Stair-specific algorithms for identification of touch-down and foot-off when descending or ascending a non-instrumented staircase

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Research Highlights

Algorithms defining touch-down and foot-off (TD/FO) in stair ambulation are presented

Performance of these algorithms was determined by comparison to force defined events

TD/ FO were determined with acceptable precision in young and old adults

The algorithms performed equally well at differing riser heights (85-255 mm)

These algorithms can be used when force-instrumented staircases are unavailable

Abstract

The present study introduces four event detection algorithms for defining touch-down and foot-off during stair descent and stair ascent using segmental kinematics. For stair descent, vertical velocity minima of the whole body centre-of-mass was used to define touch-down, and foot-off was defined as the instant of trail limb peak knee flexion. For stair ascent, vertical velocity local minima of the lead-limb toe was used to define touch-down, and foot-off was defined as the local maxima in vertical displacement between the toe and pelvis. The performance of these algorithms was determined as the agreement in timings of kinematically derived events to those defined kinetically (ground reaction forces). Data were recorded while 17 young and 15 older adults completed stair descent and ascent trials over a four-step instrumented staircase. Trials were repeated for three stair riser height conditions (85 mm, 170 mm, and 255 mm). Kinematically derived touch-down and foot-off events showed good agreement (small 95% limits of agreement) with kinetically derived events for both young and older adults, across all riser heights, and for both ascent and descent. In addition, agreement metrics were better than those returned using existing kinematically derived event detection algorithms developed for overground gait. These results indicate that touch-down and foot-off during stair ascent and descent of non-instrumented staircases can be determined with acceptable precision using segmental kinematic data.

Keywords (5 words)

Event detection; stair descent; stair ascent; touch-down; foot-off

Introduction

When staircases are instrumented with force platforms, ground reaction forces (GRF) can be measured and used to accurately define important temporal events during stair ambulation such as touch-down (TD) and foot-off (FO). Many existing studies investigating stair ambulation have used non-instrumented staircases or partially instrumented staircases (force plate located in only one of multiple steps) [e.g: 1-4]. Using such staircases, other methods of event detection are required to calculate important parameters such as stance and swing phases. These parameters are useful in understanding the influence of clinical conditions or the effects of differing stimuli on stair ambulation and stepping dynamics [5]. Algorithms based on segmental kinematics (marker based) have previously been used to define initial-contact and toe-off during overground gait. These include using local maximas in the horizontal acceleration of the toe marker [6], in the vertical velocity of the foot [7], or in the foot to sacrum change in displacement (the 'coordinate-algorithm') [8]. The recent use of trail-limb local maxima hip extension to detect lead-limb initial-contact during overground gait [9] highlights that kinematic events further up the kinetic chain can be used as accurate alternatives to using foot kinematics to define the start or end of stance. Although kinematic algorithms for overground gait exist [6-9], they are unlikely to be as accurate for event detection when applied to stair ambulation because of the differences in segmental kinematics between each mode of gait. There are no formal reports regarding the use of kinematically-derived algorithms for the detection of TD and FO in stair ambulation, and given the sparse use and/or availability of force-instrumented staircases, such algorithms could have wide appeal.

Considering stair ambulation specifically, ascent and descent require completely different kinematic strategies [10]; thus event detection algorithms used for stair descent are unlikely to be suitable for stair ascent and vice versa. The present study introduces event detection algorithms defining TD and FO based on segmental kinematics for both stair ascent and stair descent. The performance of these algorithms were assessed by determining the agreement in kinematically derived TD and FO events with those determined from GRF (i.e. 'gold standard' method). Because there are kinematic and kinetic changes in stair ambulation that occur with ageing [11-13], new algorithms developed for stair-specific event detection may not perform equally for both young and older adults. We therefore assess the performance of the new algorithms for both young and older adults and do so for a range of stair riser heights that encompass those typically encountered in private and public spaces. In addition, to highlight the need for stair-specific event detection algorithms we compare the performance of the new algorithms to that achieved when using existing kinematic overground gait event detection algorithms to determine the same stair ambulation TD and FO events.

