1-1-2019

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Accepted version. *Journal of Applied Biomechanics*, Vol. 35, No. 2 (2019): 116-122. DOI.

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Journal of Applied Biomechanics, Vol. 35, No. 2 (2019): 116-122. DOI.

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Low foot clearance and high variability may be related to falls risk. Foot clearance is often defined as the local minimum in toe height during swing; however, not all strides have this local minimum. The primary purpose of this study was to identify a nondiscrete measure of foot clearance during all strides, and compare discrete and nondiscrete measures in ability to rank individuals on foot clearance and variability. Thirty-five participants (young adults [n = 10], older fallers [n = 10], older nonfallers [n = 10], and stroke survivors [n = 5]) walked overground while lower extremity 3D kinematics were recorded. Principal components analysis (PCA) of the toe height waveform yielded representation of toe height when it was closest to the ground. Spearman's rank order correlation assessed the association of foot clearance and variability between PCA and discrete variables, including the local minimum. PCA had significant ($P < .05$) moderate or strong associations with discrete measures of foot clearance and variability. An approximation of the discrete local minimum had a weak association with PCA and other discrete measures of foot clearance. A PCA approach to quantifying foot clearance can be used to identify the behavioral components of toe height when it is closest to the ground, even for strides without a local minimum.

Keywords: falls risk; principal components analysis; walking

Trips are one of the greatest causes of falls and are the result of insufficient clearance between the foot and floor.[1] Both low foot clearance and high foot clearance variability are suspected to increase the risk of falling.[2] The local minimum approach is a common way to determine foot clearance: The toe height is plotted throughout the swing phase, and the mean and SD of the toe height at the local minimum inflection point during midswing represent foot clearance and foot clearance variability, respectively.[3],[4] However, it has been established that this local minimum does not exist for every stride, with the toe height increasing throughout the swing phase without an inflection point. This has been noted particularly among older adults,[5] individuals with a history of stroke,[6] and individuals walking under constrained conditions or in the presence of obstacles.[7],[8] Based on these observations, it has been suggested that the absence of a local minimum of toe height is an adaptive strategy to reduce tripping risk[7]; however, as a local minimum is required for the common measure of foot clearance, it cannot be determined if strides without a local minimum have a lower risk of falling due to higher foot clearance and/or lower foot clearance variability. Therefore, it is important in fall risk assessments to be able to quantify foot clearance in cases where a local minimum of toe height does not exist.

There have been several attempts to quantify foot clearance in the absence of a local minimum. Little et al[5] searched for the absolute minimum toe height during swing, which only identified the point immediately following toe-off. Another approach involves identifying a more consistently detectable point that occurs around midswing and recording toe height at that point. Three potential points that fit these criteria are the exact midpoint of swing, the point of greatest forward velocity of the foot,[9],[10] and the point of maximal limb shortening.[4],[5] Although each of these methods can be used to identify a value of toe height during midswing for all strides, it is not guaranteed that the lowest value of toe height during midswing will be identified, so the local minimum method is still commonly employed.[2],[11]–[14] When the local minimum method is used, strides without a local minimum are either discarded and information from these strides is lost, or an indicative toe height that is equal to an individual's mean location of minimum toe height during swing is assigned.[7] Aside from the extra steps required to determine an indicative toe height, a major limitation to this approach is the assumption that the toe height trajectory is similar between strides with and without a local minimum. In addition, all of these methods, including the local minimum approach, only consider a single point, which may not convey important information about foot clearance from the rest of the gait cycle.[15],[16] Therefore, a method that accurately determines foot clearance throughout swing for people with a variety of walking patterns, and especially those at risk for falling, is warranted.

A principal components analysis (PCA) approach to quantifying foot clearance and foot clearance variability may resolve these issues. PCA can be used to identify modes of variation within a waveform without choosing a discrete point and has been shown to distinguish behavioral variability from noise.[17] By performing PCA on the vertical trajectory waveform of the toe during swing, it is possible to obtain variables that represent the magnitude of toe height, not at one point, but throughout the swing phase. A PCA variable that describes variation in toe height during early to mid swing, when the foot is closest to the ground, may represent foot clearance without having to rely on discrete variables chosen a priori.

