Novel methodology for assessing total recovery time in response to unexpected perturbations while walking

Uri Rosenblum[1,2], Lotem Kribus-Shmiel[1], Gabi Zeilig[3,4], Yotam Bahat[1], Shani Kimel-Naor[1], Itshak Melzer[2], Meir Plotnik[1,5,6*]

[1] Center of Advanced Technologies in Rehabilitation, Sheba Medical Center, Tel Hashomer, Israel

[2] Department of Physical Therapy, Recanati School for Community Health Professions, Faculty of Health Sciences, Ben-Gurion University of the Negev, Beer-Sheva, Israel

[3] Department of Neurological Rehabilitation, Sheba Medical Center, Tel HaShomer, Israel

[4] Department of Physical and Rehabilitation Medicine, Sackler Faculty of Medicine, Tel Aviv University, Israel

[5] Department of Physiology and Pharmacology, Sackler Faculty of Medicine, Tel Aviv University, Tel Aviv, Israel

[6] Sagol School of Neuroscience, Tel Aviv University, Tel Aviv, Israel

***** Corresponding author

Email: meir.plontik@sheba.health.gov.il (MP)

Abstract

Walking stability is achieved by adjusting the medio-lateral and anterior-posterior dimensions of the base of support to contain an extrapolated center of mass. We aimed to calculate total recovery time after different types of perturbations during walking, and use it to compare young and older adults following different types of perturbations. Walking trials were performed in 12 young (age 26.92, SD = 3.40 years) and 12 older (age 66.83, SD = 1.60 years) adults. Perturbations were introduced at different phases of the gait cycle, on both legs and in anterior-posterior or medio-lateral directions, in random order. A novel algorithm was developed to determine total recovery time values for regaining stable step length and step width parameters following the different perturbations and compared between the two participant groups under low and high cognitive load conditions, using principal component analysis (PCA). We analyzed 829 perturbations each for step length and step width. The algorithm successfully estimated total recovery time in 91.07% of the runs. PCA and statistical comparisons showed significant differences in step length and step width recovery times between anterior-posterior and medio-lateral perturbations, but no age-related differences. Initial analyses demonstrated the feasibility of comparisons based on total recovery time calculated using our algorithm.

Introduction

For older adults, falls are a debilitating health problem affecting physical and psychological health [1]. Most falls in independent older adults occur when they slip (27%-32%) or trip (35%-47%) while walking [1]. Thirty percent of community-dwelling older adults fall at least once a year [1] and 10%-20% are recurrent fallers [2,3]. About 20% of falls are injurious, leading to reduced mobility and independence and increased morbidity and mortality rates [4]. Falls are associated with estimated medical costs of about $50 billion per year[5].

A fall is defined as a failure of the balance control system to recover from an unexpected loss of balance, or balance perturbation. Hof et al. [6,7] showed that during walking, balance is maintained by keeping an 'extrapolated center of mass' within the boundaries of the base of support [8].

Of several previous studies examining the kinematic properties of balance recovery [8–10], some have demonstrated that the stabilization of walking speed and stepping frequency following perturbation is a two-stage process [[11] [12]. The first stage (initial response) is aimed at reducing the perturbation effect to minimum, the second stage is a gradual return to steady state. Electromyogram (EMG) studies have documented the temporal process associated with the first stage of balance recovery (i.e. the first step after perturbation – first recovery step) [e.g., [13]]. However, to the best of our knowledge, no systematic method has been proposed for estimating the total recovery time of gait parameters such as step length and step width, or the period of time required to reach a routine walking pattern with stable characteristics following a perturbation (see Methods section for further details). Hof and colleagues have proposed that accurate generation of step length and step width will optimize the required timing and placement of the extrapolated center of mass within the base of support [8,9]. Recently, Madehkhaksar et al. [10] found that in order to increase dynamic stability immediately after perturbation, young adults walk with shorter, wider strides and a higher cadence, with a stronger response to medio-lateral than to anterior-posterior perturbations. Vlutters et al.[14] found similar results when applying perturbations to the hip during walking stating that "at heel strike after the perturbation, recovery from medio-lateral perturbations involved medio-lateral foot placement adjustments proportional to the medio-lateral center of mass velocity. In contrast, for anteroposterior perturbations, no significant anteroposterior foot placement adjustment occurred".

McIlroy and Maki[15] showed that young and old adults use different strategies to regain balance after medio-lateral perturbations in standing condition. The old adults, in general, use greater number of steps to recover. This result was repeated in walking[16].

The effect of cognitive load on postural stability is a subject of controversy. In a systematic review and meta-analysis Ghai et al.[17] found a negative impact of dual tasks on postural stability among fall-prone population groups affected by neurological disorders and/or with prior history of fall, as compared to younger healthier groups. However, they also found that some dual tasks enhance (e.g. auditory switch task) and other adversely impact (e.g. complex mental arithmetic task) postural stability.

In the present study, step length and step width were measured to accomplish the following aims: (1) devise an algorithm to calculate total recovery time; (2) conduct exploratory pilot analyses to demonstrate the feasibility of the new method in characterizing total recovery time among young and old adults under different perturbation conditions; and (3) explore differences in total recovery time for step length and step width parameters, as a function of perturbation direction, participant group (young versus old adults), and cognitive load. We hypothesized that total recovery time would be longer following medio-lateral than anterior-posterior perturbations, young adults would recover faster than older adults, and total recovery time would be shorter under single task than dual task conditions.

Methods

Participants

Twelve healthy young adults and twelve healthy older adults participated in the study (see demographic and physical characteristics in Table 1). Exclusion criteria were: (1) obesity (body mass index > 30 [18]); (2) orthopedic condition affecting gait and balance (e.g., total knee replacement, total hip replacement, ankle sprain, limb fracture, etc.); (3) cognitive or psychiatric conditions that could jeopardize the participant's ability to participate in the study (Mini-Mental State Exam score < 24 [19]); (4) heart condition, such as non-stable ischemic heart disease or moderate to severe congestive heart failure; (5) severe chronic obstructive pulmonary disease; (6) neurological disease associated with balance disorders (e.g., multiple sclerosis, myelopathy, etc.).

Table 1: Comparison of demographic and physical characteristics (mean ± standard deviation) in young and older adults.

	Young Adults (n = 12)	Older Adults (n = 12)	*P* value
Age (years)	26.92 ± 3.40	69.50 ± 5.20	< 0.0001*
Sex (F/M)	5/7	6/6	0.56
Height (cm)	168.42 ± 7.32	169.67 ± 6.68	0.82
Weight (kg)	63.67 ± 10.26	78.34 ± 16.22	0.02*

BMI (kg^2/cm)	24.45 ± 7.30	37.35 ± 15.35	0.01*
Years of education	15.25 ± 2.67	14.27 ± 2.24	0.66

Comparisons were made using the Mann–Whitney U test and cross-tabulation as needed; BMI, body mass index; **p* < .05.

All participants signed an informed consent prior to entering the study, which was approved by the Sheba Medical Center institutional review board (approval number 9407-12).

Apparatus

We implemented a virtual reality (VR)-based paradigm using the Computer Assisted Rehabilitation Environment (CAREN) High-End (Motek-Medical, the Netherlands; see Fig 1), a motion base platform with an imbedded treadmill, surrounded by a 360° dome shaped screen, enabling optimal immersion in a largescale VR setting. During walking trials, participants (in a safety harness) were presented with simulated ecological surroundings (e.g., urban public park).