Methods

Seventeen healthy young adults (7 females; mean ± 1 SD; age: 25 ± 4 years, height: 1.76 ± 0.09 m, mass: 72.9 ± 11.7 kg) and fifteen healthy older adults (10 females; mean ± 1 SD; age: 75 ± 3 years, height: 1.62 ± 0.07 m, mass: 69.3 ± 11.1 kg) participated, each providing written informed consent. The study received approval from the institutional ethics committee and complied with the tenets of the Declaration of Helsinki. Participants were asked to complete 3-5 stair ambulation trials, first by ascending a 4-step staircase, then descending the same 4-step staircase, at self-selected speeds. Participants led with the right limb going over the first step edge for both ascent and descent, using 'step-over-step' gait so that the trail left limb went over the second step edge. Participants completed three separate testing sessions (on separate days) and were presented (ad-hoc order) with one of three riser height conditions (85 mm, 170 mm and 255 mm) on each occasion. These heights cover those typically encountered in domestic or public environments. Tread depth (280 mm) and width (900 mm) were constant for all riser heights. Force platforms (Kistler, Switzerland), embedded in each step-going and the floor at the base of the staircase captured kinetic data at 1080 Hz. Whole body kinematic data were captured at 120 Hz using a 10-camera motion capture system (Vicon 612 system, Oxford Metrics, UK). Reflective markers were positioned according to Vicon's 'plug-in-gait' full-body marker set (Oxford Metrics Ltd) [14]. Using plug-in-gait software data were filtered using the Woltering spline smoothing routine with 'MSE' set to 25, and then uploaded (at 120Hz) to Visual 3D (C-Motion, USA) for further analysis. In Visual 3D a whole body centre-of-mass representation was calculated as the weighted average positions of the head, thorax, pelvis, thighs, shanks and feet [15].

The 'gold standard' kinetic method of determining TD and FO were defined as the instants that the vertical component of the GRF was greater or less than 20 N, respectively [8].

The algorithms

Based on our previous analysis of stair/step ambulation (5,13) and following pilot work to confirm how existing overground gait event detection algorithms [8, 9] might be adapted, TD and FO events were identified for stair descent and ascent using the following approaches:

Stair descent: Local minima in centre-of-mass vertical velocity (CVA) was used to determine TD [13]. Local maxima in trailing-limb knee flexion was used to determine FO (PKF, Figure 1, [8]).

Stair ascent: Local minima in leading-limb toe vertical velocity (TV_{min}) was used to determine TD [5]. Local maxima in vertical displacement between the trailing-limb toe and pelvis segment (VD_{max}, Figure 1, [9]) was used to determine FO.

The kinematic algorithms were implemented in Visual 3D using the following criteria. Search windows were first created for the period of ambulation over each stair of the 4-step staircase. The horizontal position of the leading limb foot relative to each stair edge was used to define the start and end of each consecutive search window (note the leading limb for consecutive steps alternated between right and left limbs). The start of the search window for the first stair was defined as the instant at which the foot of the leading limb came within 300 mm of the stair edge. The end of the search window was defined as the instant the same foot first went 300 mm beyond the same stair edge, which occurred following transfer of body weight onto the contralateral limb on the succeeding stair. Subsequent search windows for the second, third and fourth stairs were defined in the same manner. The kinematic algorithms were then implemented within each search window to determine the instants of TD and FO of each limb on alternate stairs.

In total, 581 and 639 stair descent TD events and 453 and 507 stair descent FO events were determined for young and older adults respectively. In total, 438 and 409 stair ascent TD events and 535 and 480 stair ascent FO events were determined for young and older adults respectively.

The performance of each algorithm was assessed by determining how well the timings of the kinematically derived TD and FO events ’agreed’ with those derived using the GRF, using ‘limits of agreement’ (LoA) analyses [16]. A LoA analysis assesses the agreement between two different methods that measure the same quantity, and is often used to assess how much a new measurement method is likely to differ from the old (existing and/or ‘gold standard’ method) [16]. Such analysis determines the mean difference between the two measurement methods (bias), along with 95% agreement limits which determine the precision (range of agreement).

