



**HAL**  
open science

# Stepping Strategies of Young Adults Undergoing Sudden External Perturbation From Different Directions

Thomas Chatagnon, Anne-Hélène Olivier, Ludovic Hoyet, Julien Pettré,  
Charles Pontonnier

► **To cite this version:**

Thomas Chatagnon, Anne-Hélène Olivier, Ludovic Hoyet, Julien Pettré, Charles Pontonnier. Stepping Strategies of Young Adults Undergoing Sudden External Perturbation From Different Directions. Journal of Biomechanics, 2023, 157, pp.1-12. 10.1016/j.jbiomech.2023.111703 . hal-04142469v3

**HAL Id: hal-04142469**

**<https://inria.hal.science/hal-04142469v3>**

Submitted on 21 Aug 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

# Stepping Strategies of Young Adults Undergoing Sudden External Perturbation From Different Directions

Thomas Chatagnon<sup>a</sup>, Anne-Hélène Olivier<sup>a</sup>, Ludovic Hoyet<sup>a</sup>, Julien Pettré<sup>a</sup>, Charles Pontonnier<sup>a</sup>

<sup>a</sup>*Univ Rennes, Inria, CNRS, IRISA, M2S, France*

---

## Abstract

Stepping strategies following external perturbations from different directions is investigated in this work. We analysed the effect of the perturbation angle as well as the level of awareness of individuals and characterised steps out of the sagittal plane between *Loaded Side Steps* (LSS), *Unloaded Medial Steps* (UMS) and *Unloaded Crossover Steps* (UCS). A novel experimental paradigm involving perturbations in different directions was performed on a group of 21 young adults (10 females, 11 males, 20-38 years). Participants underwent 30 randomised perturbations along 5 different angles with different levels of awareness of the upcoming perturbations (with and without wearing a sensory impairment device) for a total of 1260 recorded trials. Results showed that logistic models based on the minimal values of the Margin of Stability (MoS) or on the minimal values of the Time to boundary (Ttb) performed the best in the sagittal plane. However, their accuracy stayed above 79% regardless of the perturbation angle or level of awareness. Regarding the effect of the experimental condition, evidences of different balance recovery behaviours due to the variation of perturbation angles were exposed, but no significant effect of the level of awareness was observed. Finally, we proposed the *Distance to Foot boundary* (DtFb) as a relevant quantity to characterise the stepping strategies in response to perturbations out of the sagittal plane.

*Keywords:* Center of mass, Base of support, Stepping Strategies, Step Characterisation, External Perturbations

---

## 1. Introduction

Understanding how humans recover balance after external perturbations has a wide range of applications, from preventing injuries from falls to modelling legged robots. To extend our knowledge on balance recovery, we study the reactions of participants exposed to perturbations with controlled force and direction. Our objective is to describe and model when and how steps are taken to recover balance.

In previous work, the moment when the projected *Center of Mass* (CoM) on the ground reaches the boundary of the Base of Support (BoS) (Shumway-Cook and Woollacott, 1995; Winter, 1995) was proposed as a limit before balance recovery actions (stepping, or making contact with the environment (Maki and McIlroy, 1997)). As this description is limited to static cases, Hof et al. (2005) introduced the *Extrapolated Centre of Mass* (XCoM) to address dynamic situations.

Since XCoM takes the CoM position and velocity into account, it can be used to predict and control situations with dynamic instability (Hof et al., 2005). That led to the definition of the *Margin of Stability* (MoS), the minimal distance between XCoM and the BoS boundary (Bressel et al., 2007), with the limit when the MoS reaches a null value being considered to be the limit of dynamic stability.

Temporal variables, such as the *Time-to-boundary* (Ttb), i.e. the time for the projected CoM to reach the BoS boundary given its current velocity, were also proposed (Schulz et al., 2006) to predict recovery steps. Prediction accuracy reaches 80% following perturbations in the sagittal plane, and was later increased

---

*Email address:* [thomas.chatagnon@inria.fr](mailto:thomas.chatagnon@inria.fr) (Thomas Chatagnon)

using classification models based on kinematics-related features (Emmens et al., 2020). Following lateral perturbations three stepping strategies to maintain standing balance were identified (Mille et al., 2005) :

- *Loaded Side Steps* (LSS), sideways steps with the passively loaded leg i.e. the leg in the direction of the perturbation
- *Unloaded Medial Step* (UMS), the leg that is mechanically unloaded by the perturbation (e.g., the closest to the perturbation in case of push perturbations)
- *Unloaded Crossover Step* (UCS), the passively unloaded leg is crossing either ahead or behind the loaded leg, leading to greater axial transverse motion.