Fig 1. Experimental setup. Participants walked on a treadmill in self-paced mode. The treadmill is embedded in a moveable platform with six degrees of freedom (three translations and three rotations). They were exposed to unexpected platform (medio-lateral) or treadmill (anterior-posterior) perturbations in a virtual reality environment. Vicon, motion capture cameras, were used to calculate walking parameters of step length and step width based on marker data from the feet. A small backpack was used to carry a wireless amplifier connected to biosensors (e.g., electroencephalography, electromyography), data from which are not reported here.

Self-paced walking mode

The treadmill was operated in self-paced mode, in which the motor is operated as a function of the instantaneous position and speed of the participant, which are sampled using a motion capture system (see more details in [20]).

Physical perturbations

Two types of perturbations were implemented: (1) medio-lateral platform perturbations were achieved by displacing the moving platform 15 cm over 0.92 seconds. The platform held its new position for 30 seconds, to allow full recovery of the gait parameters (i.e., step length and step width), and then returned gradually to its original position over 3 seconds; (2) anterior-posterior treadmill belt perturbations were achieved by reducing the speed of one of the treadmill belts by 1.2 m/s with a deceleration of 5 m/s^2 (perturbation level 12, see Fig 2). To enable anterior-posterior perturbations, the treadmill speed was fixed to the measured average self-paced walking speed 5 seconds prior to perturbation onset. The perturbation was presented when the relevant gait phase was detected, and 3 seconds later the treadmill was once again set to self-paced mode (see perturbation profiles, Fig 2). Four of the twelve older adults were unable to manage this magnitude, thus lower magnitudes were used (levels 3-8, see Fig 2 legend). Perturbation magnitude and timing (see experimental procedure below) were controlled and modified by the VR system computer.

Fig 2. Perturbation profiles used in the platform (top) and treadmill (bottom) experiments.

Perturbation levels ranged from Level 1 to Level 20. For platform perturbations, we used a fixed displacement of 15 cm for all levels and the time to complete the distance was manipulated between 1.36 seconds (Level 1) to 0.6 seconds (Level 20); progression interval was 0.04 seconds per level. For treadmill perturbations we used a fixed deceleration of 5 m/s^2 for all levels and the reduction in speed was manipulated between 0.1 m/s (Level 1) to 2 m/s (Level 20); progression interval was 0.1 m/s per level. Prior to and immediately following the treadmill perturbation, the two belt speeds were fixed (periods between black and red vertical dashed lines, respectively; Level 12; see text for further details).

Capturing gait parameters

Gait speed was obtained from an encoder on the drive shaft of the treadmill motor. Spatial-temporal gait parameters (i.e., step times, step length, and step width) were obtained from a Vicon (Vicon Motion Systems, Oxford, UK) motion capture system (set of 41 body markers, 120Hz sampling rate, 0.11 cm spatial accuracy). Gait cycle phases were detected using foot marker and force plate data.

Experimental procedure

Stage I: Self-paced walking – learning and acclimation

The trials started with acclimation sessions during which participants were introduced to the self-paced walking paradigm. Participants were asked to maintain their comfortable walking speed for one minute, and then to dynamically modify their gait speed, including accelerating, decelerating, coming to a full stop, and resuming their comfortable walking speed. This was repeated until they felt confident and performed the transition from standing to comfortable walking speed smoothly.

Stage II: Introducing physical perturbations during walking

Four to twelve gait trials were introduced for each participant, each lasting five or ten minutes. Once the participant reached steady state walking velocity (SSWV; see supplementary material for further details), one of several types of unexpected perturbations was randomly presented (see below) in two trials conditions: (a) the single task condition, in which no additional cognitive load was introduced; (b) the dual task condition, in which participants were asked to perform concurrent arithmetic calculations [21] higher cognitive load. Similar arithmetic tasks were practiced by the participants prior to the gait trials, while sitting and standing. Participants were instructed to react naturally to the perturbations, to prevent themselves from falling.

Perturbation types were classified according to the following criteria: (1) gait cycle phase – immediately after initial contact, mid-stance, or towards toe off, as detected in real time from foot markers and force plates data; (2) perturbation direction –medio-lateral or anterior-posterior; and (3) foot of reference. A total of 18 possible surface perturbations were used in random order to reduce learnings effect from trial to trial. At least 30 seconds of baseline walking were implemented before and after every perturbation to allow full recovery of the kinematic gait parameters. This experiment was part of a larger study with the overall aim of developing Algorithms for the analysis of physiological networks for fall prevention in elderly subjects with and without neurological disease using virtual reality environments. Additional procedures related to the larger experimental protocol are described in the supplementary material.

Data handling and outcome calculations

The proposed algorithm for the estimation of total recovery time for gait (see below) was based on the re-stabilization of discrete step length and step width variables.

Step width and step length calculation

A MATLAB (MathWorks Inc.) Graphical User Interface was customized to assess gait cycle parameters. Motion capture data from heel markers were used to semi-automatically detect initial contact times and calculate step length and step width (see Fig 3A for more details). The following equations (conducted for each leg) were used for the calculation of step length and step width, respectively:

$$\text{(Eq. 1) } SL = HM_L(y) - HM_T(y)$$

$$\text{(Eq. 2) } SW = HM_L(x) - HM_T(x)$$

where y is anterior-posterior axis, x is the medio-lateral axis, HM_L is the leading limb heel marker at the moment of initial contact, and HM_T is the trailing limb heel marker at the moment of initial contact of the leading limb. Examples of actual step length and step width data before and after perturbations are shown in Figs 3B and 3C, respectively.

Fig 3. Step width and step length calculation and sample data.

(A) Illustration of step length and step width calculation. (B) Step length and step width behavior in response to anterior posterior treadmill belt perturbation**.** Top panel: trace of treadmill belt speed shows treadmill perturbation profile; red – right belt, blue – left belt (seen only at time of perturbation, as the two belt speeds were otherwise identical); middle panel: trace of step length values prior to and post perturbation; lower panel: trace of step width values prior to and post perturbation. (C) Step length and step width behavior in response to medio-lateral platform perturbation**.** Top panel: trace of platform displacement shows platform perturbation profile (positive values = right direction); middle panel: trace of step length values prior to and post perturbation; lower panel: trace of step width values prior to and post perturbation. Negative step length values represent backward steps of the leading limb, while negative step width values represent a crossover step with the leading limb. (B) and (C) depict 45 and 40 seconds, respectively, of walk trials from one participant. Values from the right and left leg are depicted in all panels (alternating; not distinguished in the trace). Vertical dashed line represents perturbation onset time.

Definition of an automated algorithm to detect total recovery time

Given a graph that represents a vector of gait parameter data (i.e., step length or step width) with a perturbation at time t, the goal of the algorithm is to detect the first point after t at which the graph (i.e., the values in the vector) is considered "recovered," having reached a stable pattern.

Fig 4 will be used to facilitate our explanation of the algorithm, which operates in three stages: (1) computes two implied graphs using a moving window, a graph of means and a graph of standard deviations, from the original data; (2) standardizes the implied graphs, and creates a combined graph; and (3) scans the combined graph from left to right and continually updates an index, which eventually represents the point of recovery.