To assess the criterion validity of the new algorithms, agreement metrics for detecting stair ambulation TD and FO events were compared to those obtained using commonly used and/or recently developed existing overground gait kinematically derived event detection algorithms. For stair descent, these were the Foot Acceleration Algorithm (FAA, [6]) and the Foot Velocity Algorithm (FVA, [7]), both of which are used to determine FO in overground gait. FAA determines FO from local maxima in trailing-limb toe horizontal acceleration, whilst FVA determines FO from local maxima in trailing-limb foot centre vertical velocity. For stair ascent, one TD algorithm (ADmax, [8]) and one FO algorithm (PDmax, [8]) were included. These algorithms determine TD and FO from local maxima in the anterior and posterior displacement of the toe relative to the pelvis respectively.

To provide a global assessment of how each age group descended and ascended the stairs at each of the three stair riser height conditions, total stair descent and ascent durations were compared between age groups. Stair descent duration was determined from the instant of leading-limb FO prior to stepping over/down the top stair to the instant of leading-limb TD on the ground. Stair ascent duration was determined from the instant of leading-limb FO prior to stepping onto the initial stair above the ground to leading-limb TD on the landing above the top stair. The above FO and TD events were determined using the new algorithms. Average total descent and ascent times across the repeated trials were compared using mixed-design repeated measures ANOVA with age group (old, young) as between factor, and direction (stair descent, stair ascent) and stair riser height (85 mm, 170 mm, and 255 mm) as repeated factors. Post-hoc analysis was performed using Tukey's HSD.

Results

Stair descent and ascent durations

Descent/ascent durations were affected by age group ($p = 0.001$), direction ($p < 0.001$) and by stair riser height ($p < 0.001$), and there was also a group by riser height interaction ($p < 0.001$). Durations were longer in older compared to young adults, were longer for ascent than descent, and the increase in duration as riser height increased (both ascent and descent) was more pronounced in older adults (Table 1).

Agreement metrics for each algorithm

The mean (± 1 SD) bias, and 95% LoA in determining TD and FO events of each algorithm (new and existing) at each riser height condition and the average of all riser heights are presented for young and older adults in Tables 2 and 3 for descent and ascent respectively. Metrics data were normally distributed ($p > 0.05$).

Descent touch-down using CVA

In both groups TD occurred on average prior to (negative bias) kinetic TD across all riser heights (Table 2). CVA derived TD showed acceptable agreement with kinetic TD in both young and older adults across all riser heights.

D*escent foot-off using PKF*

In both groups FO occurred on average after (positive bias) kinetic FO across all riser heights (Table 2). PKF derived FO showed better agreement with kinetic FO in young compared to older adults, i.e. the 95% LoA were slightly smaller in young compared to older adults. FAA and FVA produced slightly smaller bias than PKF did, in both age groups. However, the 95% LoA when using these overground gait algorithms, were much larger compared to those determined with PKF, except at the riser height of 85 mm where the 95% LoA were less than that produced by PKF (in young both FAA and FVA performed better, whilst in older adults only FVA performed better).

Ascent touch-down using TV_{min}

In both groups TD occurred on average prior to (negative bias) kinetic TD across all riser heights (Table 3). There was reduced bias between TV_{min} derived TD and kinetic TD in older compared to young adults across all riser heights, though the 95% LoA were reduced in young adults. By comparison, AD_{max} indentified TD compared with kinetic TD with slightly smaller bias than TV_{min} did in both young and older adults. However, in both age groups the 95% LoA when using AD_{max} were much greater than those returned using TV_{min}.

Ascent foot-off using VD_{max}

In both groups FO occurred on average after (positive bias) kinetic FO across all riser heights (Table 3). Both VD_{max} and PD_{max} showed acceptable agreement with kinetic FO across all riser heights in young adults. However, in older adults VD_{max} showed much better agreement with kinetic FO than PD_{max}. The 95% LoA using PD_{max} were larger than those for $VD_{max,}$ in both young and older adults, across all riser heights.

Discussion

The results of the present study indicate that TD and FO events during stair ascent and descent can be determined with reasonable precision from segmental kinematics using newly presented event detection algorithms. Findings also indicate that the new stair-specific algorithms performed better at detecting stair ambulation TD and FO events than when using existing overground gait event detection algorithms.