The primary purpose of this study was to identify a nondiscrete variable that represents foot clearance during all strides, including those without a local minimum of toe height. The secondary purpose was to compare the nondiscrete measure of foot clearance with the discrete measures in the ranking of individuals of various walking abilities according to foot clearance and foot clearance variability during strides with and without a local minimum of toe height. A third purpose of this study was to investigate the differences in percentage of strides without a local minimum of toe height across young adults, older fallers and nonfallers, and stroke survivors to identify demographic groups that would benefit from a measure of foot clearance that does not rely on the presence of a local minimum. The hypotheses were that PCA would yield a variable that describes variation in toe height during early to mid swing, when the foot is closest to the ground. This PCA variable was expected to have a strong association based on rank order with discrete measures of foot clearance and foot clearance variability for strides with a local minimum of toe height, while the indicative toe height was expected to have a weak association with discrete and PCA measures of foot clearance and foot clearance variability for strides without a local minimum of toe height. In addition, it was expected that there would be a lower percentage of strides without a local minimum for young adults compared with older nonfallers and fallers and stroke survivors.

Methods

This study was approved by the institutional review board at the University of Wisconsin-Milwaukee, and all participants gave informed consent. A total of 35 community-dwelling participants were included: young adults, older adults without a history of falls, older adults with a history of falls, and adults who had experienced a stroke more than 6 months earlier (Table 1). Falls history was determined as a self-reported fall—unintentionally coming to rest on the ground[18]—in the last 6 months. To quantify sensorimotor impairment, a lower extremity Fugl-Meyer evaluation was performed on the stroke survivors by a licensed physical therapist (Table 1).[19] All participants were able to walk without an assistive device for 5 minutes at a time. Inclusion was limited to participants with a score greater than 22 on the mini-mental state examination.[20]

Table 1 Participant Characteristics

	Young adult	**Older adult—nonfaller**	**Older adult—faller**	**Stroke**
N	10	10	10	5
Age (range), y	30.5 (22–44)	71.9 (65–87)	75.3 (66–91)	61.6 (40–83)
Height (SD), m	1.74 (0.14)	1.68 (0.08)	1.72 (0.12)	1.68 (0.10)
Weight (SD), kg	76.0 (18.1)	75.9 (16.2)	86.3 (23.0)	82.6 (13.4)
Sex	5 males and 5 females	3 males and 7 females	5 males and 5 females	2 males and 3 females
Number of falls in the last 6 mo (range)	0.1 (0–1)	0	1.4 (1–3)	0.4 (0–1)
Mini-mental state exam (range)	29.6 (28–30)	29.3 (28–30)	28.6 (27–30)	27.6 (24–30)
LE Fugl-Meyer (range)	–	–	–	24.6 (17–31)

Affected side	–	–	–	3 on right side and 2 on left side
Type of stroke	–	–	–	5 ischemic
Time since stroke onset (range), mo	–	–	–	43.2 (10–120)

Abbreviation: LE, lower extremity.

Each participant was provided a pair of standard laboratory shoes in their proper size (Saucony Jazz, Lexington, MA) and tight-fitting shorts. Retroreflective markers for motion capture were applied bilaterally to the pelvis and feet. Tracking markers were placed on the right and left anterior and posterior superior iliac spines, and a rigid 4-marker cluster was attached to the heel counter of the shoes. A 3-second standing calibration was recorded with calibration markers on the greater trochanters, the distal end of each shoe, and the second metatarsal head. The joint center of each hip was established as 25% of the distance between the left and right greater trochanters,[21] and the pelvis tracking markers were used to identify the location of the hip joint center during walking. The heel marker cluster was used to determine the locations of the second metatarsal head and the distal end of the shoe during the movement trials, using a modification of the virtual marker representation outlined by Nagano et al.[11] Based on the assumption that the shoe is rigid during the swing phase, particularly during midswing, the virtual location of the distal toe marker position represented the toe trajectory during swing. The 3-dimensional positions of each tracking marker were collected at 200 Hz with a 10-camera system (Eagle; Motion Analysis Inc, Santa Rosa, CA), then filtered using a fourth-order, zero-lag, recursive Butterworth filter with a cutoff at 10 Hz. Processing of the kinematic data was done using Visual 3D software (version 5.00.24; C-Motion Inc, Rockville, MD).

