. Slopes were calculated from published results tables. Note: Murray and Clarkson [13] reported increases in TCl and Toemax2 from “slow” to “fast” speeds, but no velocities were given for the two conditions, so no slopes could be shown in this table.

Parameter	Authors	Subjects	Walking condition	Slope (mm/(m/s))
TCl	*This Study*	Young/middle age adults	Treadmill	-4.3
	Osaki et al., 2006	Young adults	Treadmill	No trend
	Karst et al., 1999	Elderly females	Overground	-7.5
	Elble et al., 1991	Young adults	Overground	6.1
		Elderly adults	Overground	11.1
Toemax2	*This Study*	Young/middle age adults	Treadmill	59.1
	Osaki et al., 2006	Young adults	Treadmill	Indeterminate *
	Elble et al., 1991	Young adults	Overground	18.4
		Elderly adults	Overground	13.3
	Murray et al., 1984	Young females	Overground	41.7

* -- Osaki et al. (2006) normalized speeds and distances to Froude number and subject leg length, respectively. Therefore no slope could be calculated.

Table 5

Standard deviations (SD) for toe clearance (TCl) and toe peak just before heel strike (Toemax2) from this study compared with those of others.

Parameter	Authors	Subjects	Walking condition	Speed (m/sec)	SD (mm)
TCl	*This Study*	Young/middle age adults	Treadmill	0.9	2.4
				1.1	2.3
				1.3	2.2
				1.6	2.5
				1.8	2.9
	Dingwell et al., 1999*	Middle age	Treadmill	1.0	2.6
	Mills & Barrett, 2001*	Young males	Overground	1.4	3
		Elderly males		1.4	2
	Karst et al., 1999	Elderly females	Overground	1.3	6.8
				1.6	7.3
	Winter, 1992	Young adults	Overground	"natural"	4.5**
	Elble et al., 1991	Young adults	Overground	1.2	4
				1.7	7
		Elderly adults	Overground	0.9	7
				1.4	8
Toemax2	*This Study*	Young/middle age adults	Treadmill	0.9	7.4
				1.1	6.1
				1.3	5.4
				1.6	4.7
				1.8	4.9
	Elble et al., 1991	Young adults	Overground	1.2	9
				1.7	10
		Elderly adults	Overground	0.9	8
				1.4	11
	Murray et al., 1984	Young females	Overground	0.8	4.0
				1.4	4.0
				1.9	8.0
	Murray & Clarkson, 1966a	Adult males (age 20 – 65)	Overground	"free"	19
				"fast"	25

* – Mills & Barrett and Dingwell et al. tracked the path of a marker on the 5th metatarsal head, as opposed to on the toe.
** – Winter reported a "…±0.45 cm toe clearance variability." However variability was not defined as variance, standard error or standard deviation.

Figure 1 The subjects were shown one of four Landholt-C optotypes (center) for 150 msec on a “far” target screen (left) or a “near” target mini-screen (right).

Figure 2 Graph of the vertical toe trajectory vs. percent gait cycle for a representative stride. The three events of interest during swing phase are shown: Toemax1, TCl, and Toemax2.

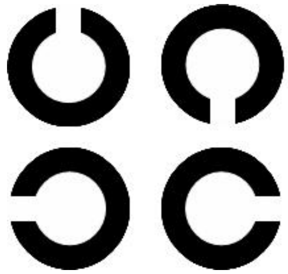
Figure 3 Graph of vertical toe clearance (mm) vs. walking speed (m/sec) for far and near target tasks. Toe clearance significantly decreased with increasing speed (slope = -4.3 mm/(m/sec)). Toe clearance was not affected by visual target distance.

Figure 4 Graph of maximum vertical toe position just after toe-off (mm) vs. walking speed (m/sec) for far and near target tasks. Toemax1 was significantly greater while performing a far target task than a near target task. Toemax1 was not affected by speed.

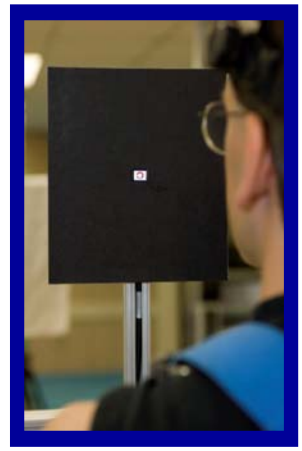
Figure 5 Graph of maximum vertical toe position prior to heel strike (mm) vs. walking speed (m/sec) for far and near target tasks. Toemax2 significantly increased with increasing speed (slope = 59.1 mm/(m/sec)). Toemax2 was not affected by visual target distance.