For stair descent, the results suggest that PKF derived FO was determined with better agreement than FAA and FVA. However at a riser height of 85 mm the 95% LOA suggest there was better agreement between FAA or FVA and kinetic FO than PKF. This suggests that the overground algorithms might be more appropriate for detecting FO when descending smaller riser heights such as a kerb. However, British (building) standards for staircase design [17] state the minimum height of domestic and public staircases is 150 mm. Given such height restrictions, the present study's results suggest PKF would be a more appropriate method of identifying FO during stair descent of the majority of staircases that meet with existing building regulations. CVA derived TD showed very good agreement with kinetic TD across all riser heights, with slightly increased 95% LoA in older adults compared to young adults, which is likely a result of the higher inter-subject variability (Table 2) in the older group.

For stair ascent, although AD_{max} returned slightly better agreement than TV_{min} derived TD, the narrow 95% LoA and smaller variation in bias (reduced SD) for TV_{min} suggest that the newly defined algorithm would be the more appropriate method to use. A detailed inspection of the results produced by PD_{max} in young adults (Table 3) highlights that the average agreement between PD_{max} derived FO and kinetic FO across all riser heights is misleading. PD_{max} derived FO was determined to occur with either a negative or positive bias across the different riser height conditions. This random fluctuation between negative and positive bias gives the false impression of good average agreement (i.e. small mean bias) if all riser heights are combined. Moreover, the 95% LoA produced by PD_{max} were much greater than $VD_{max,}$ in both young and old adults, across all riser heights. These findings suggest that using the newly defined VD_{max} algorithm would provide a more valid method of determining FO.

It is noteworthy that the new stair descent and stair ascent TD algorithms determined TD events with a negative bias, indicating they identified the event prior to when it actually occurred (as determined by the force-derived method). In comparison the new stair descent and stair ascent FO algorithms determined FO events with a positive bias, indicating the event was identified after it actually occurred. This negative and positive bias may have been a result of the vertical GRF threshold (20 N) used to determine the instant of when TD and FO occurred (TD was the instant vertical GRF first became greater than 20N and FO was the instant vertical GRF became less than 20 N). We chose a threshold of 20 N because it clearly distinguished force readings from those from the unloaded force platform, which ranged between ± 1-3 N. If we had chosen a smaller threshold (e.g. 10 N) these bias's may have been reduced, however this would likely only reduce bias by at most one sampling frame (i.e. ~ 0.01 s). This highlights that any bias greater than 0.01 s indicated that the kinematically derived TD/FO event did indeed happen prior to/after the actual event (as determined from GRF's). Consequently, we recommend that a temporal correction is applied when using any of the new algorithms that returned a bias > 0.01 s in order to compensate for the bias. For bias's ≤ 0.01 s we suggest no correction is necessary. For algorithms with a bias > 0.01 s, we suggest that a temporal correction equal to the bias rounded to the nearest hundredth of a second should be applied.

Despite stair descent and stair ascent completion times being greater in the older compared to young participants, with such increases becoming more pronounced with increased riser height (Table 1), the agreement between events derived using the newly defined kinematic algorithms and kinetic derived events was comparable across the different groups and riser heights. This suggests the event detection algorithms are sufficiently robust for detecting TD and FO in a relatively wide range of experimental conditions.

Motion capture systems are routinely used to capture full body human movement, and post-processing techniques are widely available to extract meaningful results from the action performed. The complexity of implementing the newly defined event detection algorithms during post-processing of stair descent or stair ascent movement trials is no more onerous than what would be undertaken during routine gait analyses [6-9]. In addition, the newly defined methods of event detection can be easily applied retrospectively; which facilitates the calculation of stance and swing phase durations from existing datasets where non-instrumented staircases were used. It is worth highlighting that when determining FO using the VD_{max} algorithm, the present study considered the pelvis segment to be a more appropriate reference than using a single sacrum marker. We used this approach because not all kinematic modelling approaches require a sacrum marker to define the pelvis [15]. As such, use of VD_{max} should have wide appeal as it avoids restricting its use to a particular modelling approach.