Each participant walked approximately 10 m overground at a self-selected walking pace, and data were collected for 1 stride in the middle of the walkway and recorded as 1 trial. A total of 20 trials—10 each leg—were recorded for each participant, and participants returned to the original starting point at the beginning of each trial. Participants could rest if their rating of perceived exertion was above 9 (very light) to prevent potential confounds from fatigue.[22] Each swing phase was time normalized to 50 data points, with toe-off defined as the point when the horizontal (forward) velocity of the virtual location of the second metatarsal head marker changed from negative to positive, and heel-strike defined as the point when the horizontal velocity of the most distal heel marker changed from positive to negative.[23]

To determine the major modes of variation in toe height, PCA was applied to the vertical toe position waveform during the swing phase of all trials.[17] All trials of all subjects were organized into n rows of a matrix with the vertical toe position during swing filling 50 columns ($X_{n\times 50}$, where $\bar{x}_{1\times 50}$ is the mean of all trials). Eigenvector analysis produced the eigenvector matrix $U_{50\times 50}$. Each eigenvector represented a principal component (PC) that described 1 mode of variation within the data set. The eigenvalues ranked each PC's contribution to the total variation in the data. A parallel analysis with an equivalently sized input matrix of normally distributed randomly generated numbers revealed the variance explained by random error, and only PCs whose variance exceeded this threshold were retained. Each retained PC was interpreted according to the single PC reconstruction method.[24] Each trial was given a score for each of the retained PCs (Equation 1). $Z_{n\times 50}=[X_{n\times 50}-(1_{n\times 1}\times\bar{x}_{1\times 50})]\times U_{50\times 50}'$ (1)A local minimum was sought for all strides by searching for a negative peak in the toe height trajectory using the *findpeaks* function in MATLAB, and toe height at the local minimum was recorded as LM. For each stride that did not have a local minimum, the toe height at the mean location for the local minimum of that participant was used as an indicative measure of LM.[7] The central difference method was used to calculate the velocity of the toe in the horizontal (forward) direction, and the toe height at the maximal horizontal velocity was recorded as HV. The point of maximal limb shortening was identified as the minimum of the instantaneous distance between the hip joint center and toe divided by the instantaneous height of the hip joint center relative to the ground,[5] and toe height at the point of maximal limb shortening was recorded as MLS. Toe height at 50% of swing was recorded as S50. In addition, the location of each discrete point was recorded as a percentage of swing, and the number of strides without a local minimum of toe height was reported as a percentage of the total number of strides for that participant. Calculation of all variables was done using custom software (MATLAB version 8.0.0.783; Mathworks Inc, Natick, MA).

Each participant's mean and SD across all trials for each PC score and each discrete measure (LM, HV, MLS, and S50) were determined, and participants were ranked according to foot clearance and foot clearance variability, respectively. To identify the strength of associations between measures in ranking individuals based on foot clearance and foot clearance variability, 2-tailed Spearman's rank-order correlations were determined. To assess the effect of strides with and without a local minimum on the associations between measures of foot clearance and foot clearance variability, the correlation analysis was performed on 5 different subsets of the data set: (1) all participants, all strides; (2) all participants, strides with local minimum only; (3) participants with all strides containing a local minimum, all strides; (4) participants with at least 1 stride with no local minimum, strides with local minimum only; and (5) participants with at least 1 stride with no local minimum, strides with no local minimum only. Associations were defined as strong ($\rho > 0.7$), moderate ($0.7 \geq \rho \geq 0.3$), and weak ($0.3 > \rho$), with significance at $P < .05$. A Welch's F test was used to compare the percentage of strides without a local minimum across groups. All statistical analyses were done in SPSS (version 24.0.0.1; SPSS Inc, Chicago, IL).