Figure 1

4 m target distance (“Far”)



Landholt-C
optotypes



0.5 m target distance (“Near”)

Figure 2

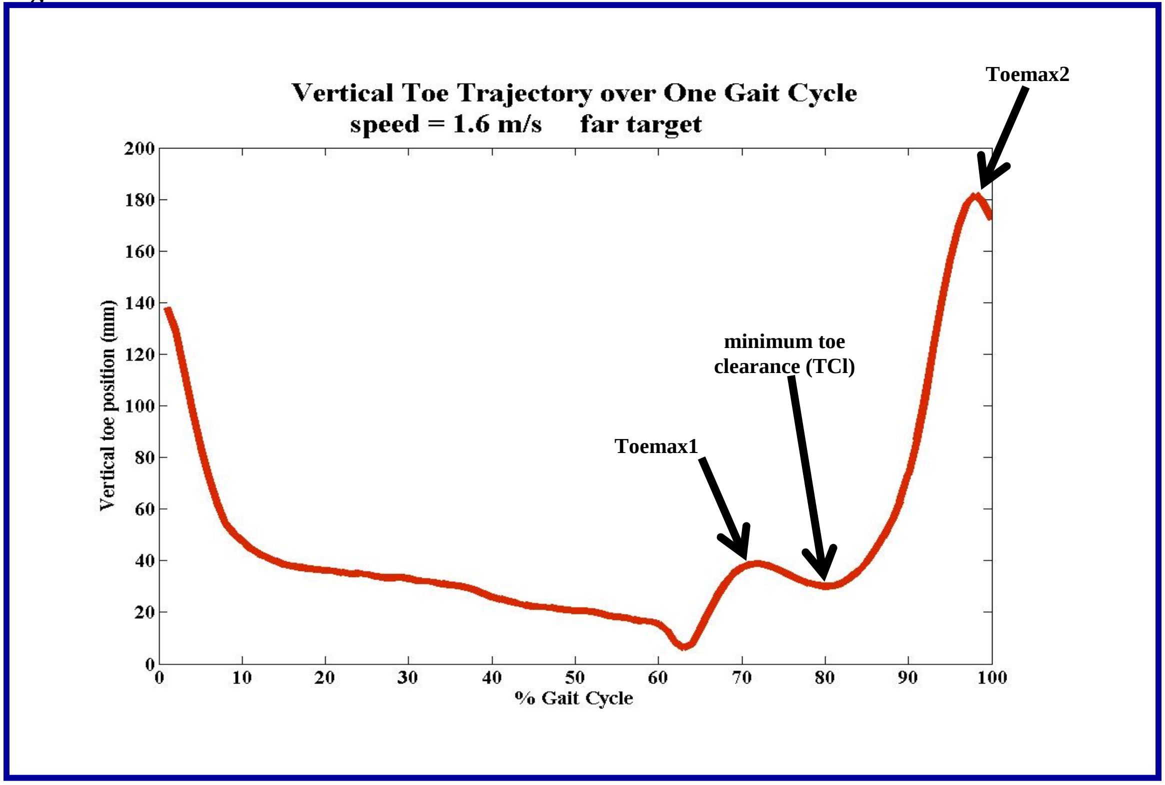

Vertical Toe Trajectory over One Gait Cycle
speed = 1.6 m/s far target
Toemax2
minimum toe clearance (TCl)
Toemax1
Vertical toe position (mm)
% Gait Cycle
0
20
40
60
80
100
120
140
160
180
200
0
10
20
30
40
50
60
70
80
90
100