In summary, this study formally introduces and validates four event detection algorithms for detecting TD and FO during stair descent (algorithms CVA and PKF) and stair ascent (algorithms TV_{min} and VD_{max}) using segmental kinematics. The results of the study revealed that use of these algorithms identified TD and FO events with acceptable agreement compared to force-derived TD and FO, and all performed better at detecting stair ambulation TD and FO events than existing overground gait event detection algorithms did. These findings indicate that the new algorithms can be used to detect TD and FO events in stair ambulation studies that use non-instrumented staircases. Furthermore, these algorithms performed equally well in both young and older adults and across differing stair riser height conditions, suggesting they can be used over a wide range of stair ambulation studies with differing methodology.

Conflict of interest statement

There are no conflicts of interest in this work.

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Table 1. Average movement duration times (s) of stair descent and ascent in young and older adults.

		Movement duration (s)		
	Riser height:	85 mm	170 mm	255 mm
Stair descent	Young	2.246 ± 0.273	2.276 ± 0.246	2.580 ± 0.340
	Older*	2.386 ± 0.350	2.647 ± 0.438	3.172 ± 0.474
Stair ascent	Young	2.882 ± 0.417	2.839 ± 0.335	3.075 ± 0.339
	Older*	3.036 ± 0.282	3.012 ± 0.397	3.545 ± 0.450

*significantly different to young ($p = 0.001$): a significant group-by-riser height interaction effect ($p < 0.001$) indicated differences became more pronounced at the higher riser heights.

Table 2. Mean difference (± 1 SD) and variability (95% LoA) of how well each algorithm defined touch-down (TD) and foot-off (FO) events compared to kinetically defined TD and FO during stair descent for each riser height condition in young and older adults.

Event	Algorithm	Riser (mm)	Mean Difference (s)		95% LoA (s)	
			Young	*Older*	*Young*	*Older*
TD	Vertical velocity of the whole body centre-of-mass (CVA)	Combined	- 0.004 ± 0.020	- 0.007 ± 0.033	- 0.044 / + 0.035	- 0.071 / + 0.057
		85	+ 0.005 ± 0.018	- 0.016 ± 0.034	- 0.030 / + 0.041	- 0.083 / + 0.051
		170	- 0.015 ± 0.018	- 0.011 ± 0.036	- 0.053 / + 0.023	- 0.082 / + 0.060
		255	- 0.0002 ± 0.017	- 0.006 ± 0.021	- 0.034 / + 0.034	- 0.036 / + 0.048
FO	Peak knee flexion (PKF)	Combined	+ 0.044 ± 0.020	+ 0.050 ± 0.026	+ 0.005 / + 0.083	- 0.001 / + 0.101
		85	+ 0.056 ± 0.020	+ 0.060 ± 0.017	+ 0.016 / + 0.097	+ 0.027 / + 0.093
		170	+ 0.043 ± 0.015	+ 0.050 ± 0.024	+ 0.014 / + 0.073	+ 0.002 / + 0.098
		255	+ 0.033 ± 0.017	+ 0.040 ± 0.031	+ 0.000 / + 0.066	- 0.022 / + 0.101
	*Foot acceleration algorithm (FAA)	Combined	+ 0.011 ± 0.050	+ 0.036 ± 0.059	- 0.087 / + 0.110	- 0.080 / + 0.151
		85	+ 0.006 ± 0.012	+ 0.016 ± 0.021	- 0.018 / + 0.030	- 0.026 / + 0.058
		170	- 0.004 ± 0.051	+ 0.020 ± 0.049	- 0.105 / + 0.097	- 0.077 / + 0.117
		255	+ 0.032 ± 0.063	+ 0.075 ± 0.075	- 0.093 / + 0.127	- 0.074 / + 0.223
	*Foot velocity algorithm (FVA)	Combined	- 0.037 ± 0.040	- 0.049 ± 0.033	- 0.115 / + 0.042	- 0.114 / + 0.016
		85	- 0.029 ± 0.015	- 0.031 ± 0.013	- 0.060 / + 0.002	- 0.057 / - 0.005
		170	- 0.037 ± 0.051	- 0.049 ± 0.025	- 0.138 / + 0.063	- 0.099 / + 0.000
		255	- 0.043 ± 0.042	- 0.067 ± 0.044	- 0.127 / + 0.041	- 0.154 / + 0.020