Results

The results of the PCA of the vertical toe position during swing yielded 3 retained PCs, which accounted for a total of 95.34% of the total variance of the toe height waveform (Figure 1). Upon visual inspection of the features of toe height during swing characterized by each PC, the first PC (PC1) explained 72.13% of the overall variance in the toe height waveform and represented the magnitude of toe height during the second half of swing (50%–90%). The second PC (PC2) explained 12.42% of the overall variance in the toe height waveform and demonstrated a range in toe height, with almost all the variance explained by PC2 occurring during early to mid swing (0%–60%) when the toe was closest to the ground. The third PC (PC3) explained 10.79% of the overall variance in the toe height waveform and explained some of the variance during early swing (0%–40%), while the greatest amount of variance explained by PC3 occurred in the final part of swing (90%–100%) when the toe was farthest from the ground. Due to their relevance to toe height during midswing, the expected order of importance of the PCs to describe foot clearance was PC2, PC1, and then PC3. Among the discrete measures of foot clearance, LM was, by definition, the lowest measure of foot clearance (Table 2 and Figure 2).

Graph: Figure 1 —The effect of each of the 3 retained PCs on toe height during swing and the variance explained by each retained PC. PC1 represents the magnitude of toe height during the second half of swing, PC2 represents the magnitude of toe height during early to mid swing, and PC3 represents the magnitude of toe height primarily during the last 10% of swing. PC indicates principal component.

Table 2 Mean (SD) of Toe Height and Point During Swing Where Discrete Measure Occurred for All Participants

	Toe height, m	**Swing, %**
LM	0.025 (0.011)	47.408 (5.625)
S50	0.027 (0.011)	50.000 (0.000)
HV	0.027 (0.011)	55.166 (3.784)
MLS	0.032 (0.010)	45.755 (5.019)

Abbreviations: HV, toe height at greatest horizontal velocity; LM, toe height at local minimum; MLS, toe height at maximal limb shortening; S50, toe height at half of swing phase. By definition, the point during swing for S50 was 50% for all participants.

Graph: Figure 2 —Mean and SD across all participants of toe height throughout the swing phase. The mean locations of the LM, S50, HV, and MLS are identified. For strides where no local minimum was present, an indicative toe height was used for LM. HV indicates toe height at greatest horizontal velocity; LM, toe height at the local minimum; MLS, toe height at maximal limb shortening; S50, toe height at half of swing phase.

The results of the correlation analysis for the full data set (all participants and all strides) indicated a moderate or strong association between PC2 and all discrete measures of foot clearance and foot clearance variability rank, except MLS variability. The associations of PC1 and PC3 with the discrete variables were weaker than the PC2 associations. Among the discrete variables, there were strong associations between LM, S50, and HV, with moderate or strong associations between MLS and the other discrete variables. The associations for the second, third, and fourth subsets of the data set—for only strides with a local minimum—were similar to the associations from the full data set. In the fifth subset—for only strides without a local minimum—LM was calculated as the indicative toe height and had weak or negative associations with PC2 and the other discrete measures of foot clearance rank (Figure 3).

Graph: Figure 3 —Spearman's rho for the rank-order correlation between measures of foot clearance and foot clearance variability. (1) All participants (n = 35), all strides (669 strides), LM for strides with no local minimum set to participant mean for LM; (2) All participants (n = 35), strides with local minimum only (610 strides); (3) Participants with local minimum for all strides (n = 20), all strides (383 strides); (4) Participants with at least 1 stride with no local minimum (n = 15), strides with local minimum only (227 strides); and (5) Participants with at least 1 stride with no local minimum (n = 15), strides with no local minimum only, LM for strides with no local minimum set to participant mean for LM (59 strides). Note. HV indicates toe height at greatest horizontal velocity; LM, toe height at the local minimum; MLS, toe height at maximal limb shortening; PC, principal component; S50, toe height at half of swing phase. * P <.05, ** P <.01, and *** P <.001.