Fig 4. Algorithm performance steps.

(A) Graph of step width values (blue circles; connected to graphically enhance perturbation effect). (B) Implied graphs for means (M; red) and standard deviations (SD; yellow), calculated using a moving window of six samples. Each point in the graphs represents data from six preceding original data points (depicted by the black vertical arrow between panel A and B). For each implied graph, 20 samples prior to perturbation onset were taken as baseline (**M_{BL}** and **SD_{BL},** denoted by horizontal black brackets). (C) **M_{BL}** and **SD_{BL}** were used to standardize the implied graphs, to create the overall sum of deviations (OSDev – blue line, calculated using Eq. 3). To determine the recovery point, the algorithm scanned the OSDev graph from left to right, using a moving window of 20 values starting at perturbation onset. The recovery point is then defined using a mathematical criterion (see details in Methods and supplementary material) that assesses minimal changes in signal amplitudes (green circle; corresponds to the original step value indicated by the green arrow in panel A).

Black dashed line represents perturbation onset.

Stage 1. The original walking parameter graph (Fig 4A) is scanned using a moving window of six samples to compute two graphs: mean and standard deviation (Fig 4B). Each point in the graphs represents the mean or standard deviation of the six original samples prior to it.

Stage 2. For each implied graph, 20 samples prior to perturbation onset were taken as baseline (**M_{BL}** and **SD_{BL}**; Fig 4) to standardize the implied graphs. Mean and standard deviation were calculated for each baseline. Then, each value M_i and SD_i of the implied graphs is standardized, and matching standardized data points are summed to obtain the overall sum of deviations (OSDev – Fig 4C) using the following equation:

(Eq. 3)

$$\text{OSDev}, i = 0.25 * \left|\frac{Mi - mean(\boldsymbol{M_{BL}})}{stdev(\boldsymbol{M_{BL}})}\right| + max\left(0, \frac{SDi - mean(\boldsymbol{SD_{BL}})}{stdev(\boldsymbol{SD_{BL}})}\right)$$

where i = 1, 2, …, L; and L = length of implied graphs. Intuitively, the combined graph estimates the deviation from the behavior of the graph prior to perturbation. The second element in the equation takes the positive values and replaces the negative values with zeros, as negative values mean lower standard deviation, which corresponds to smaller variance (i.e., more stable). Since the average value is less indicative of gait recovery, the elements in Eq. 3 are summed up with a ratio of 1:4 in favor of the second element. The outcome of this stage is the OSDev graph (Fig 4C), which is used to inspect the recovery criteria.

Stage 3. To determine the point of recovery, the algorithm scans the OSDev graph from left to right, using a moving window of 20 values starting at perturbation onset. For each window, the algorithm computes ‘amplitude,’ defined as the maximum difference between any two values in the window. The point of recovery is the point at which the amplitude difference is small enough relative to the ‘distance’ from perturbation (see Eq. S1 in supplementary materials). Complete definitions and mathematical descriptions of the criteria and conditions for defining the point of recovery (including the case in which no point of recovery was detected) are described in the supplementary materials.

Data and statistical analyses

Non-parametric statistics were used. Medians and 95% confidence interval of the median were used to describe central tendency of the total recovery time distributions. To explore the effects of perturbation direction (medio-lateral versus anterior-posterior), the group (young versus older adults), and cognitive load (single task versus dual task) on total recovery times, principal component analysis (PCA) was used, applying the singular value decomposition (SVD). Total recovery time values for regaining stable step length and step width parameters were the PCA variables. PCA was performed using MATLAB R2016b (MathWorks Inc.). Comparison of central tendencies along the different principal components (PC) was used to test the effects above.

Results

Algorithm performance

Total recovery time values were calculated for step length and step width separately, based on 829 samples. ‘No deviation’ was found in 47 and 57 perturbations for step length and step width, respectively (11 overlapping). ‘No recovery’ was detected in 11 and 33 perturbations for step length and step width, respectively (1 overlapping; see Fig 5).

Fig 5. Flow chart of algorithm performance for gait parameters of step length (SL) and step width (SW).

The 829 perturbations include samples from pilot trials aimed at defining the appropriate baseline period (>18 seconds of undisturbed walking prior to perturbation to include at least 26 steps – see supplementary material).

Total recovery time distributions

Distribution of total recovery time in the two groups, for step length and step width, across all participants, experimental conditions, and perturbation types and intensities are presented in Figs 6A-D. In most cases, participants recovered from the unexpected mechanical perturbations after 4-6 seconds regardless of the perturbation type

(Fig 6A-D). The 95% confidence intervals of the medians of total recovery time were 4.70-5.09 seconds for step length in older adults, 5.38-6.00 seconds for step width in older adults, 4.92-5.23 seconds for step length in young adults and 5.47-5.97 seconds for step width in young adults (Table 2).

Fig 6. Total recovery time distributions.

Bins of two seconds were used. (A), (C), distribution of step length total recovery time for older and young adults, respectively. (B), (D), distribution of step width total recovery time for older and young adults, respectively.

Table 2. Central tendency measures and variability of recovery times by group, condition, and perturbation group type.

		PLtMsLt		PLtMsRt		PRtMsLt		PRtMsRt		TmMsLt		TmMsRt	
		SL	SW	SL	SW	SL	SW	SL	SW	SL	SW	SL	SW
OA ST	Median (n)	5.06 (21)	5.32 (21)	4.733 (22)	5.70 (22)	4.63 (18)	5.67 (18)	5.03 (23)	6.00 (23)	4.13 (8)	5.96 (8)	4.60 (20)	7.20 (20)
	Min	3.92	4.17	3.58	4.00	3.57	3.57	3.50	4.25	3.66	5.45	3.74	3.75
	Max	21.13	13.99	14.47	22.07	12.33	9.85	27.61	16.30	4.71	10.61	8.31	28.18
OA DT	Median (n)	4.67 (36)	5.28 (36)	5.59 (22)	6.42 (22)	4.67 (10)	5.19 (10)	5.39 (20)	5.08 (20)	4.62 (21)	5.77 (21)	4.68 (18)	7.40 (18)
	Min	3.82	3.74	3.56	4.15	3.30	4.62	3.62	4.06	0.97	3.27	3.81	4.30
	Max	17.72	14.25	28.55	21.13	7.61	6.07	10.97	11.19	10.19	17.51	19.92	25.77
YA ST	Median (n)	5.37 (29)	5.36 (29)	5.02 (19)	7.13 (19)	4.87 (21)	5.63 (21)	5.85 (23)	5.59 (23)	4.70 (27)	6.09 (27)	4.62 (27)	5.20 (27)
	Min	3.80	4.32	3.83	4.22	3.49	4.30	3.65	4.18	4.05	2.34	2.81	3.83
	Max	15.56	11.17	15.25	18.32	24.80	23.49	20.89	16.22	20.31	21.18	10.20	25.30
YA DT	Median (n)	5.09 (26)	5.82 (26)	4.86 (21)	7.42 (21)	4.96 (21)	5.82 (21)	5.37 (33)	5.49 (33)	4.86 (31)	5.99 (31)	4.62 (27)	6.06 (27)
	Min	4.31	4.07	3.61	4.54	3.85	2.28	3.97	4.33	1.29	2.40	3.81	2.62
	Max	25.94	20.58	12.72	17.93	25.51	25.01	15.39	17.85	18.86	22.72	24.47	22.64

Min = minimum; Max = maximum; OA= older adults; YA = young adults; ST = single task; DT = dual task; PLtMsLt = platform left mid-stance left; PLtMsRt = platform left mid-stance right; PRtMsLt = platform right mid-stance left; PRtMsRt = platform right mid-stance right; TmMsLt = treadmill mid-stance left; TmMsRt = treadmill mid-stance right;

Exploratory analyses: Effects of perturbation type, group, and cognitive load

PCA plots comparing total recovery times for step length and step width are shown in Fig 7 and in Table 3. Statistically significant differences were found between total recovery time values in response to medio-lateral versus anterior-posterior perturbations, but not between older and young adults or between cognitive task conditions. Furthermore, the plots show similar variability in each pair of calculated principal components (e.g., 53% and 47% for PC1 and PC2, respectively, Fig 7B), which means that each PC of the transformed total recovery time values for regaining regular, stable step length and step width parameters contributed roughly equally to the ability to find differences in the above comparisons.