* Existing overground gait event detection algorithms [6, 7]

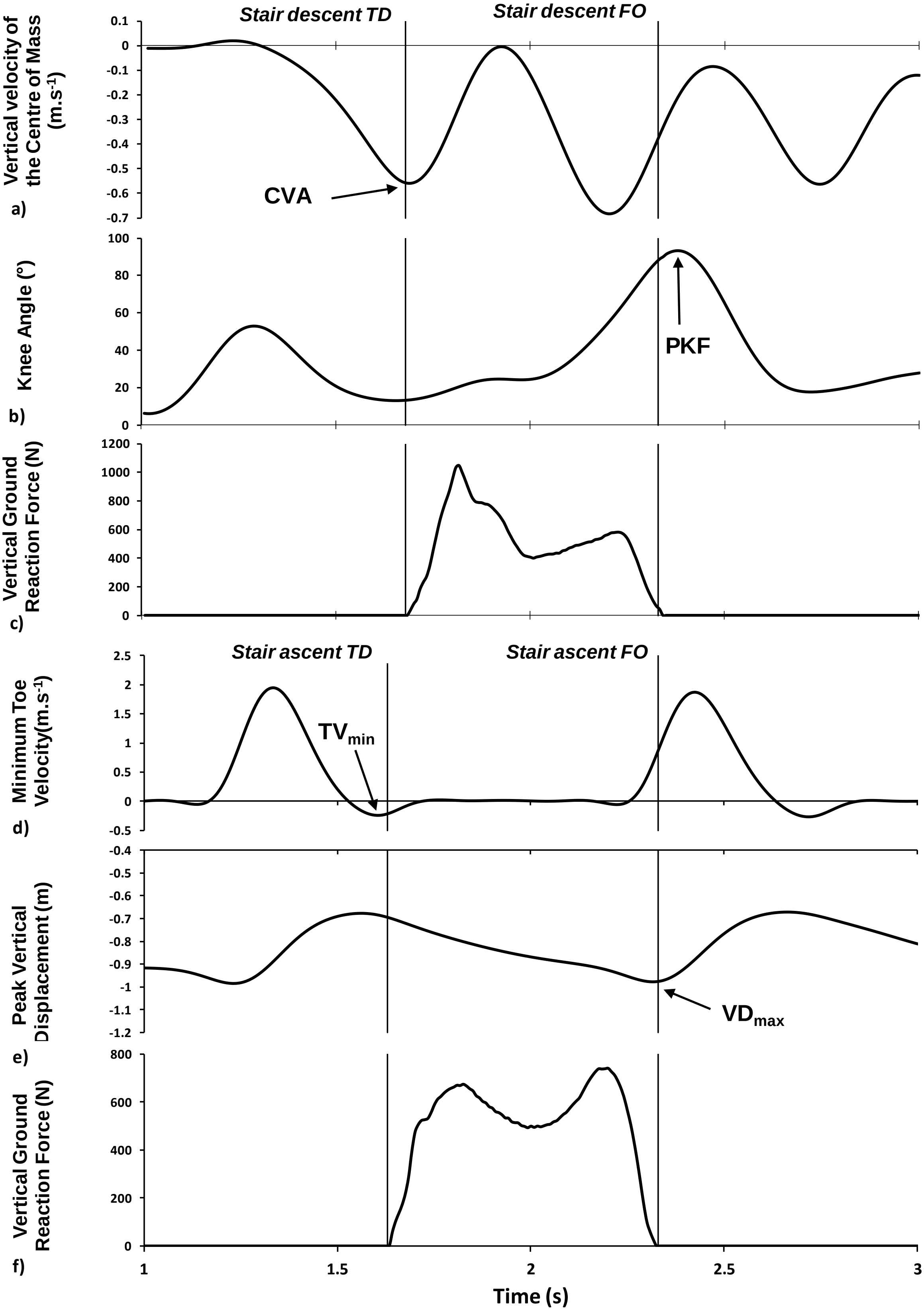
Table 3. Mean difference (± 1 SD) and variability of how well each algorithm defined touch-down (TD) and foot-off (FO) events compared to kinetically defined TD and FO during stair ascent for each riser height condition in young and older adults.