Of the 669 strides that could be processed, an LM was not present during swing for 59 strides (8.8% of all strides) from 15 participants (42.9% of all participants; Table 3). For 3 nonfallers, 1 faller, and 2 stroke survivors, at least 35% of their strides did not have a local minimum (Figure 4). The difference in percentage of strides without a local minimum across groups did not reach statistical significance ($F_{3,10.693}$ = 3.060, P =.075).

Table 3 Number and Percentage of Strides and Participants Without a Local Minimum for Each Group

	Strides without local minimum, N (%)	**Participants without local minimum, N (%)**
Young adult	1 (0.5)	1 (10.0)
Older adult—nonfaller	18 (9.0)	5 (50.0)
Older adult—faller	26 (13.3)	6 (60.0)
Stroke	14 (17.7)	3 (60.0)
Total	59 (8.8)	15 (42.9)

Graph: Figure 4 —Top: Vertical position of the toe during swing for the strides where a local minimum was not present, normalized to 0% to 100% of swing. Bottom: Number of participants in each percentile of strides without a local minimum (LM). The shade of each toe height waveform in the top graph corresponds to the shade of the bar in the bottom graph, and the white bar in the bottom graph represents the number of participants that had a local minimum for all of their strides.

Discussion

It is common practice to quantify foot clearance by finding a local minimum of toe height during swing.[2],[11]–[14] Yet, the results of this study supported previous work that indicated that a local minimum of toe height does not exist for all individuals or during every stride for a given individual.[5]–[8],[25] In addition, recent studies have utilized the toe trajectory throughout the swing phase to successfully quantify the probability of tripping or the risk of falling due to a trip.[15],[16] Therefore, the goal was to identify a nondiscrete measure of foot clearance that is capable of quantifying foot clearance during all strides, including those without a local minimum of toe height.

A PCA-based measure of foot clearance and foot clearance variability is accurate and applicable to all strides, particularly for PC2. In associations with the discrete variables, Spearman's rho was greater for PC2 than PC1 and PC3 for all measures of foot clearance and foot clearance variability. This result is likely due to the timing of each foot clearance measure. The discrete measures all occurred around 45% to 55% of swing, and most of the variance explained by PC2 also occurred during early to mid swing, while most of the variance explained by PC1 and PC3 occurred later in swing when the toe was typically raised. Therefore, PC2 and measures that have a strong association of foot clearance and foot clearance variability rank with PC2 should be considered appropriate for quantifying the minimum distance between the toe and the walking surface. However, there are benefits for using PCA instead of discrete variables. The role of PCA is to identify the major modes of variation within the data and, as such, the primary PCs represent nonrandom, behavioral components of toe height.[17] On the other hand, the discrete measures have no means of eliminating noise from the toe height signal. Therefore, the associations of foot clearance variability rank between PC2 and discrete measures are comparing the behavioral variation quantified by PCA and the combination of behavioral and random variation captured by the discrete measures.

Although similarities between the discrete measures were identified, differences in how these measures are calculated may affect their utilization. Computation of MLS requires tracking the location of the hip in addition to the toe—an extra step if foot clearance is the only desired kinematic measure. LM cannot be computed reliably. Nearly half of the participants had at least 1 stride where a local minimum did not exist, accounting for 8.8% of all strides and 60% of the strides of 1 participant. It may not be possible to know ahead of time which individuals are prone to walking without a local minimum of toe height. Although the effect of group on percentage of strides without a local minimum did not reach statistical significance in this study, previous research has shown that a lack of a local minimum is common among individuals with a history of stroke[5] and older adults,[6] and this trend was also observed in this study. Nevertheless, a lack of a local minimum was present even for a young adult, suggesting that LM may not be reliably measured among any demographic. Furthermore, using an indicative measure of toe height may not be an appropriate substitution for strides without a local minimum. In the subset of strides without a local minimum, LM represented by the indicative toe height had a weak association with PC2 and with all other discrete measures of foot clearance. This suggests that the trajectory of the toe is different for strides with and without a local minimum, and measures of foot clearance should be able to detect the appropriate features of the toe trajectory.