Fig 7. Principal component plots of total recovery time values.

Principal component plots of total recovery time values for regaining stable gait parameters (step length and step width) for the following comparisons: (A) perturbation direction – anterior-posterior (blue dots) versus medio-lateral (red dots); (B) group – older adults (blue dots) versus young adults (red dots); (C) cognitive load conditions – single task (blue dots) versus dual task (red dots) among older adults; and (D) cognitive load conditions – single task (blue dots) versus dual task (red dots) among younger adults. PC1 and PC2 are the two components found by the PCA and the percentages represent the percent of variation explained in the data by each component.

SL = step length; SW = step width; OA = older adults; YA = young adults; AP = anterior-posterior; ML = medio-lateral; ST = single task; DT = dual task; PC = principal component.

Table 3. Recovery time for step length and step width: Independent samples comparisons of perturbation direction, participant group, and cognitive load for the first and second principal components.

		ML vs. AP		OA vs. YA		ST vs. DT in OA		ST vs. DT in YA	
		AP	ML	OA	YA	ST	DT	ST	DT
PC1	Standardized mean	0.11	-0.05	0.03	-0.04	0.02	-0.10	-0.05	0.08
	Z Value	0.24		0.15		0.62		-1.23	
	P value	0.81		0.88		0.54		0.22	
PC2	Standardized mean	-0.39	0.13	0.01	-0.03	0.02	-0.02	0.0003	0.02
	t	-5.64		0.38		0.33		-0.14	
	P value	<0.00001*		0.7		0.74		0.89	

SL = step length; SW = step width; PC = principal component; AP = anterior-posterior; ML = medio-lateral; OA = older adults; YA = young adults; ST = single task; DT = dual task.

Discussion

A newly developed algorithm successfully estimated total recovery time in 91.07% of the samples, detected no deviation in 6.27%, and could not converge on the available data points in 2.65% (Fig 5). Across groups, conditions, and perturbation types, step length and step width regained stability within the first six seconds after perturbation (Fig 6). An exploratory PCA identified a significant difference between anterior-posterior and medio-lateral perturbations but no significant difference between older and young adults or between single task and dual task conditions (Table 3).

Total recovery time from physical perturbations — Earlier estimations

Response times to physical perturbations during walking were previously described based on muscle recruitment (EMG findings) [e.g., [22,23]] and on first recovery step (e.g., 'crossover' or 'lateral' step) [e.g., [8]]. These studies indicated relatively fast responses (~100-350 ms and >300 ms, respectively). In the present study, we assessed the time it took to regain stable gait parameter patterns after surface perturbations, and found that it was 10-20 times longer than initial step responses.

Hof et al. [8] reported that two steps should be sufficient to contain the extrapolated center of mass in the boundaries of the base of support after a perturbation while walking. This is only a partial view of the recovery process, as some gait parameters (e.g., step length and step width) take longer to reach a stable state. The relationship between the extrapolated center of mass and the base of support is calculated for the limb towards which the center of mass is moving, or the limb placed in the direction of the velocity of the center of mass (the leading limb). In the case of a perturbation, such as a 'slip' (i.e., loss of footing of the stance foot) or a 'trip' (i.e., obstruction of the swinging foot), the extrapolated center of mass might cross the base of support, implying instability. Thus, a recovery step in the same direction and of equal magnitude to the displacement of the extrapolated center of mass is essential to keeping equilibrium [8,9]. This mechanism leads to rapid containment of the extrapolated center of mass within the base of support, and prevents a fall.

Our results differ from those reported by O'Connor and Donelan [11], who showed that people gradually return to steady state baseline walking speed in ~365 seconds after a visual walking speed perturbation. Specifically, the researchers used VR to manipulate visually presented speed while allowing participants to walk freely on a self-paced treadmill. They manipulated the ratio between selected walking speed and the speed of visual flow, to quantify the dynamics of walking speed adjustments in response to visual speed perturbations. Two types of perturbations were used in their study: step changes in visually presented speed and sinusoidal changes in speed ratio. We believe that the discrepancy between these findings and our own is directly related to the paradigm, as visual stimuli (perturbations) are known to elicit a delayed response time (5.7 seconds, in this case) [24]. Another factor differentiating the studies is duration of perturbation. Our participants were exposed to a relatively short, discrete perturbation, while O'Connor and Donelan introduced either one gradual perturbation or a series of sinusoidal perturbations. We believe that in the latter case, continuous processes of adaptation to the inherently unstable environment delay the stabilization process. Finally, changes in step length affect walking speed, which can explain the shorter total recovery times in the current study (4-6 seconds in the majority of cases, see Fig 6).

Total recovery time distribution and variability

Figs 6 and 7 suggest high variability in total recovery times, with a central tendency skewed to the right. Recovery stepping responses to unexpected perturbations are constrained by a floor effect, as there is a limit to the minimal time required to react. In addition, participants had to respond promptly in order to prevent a fall, pushing the median towards lower values. However, after the initial recovery step response, gait amendments are not essential to prevent a fall, and the process of regaining a stable pattern of gait parameter generation lasts longer. The price paid for slow gait recovery is marginal (i.e., more energy expenditure [25,26]) and can therefore be overlooked at times.

Algorithm advantages

Our method calculates total recovery time from unexpected physical perturbations during human walking. It can be used to find the point of recovery with respect to any discrete variable for which sufficient data points prior to and post perturbation are available. It is relatively simple, based on an algorithm that uses mean, standard deviation, and amplitude differences as independent variables. Finally, from an engineering perspective, the algorithm is advantageous because changing its operating parameters allows for assessment of restabilization in general (see supplementary material).

Implications, limitations, and future directions

In the current work, we calculated recovery of step length and step width to a steady state. Further study is warranted to address other parameters. Furthermore, we used PCA plots (Fig 7A-D) to depict comparisons between total recovery times for different perturbation directions (anterior-posterior versus medio-lateral), age groups (young versus older), and cognitive load conditions (single versus dual task), respectively. The results presented in Figs 7C and D, along with Table 3, suggest that gait recovery processes are hardwired into our motor system and persist throughout our adult life with no significant changes. These results should be confirmed using a larger sample.