Figure 3

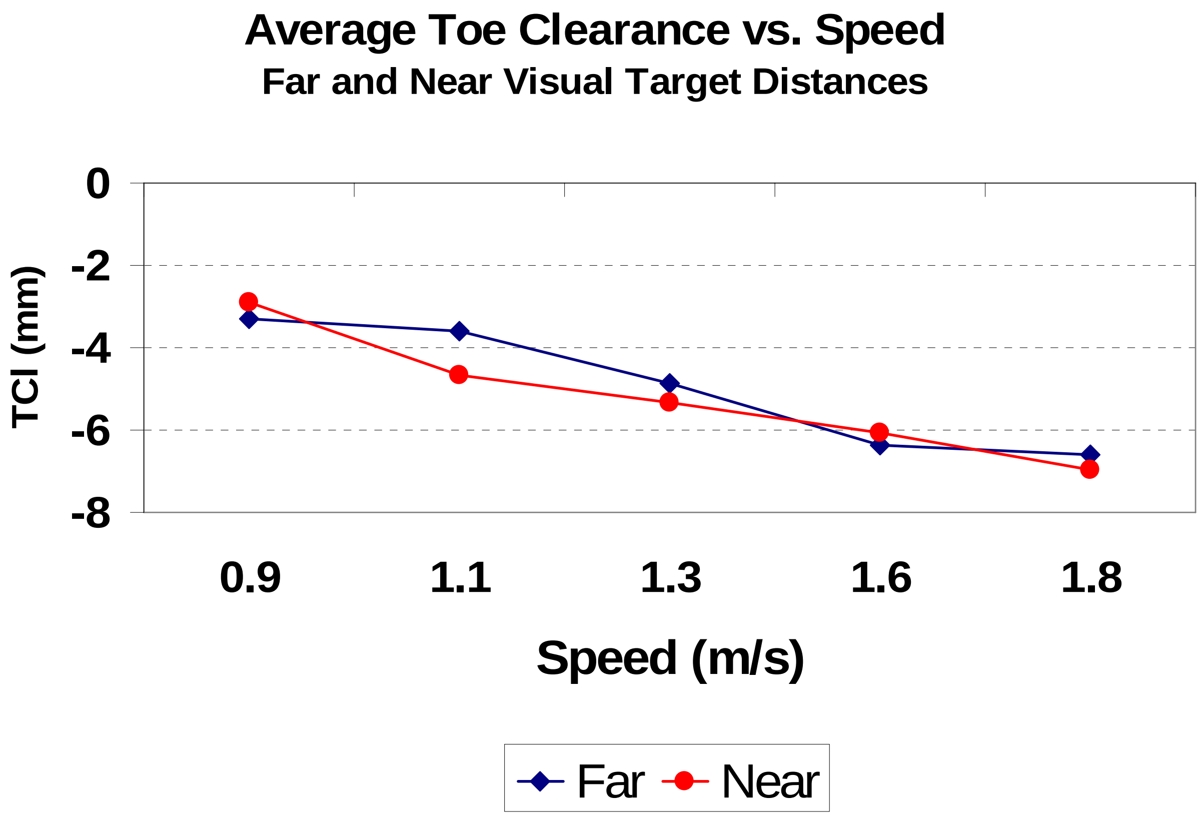

Average Toe Clearance vs. Speed
Far and Near Visual Target Distances
0
-2
-4
-6
-8
TCI (mm)
0.9
1.1
1.3
1.6
1.8
Speed (m/s)
Far
Near