The other alternative discrete measures explored in this study involved identifying S50 and HV. Contrary to MLS, these values can be computed using only the trajectory of the toe and, unlike LM, the means to compute these values exist for all strides. In addition, among the discrete measures of foot clearance, HV and S50 had the strongest associations with LM for strides with a local minimum. Considering these measurements can be computed for all strides, HV and S50 appear to be the most reasonable options for quantifying foot clearance as a discrete measure. Although HV and S50 have among the highest associations of foot clearance and foot clearance variability rank with PC2 score, there may be other discrete variables that have a similar association, particularly regarding different locations on the foot and under various walking conditions.[26],[27] In addition, the PCA approach may provide a more robust measure of foot clearance than a discrete variable.

As the PCA approach relates information about foot clearance throughout the swing phase, it may provide better information regarding the risk of tripping. There is evidence to support this based on alternative, nondiscrete methods designed to evaluate the risk of tripping.[15],[16] These investigations highlight the importance of using the entire swing phase rather than a discrete point in the evaluation of the risk of tripping. One of the challenges of using a more abstract measure of foot clearance that incorporates the entire swing phase is that it cannot be interpreted as easily as discrete measures. In this study, the PC scores increased or decreased depending on the toe height during swing; however, the value of those PC scores does not represent the height of the toe in standard length units like the discrete measures. Despite this limitation in interpreting the PC scores, the PC scores can be used to rank individuals according to foot clearance and foot clearance variability. Although it is expected that low foot clearance and high foot clearance variability are related to the risk of falling,[2] it is beyond the scope of this study to quantify the risk of tripping based on the PCA or discrete measures of foot clearance and foot clearance variability.

One methodological limitation of this study was the use of a virtual marker defined by the heel cluster to represent the trajectory of the toe. The calibration marker on the most distal point of the shoe was not tracked during the movement trial as it extended the length of the shoe and may have affected the participants' foot clearance strategies. However, using the heel cluster to define the virtual toe marker relies on the incorrect assumption that the foot is rigid throughout the gait cycle. Therefore, a distortion in the toe trajectory occurred at points where the rearfoot moves independently from the toes, particularly around toe-off. This explains why the toe height appears to be negative at toe-off (Figures 1–3). However, considering that the period of interest in the gait cycle for this study was midswing, and the distance between the heel and the most distal point of the shoe was likely to be unchanged when the foot was completely off the ground, it is possible that any effect on the measures of foot clearance used in this study was minimal. The more proximal location of the separate virtual marker located at the second metatarsal head and used for the gait event detection algorithm[23] reduced the effect of within-foot motion on the timing of the gait events.

In summary, the results of this study indicate that a PCA approach to quantifying foot clearance and foot clearance variability can be used to identify the behavioral components of the height of the toe when it is closest to the ground, even for strides without a local minimum. Representation of LM with an indicative toe height for strides without a local minimum has a weak association with PCA and other discrete measures of foot clearance and may not be an appropriate estimation of foot clearance. As they do not consider the toe height throughout swing, discrete measures are likely not as useful as a PCA approach to quantify foot clearance and variability. However, HV and S50 appeared to be similar in the ranking of both magnitude and variability to the PCA variable that represents foot clearance in early to mid swing.

Acknowledgments

The authors thank Barbara Safarovic and Thomas Gus Almonroeder, PhD, DPT for their assistance with data collection, and Alexander Morgan, Alexandra Johnson, Stacey Benson, Hope Benson, and Thomas Benson for their assistance with data processing. This work was supported by the International Society of Biomechanics Matching Dissertation Grant and the University of Wisconsin-Milwaukee Student Research Grant. The sponsors had no role in the study design; in the collection, analysis, and interpretation of data; in the writing of the manuscript; or in the decision to submit the manuscript for publication. The authors have no conflicts of interest to disclose.

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