We recommend at least 30 seconds of stable baseline prior to exposure to unexpected perturbations in future studies. Similarly, permitting more than 30 seconds after perturbation (prior to preparation for a new perturbation) might increase the likelihood of detecting total recovery time in cases where 'no recovery' would otherwise be designated. Our study can pave the way to incorporating total recovery time after unexpected loss of balance as a tool in the assessment of walking and balance impairments, to aid in diagnosis and in monitoring of treatment outcomes.

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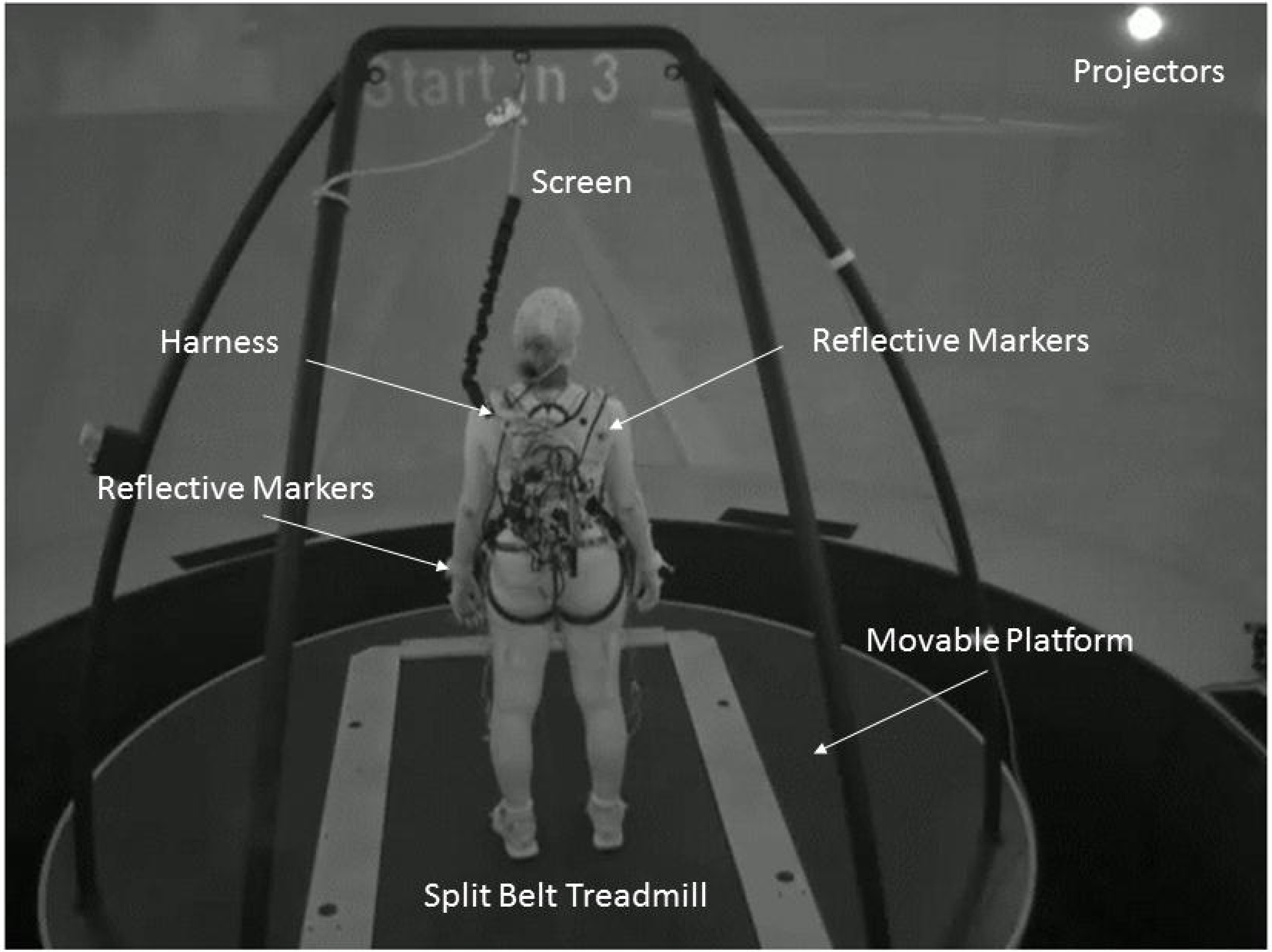
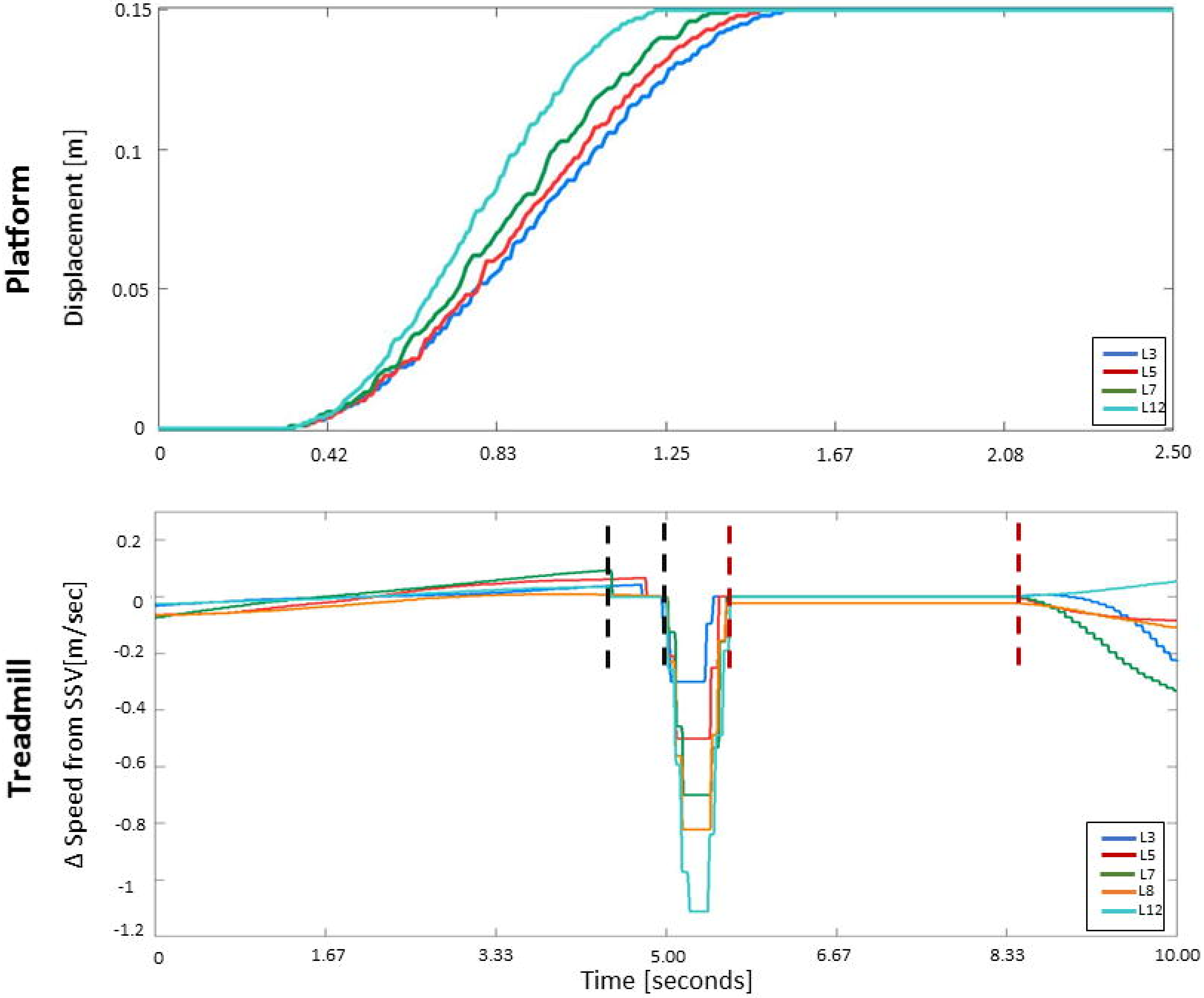
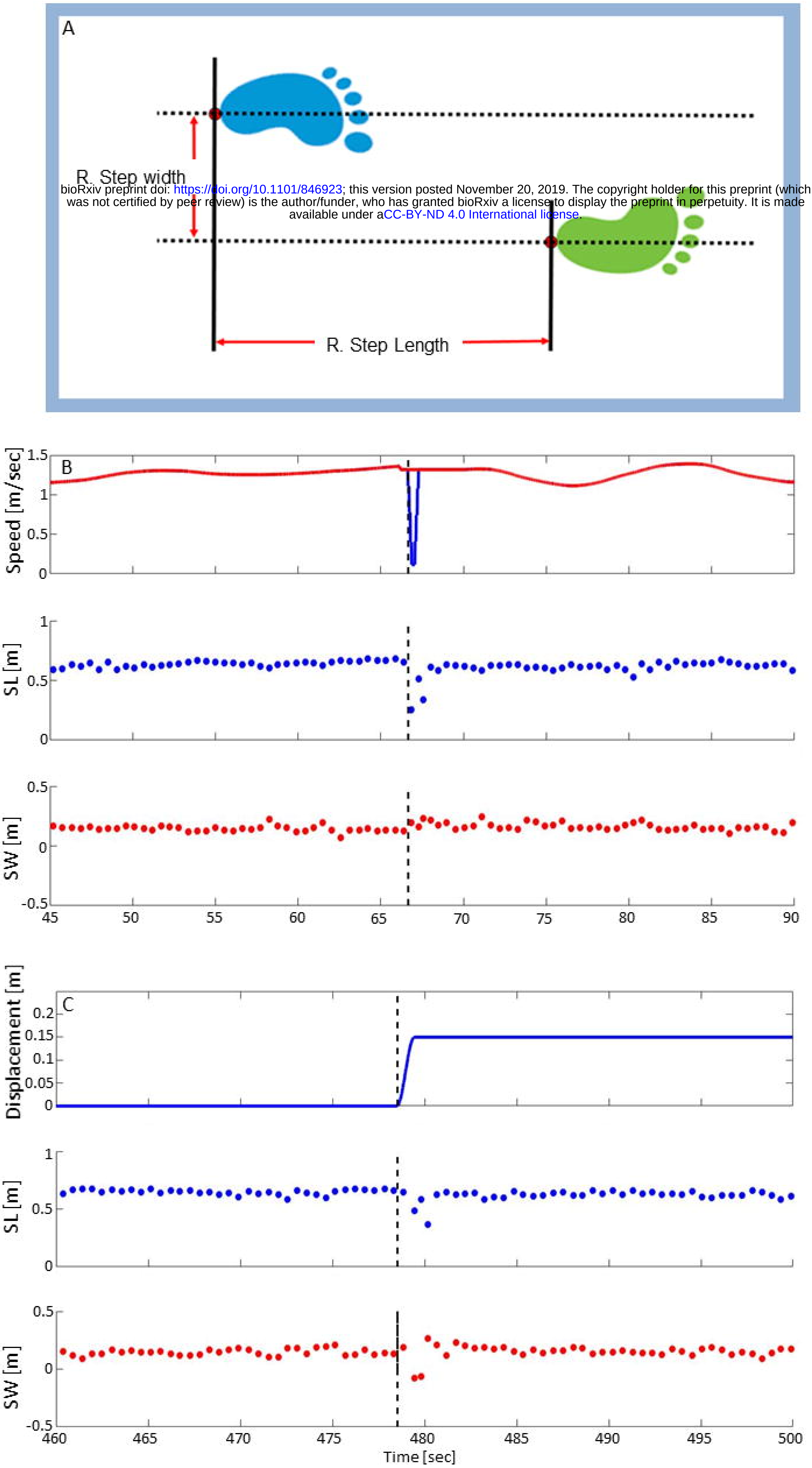
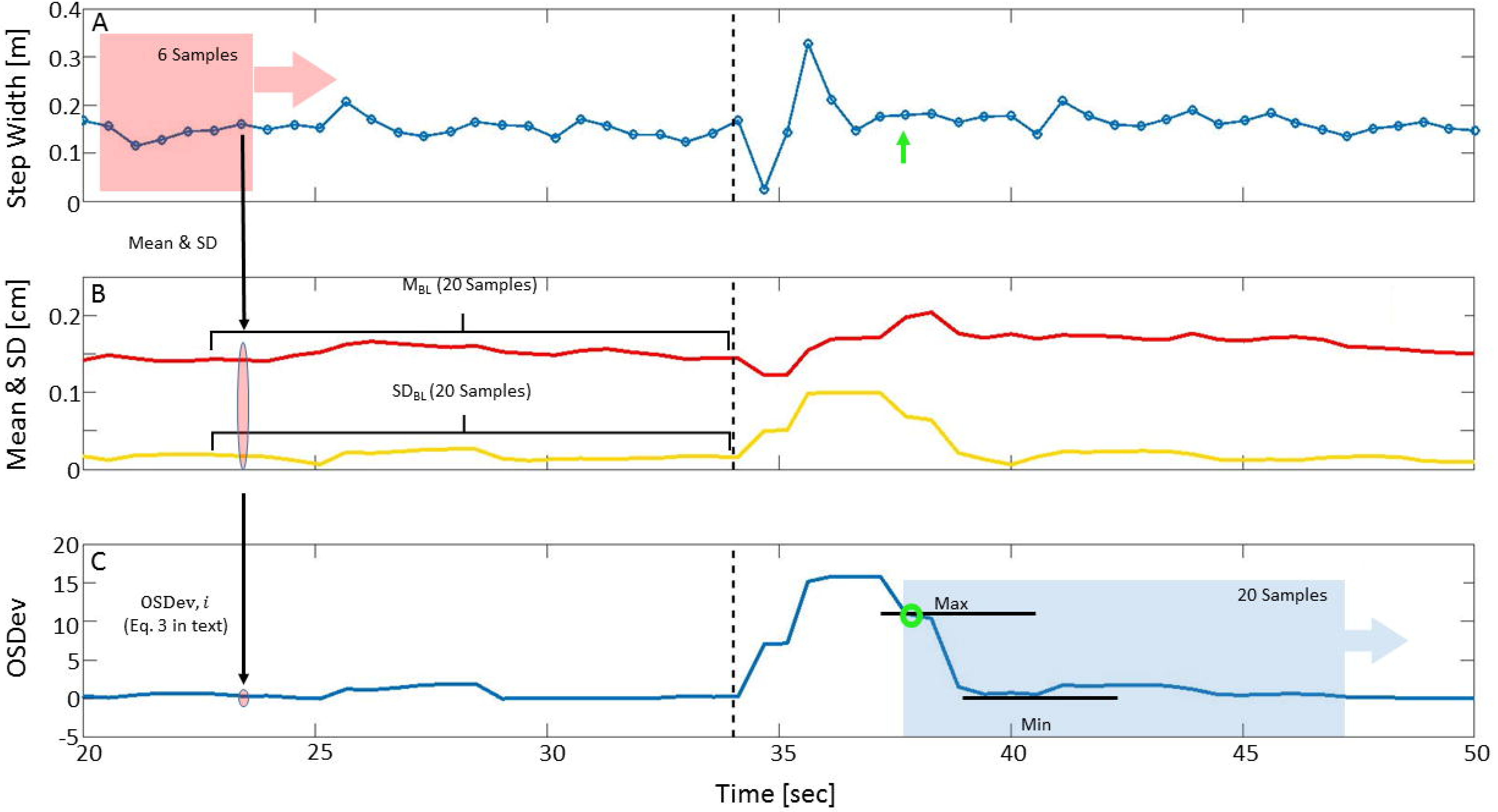
Supporting information