Figure 4

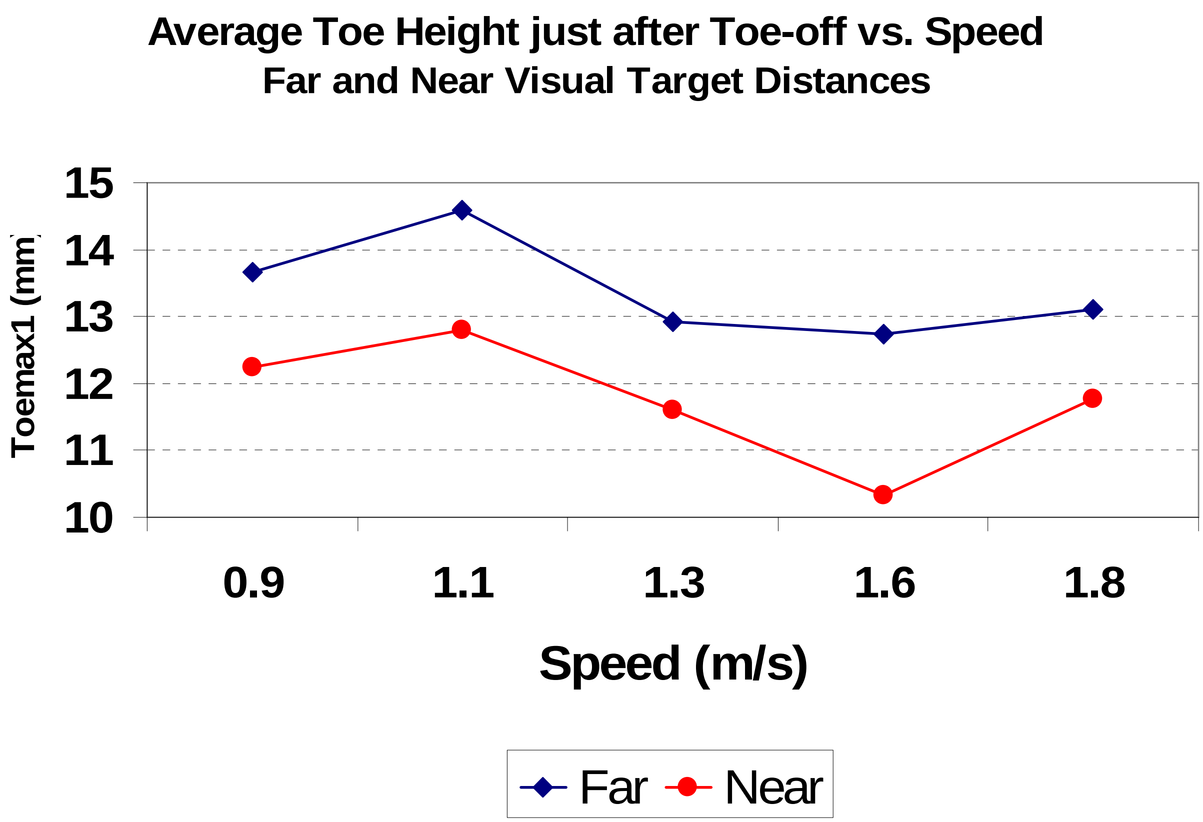
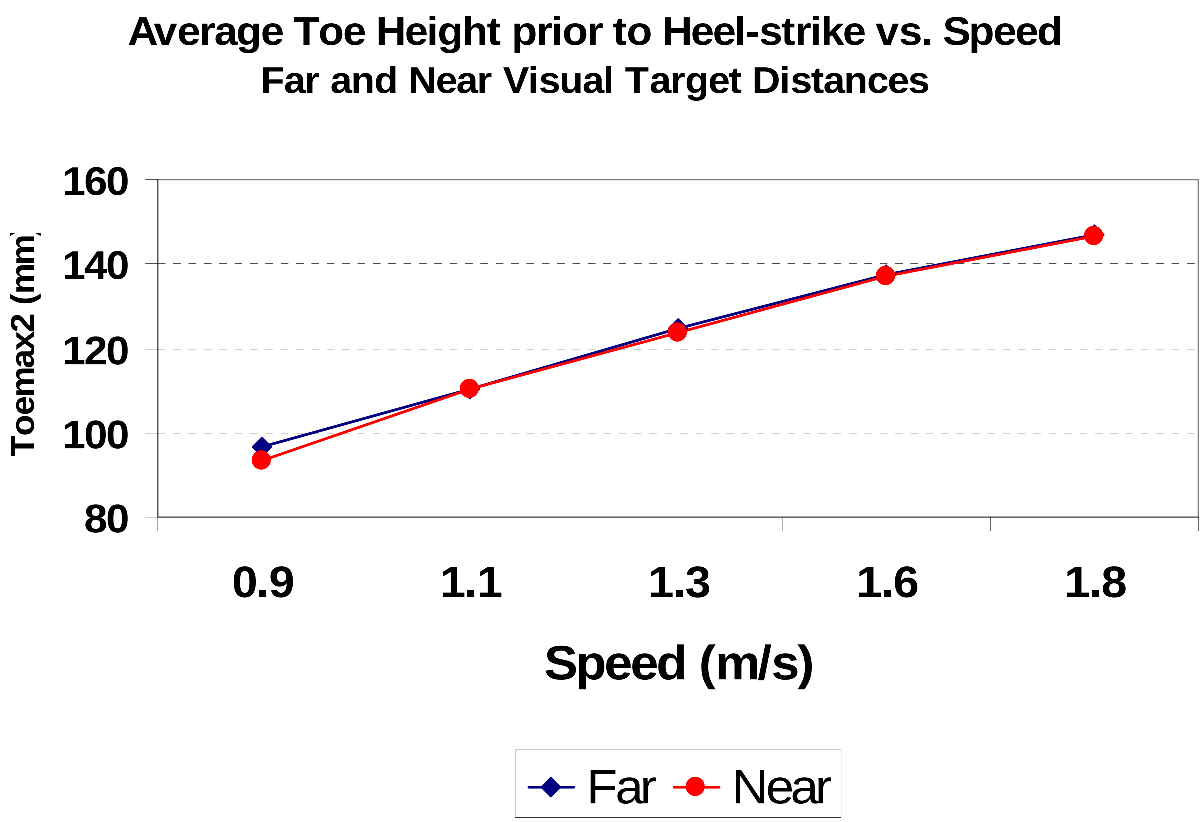

Average Toe Height just after Toe-off vs. Speed
Far and Near Visual Target Distances
15
14
13
12
11
10
Toemax1 (mm)
0.9
1.1
1.3
1.6
1.8
Speed (m/s)
Far
Near

Figure 5


Average Toe Height prior to Heel-strike vs. Speed
Far and Near Visual Target Distances
Toemax2 (mm)
160
140
120
100
80
0.9
1.1
1.3
1.6
1.8
Speed (m/s)
Far
Near