Event	Algorithm	Riser (mm)	Mean Difference (s)		95% LoA (s)	
			Young	*Older*	*Young*	*Older*
TD	Vertical velocity of the toe marker (TV_{min})	Combined	- 0.040 ± 0.019	- 0.031 ± 0.025	- 0.077 / - 0.003	- 0.081 / + 0.018
		85	- 0.039 ± 0.024	- 0.018 ± 0.013	- 0.087 / + 0.010	- 0.045 / + 0.009
		170	- 0.037 ± 0.015	- 0.045 ± 0.018	- 0.066 / - 0.008	- 0.081 / - 0.008
		255	- 0.044 ± 0.016	- 0.029 ± 0.033	- 0.074 / - 0.013	- 0.094 / + 0.035
	*Peak Anterior Displacement (AD_{max})	Combined	- 0.028 ± 0.032	- 0.015 ± 0.081	- 0.090 / + 0.034	- 0.176 / + 0.145
		85	- 0.033 ± 0.040	- 0.029 ± 0.033	- 0.111 / + 0.046	- 0.095 / + 0.037
		170	- 0.024 ± 0.019	- 0.026 ± 0.042	- 0.061 / + 0.013	- 0.108 / + 0.057
		255	- 0.028 ± 0.033	- 0.014 ± 0.133	- 0.093 / + 0.038	- 0.249 / + 0.277
FO	Peak Vertical Displacement (VD_{max})	Combined	+ 0.013 ± 0.022	+ 0.015 ± 0.028	- 0.030 / + 0.057	- 0.041 / + 0.071
		85	- 0.004 ± 0.018	+ 0.009 ± 0.015	- 0.031 / + 0.039	- 0.021 / + 0.039
		170	+ 0.003 ± 0.016	+ 0.011 ± 0.025	- 0.029 / + 0.035	- 0.038 / + 0.060
		255	+ 0.029 ± 0.020	+ 0.025 ± 0.037	- 0.010 / + 0.070	- 0.047 / + 0.098
	*Peak posterior displacement (PD_{max})	Combined	- 0.013 ± 0.062	+ 0.105 ± 0.112	- 0.136 / + 0.109	- 0.116 / + 0.325
		85	- 0.110 ± 0.065	+ 0.079 ± 0.071	- 0.239 / + 0.019	- 0.062 / + 0.219
		170	+ 0.117 ± 0.060	+ 0.116 ± 0.085	- 0.001 / + 0.235	- 0.051 / + 0.282
		255	+ 0.143 ± 0.085	+ 0.111 ± 0.156	- 0.025 / + 0.311	- 0.196 / + 0.419

* Existing overground gait event detection algorithms [8]

Figure 1. Vertical velocity of the whole body centre-of-mass (a), sagittal knee angle (b) and vertical ground reaction force (c) during an exemplar stair descent trial, and vertical velocity of the toe marker (d), peak vertical displacement of the toe marker relative to the pelvis segment (e) and vertical ground reaction force (f) during an exemplar stair ascent trial. Vertical lines indicate instants of touch-down (TD) and foot-off (FO) defined using ground reaction force data. CVA indicates vertical velocity minima of the whole body centre-of-mass. PKF indicates trail limb peak knee flexion. TV_{min} indicates vertical velocity minima of the toe marker. VD_{max} indicates the instant of peak vertical displacement between the toe marker and pelvis.

Figure 1.



Stair descent TD
Stair descent FO
a) Vertical velocity of the Centre of Mass (m.s-1)
CVA
b) Knee Angle (°)
PKF
c) Vertical Ground Reaction Force (N)
Stair ascent TD
Stair ascent FO
d) Minimum Toe Velocity(m.s-1)
TVmin
e) Peak Vertical Displacement (m)
VDmax
f) Vertical Ground Reaction Force (N)
Time (s)