S1 Appendix. Supplementary materials for methods and discussion.

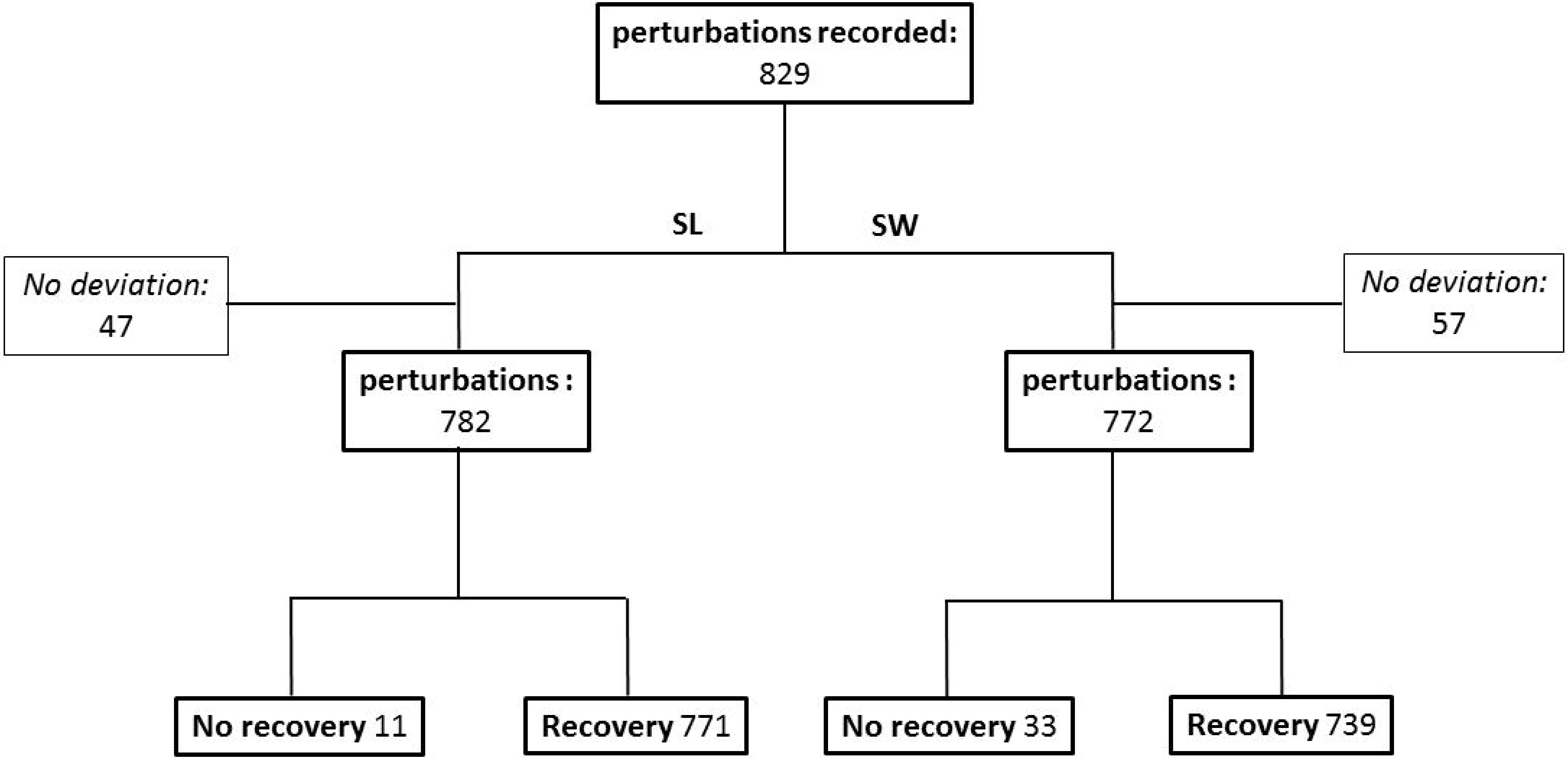

Projectors
Screen
Harness
Reflective Markers
Reflective Markers
Movable Platform
Split Belt Treadmill

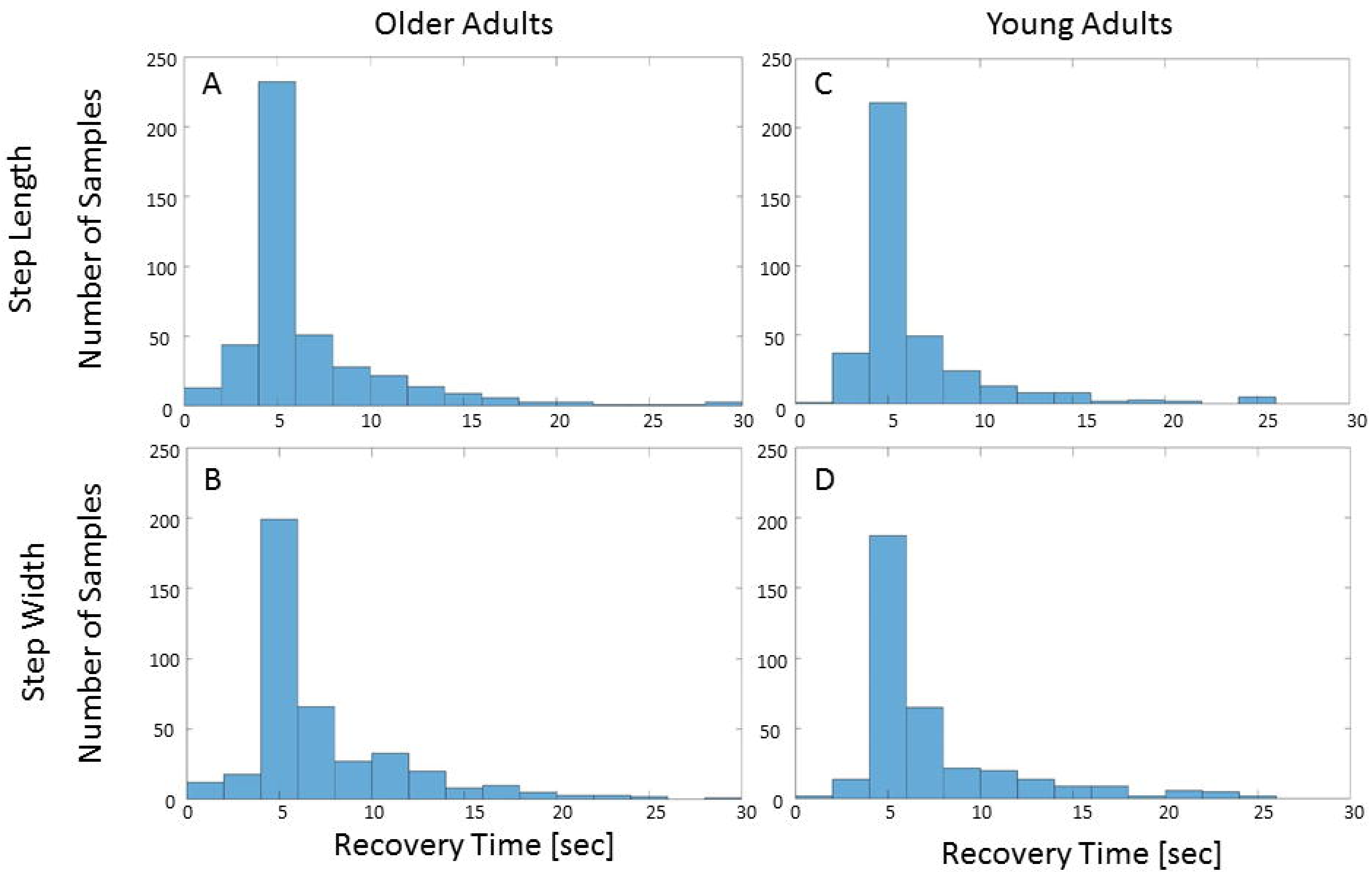

Platform
Displacement [m]
0.15
0.1
0.05
0
0
0.42
0.83
1.25
1.67
2.08
2.50
L3
L5
L7
L12
Treadmill
Δ Speed from SSV[m/sec]
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
0
1.67
3.33
5.00
6.67
8.33
10.00
Time [seconds]
L3
L5
L7
L8
L12

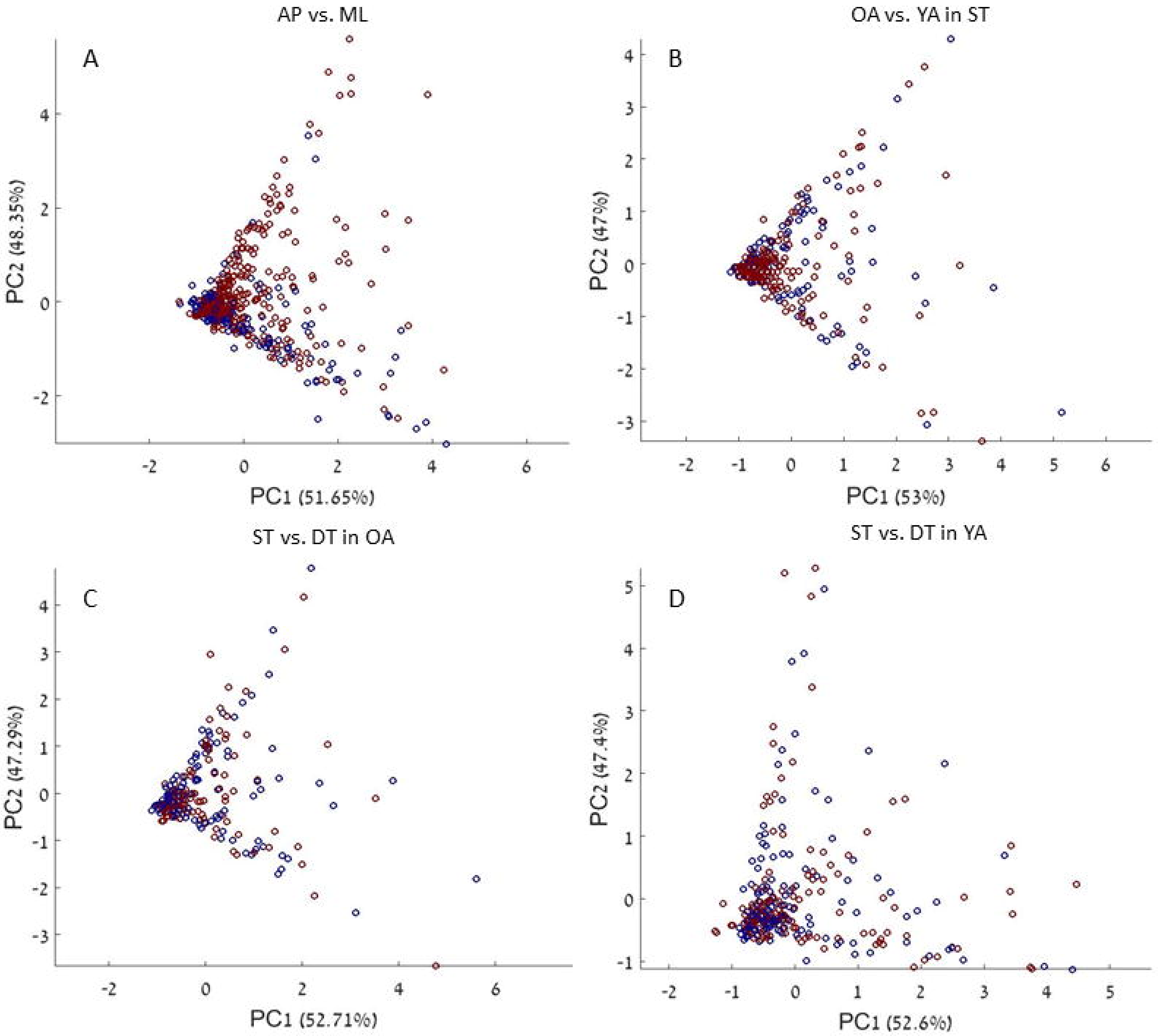

A
R. Step width
R. Step Length
B
Speed [m/sec]
SL [m]
SW [m]
C
Displacement [m]
SL [m]
SW [m]
Time [sec]



A
6 Samples
Step Width [m]
Mean & SD
B
M_BL (20 Samples)
SD_BL (20 Samples)
Mean & SD [cm]
C
OSDev, i
(Eq. 3 in text)
Max
Min
20 Samples
OSDev
Time [sec]


perturbations recorded:
829
SL
SW
No deviation:
47
No deviation:
57
perturbations :
782
perturbations :
772
No recovery 11
Recovery 771
No recovery 33
Recovery 739


Older Adults
Young Adults
Step Length
Step Width
Number of Samples
A
B
C
D
0
50
100
150
200
250
0
5
10
15
20
25
30
Recovery Time [sec]



AP vs. ML
A
PC2 (48.35%)
PC1 (51.65%)
OA vs. YA in ST
B
PC2 (47%)
PC1 (53%)
ST vs. DT in OA
C
PC2 (47.29%)
PC1 (52.71%)
ST vs. DT in YA
D
PC2 (47.4%)
PC1 (52.6%)