These strategies differ in their spatio-temporal characteristics of the CoM motion relative to the BoS, and can vary due to ageing (Borrelli et al., 2021).

Regarding external perturbations, from a methodological point of view, authors relied on sudden ground motion or force-controlled push/pull (Tokur et al., 2020). In the latter case, it should be noted that perturbations were applied in the anteroposterior (Robert et al., 2018; Emmens et al., 2020), mediolateral (Fujimoto et al., 2017; Gray et al., 2017; Borrelli et al., 2021) or both (Sturnieks et al., 2013; Hof and Curtze, 2016) directions. We could not find any study investigating reactions to perturbations outside of these directions.

Balance recovery may also be influenced by the level of awareness (LoA) to upcoming perturbation. Limited LoA may generate a higher level of anxiety and induce a greater body stiffness (Stins et al., 2011). Santos et al. (2010) showed that the anticipation of upcoming pushes has an effect on the motion of the CoM. So far the influence of the LoA on the *limit of standing balance* (LoSB) has been studied using unexpected timing for experiments with external perturbations (Emmens et al., 2020; Li et al., 2020; Robert et al., 2018). The effect of visual impairment (closed eyes) on standing balance was also studied (Hof et al., 2005; van Wegen et al., 2002). To our knowledge, sensory limitations to control the LoA were never used in studies regarding standing balance following external perturbations.

With regard to the aforementioned limitations, our work investigates stepping strategies following sudden force-controlled perturbations from five different directions, with two different LoA to upcoming perturbations. We evaluated how MoS and Ttb could be used to identify the LoSB in and out of the sagittal plane with different LoA. We expected a more robust separation between trials with and without steps for perturbations in the sagittal plane, as MoS and Ttb have initially been proposed to study the LoSB in this context. We also expected the LoA to affect the LoSB, due to body stiffness, although we expected the effect of perturbation angles on balance recovery to be greater than the effect of LoA. Eventually, we studied the separation between *Loaded* and *Unloaded* stepping strategies using only kinematic information.

## 2. Materials and Methods

### 2.1. Data Collection

The experiment received approval from our national ethics committee (*Comité de Protection des Personnes EudraCT: 2021-A01378-33*). Twenty-one healthy young adults participated in the study (10 females, 11 males). They all signed an informed consent form relative to data processing. Their average age, mass and height were  $27.2 \pm 4.2$  years,  $70.2 \pm 12.1$ kg and  $1.74 \pm 0.08$ m respectively. All but one subject were considered having an overall right side preference (laterality test (Coren, 1993) mean:  $9.45 \pm 3.28$ ).

To assess the effect of LoA on stepping strategies, the experiment was divided into two blocks of level of awareness performed in random order: *Sensory Impairment* (SI) or *No Impairment* (NI). For SI trials participants wore a noise-canceling headset (3M PELTOR Optim II, 30dB) with mounted opaque plastic sheets limiting peripheral vision.

We investigated the effect of perturbation angles using five different angles, detailed in Fig. 1. A trial corresponded to a single reaction to an external perturbation, applied using a pole equipped with an unilateral force sensor (U9C 0.5kN, HBK) followed by a rounded steel plate. During the experiments the pole was held as horizontal as possible using a mounted spirit level. The perturbations occurred at shoulder height for

five different angles, with intensities divided into three ranges ('Low', 'Medium', 'High'). Each perturbation lasted for  $0.74 \pm 0.14s$ . The perturbations were sharp bell shaped with average maximal intensities of  $54 \pm 12N$ ,  $68 \pm 13N$  and  $88 \pm 20N$  for 'Low', 'Medium' and 'High' intensities respectively. Intensities were selected to ensure balance recovery with and without steps, based on the literature (Robert et al., 2018) and observations during pilot experiments. Perturbations of the same intensity level and angle were repeated twice. Participants received six perturbations at the same angle during each block, for a total of 30 trials per block ( $5 \text{ Angles} \times 3 \text{ Intensities} \times 2 \text{ Repetitions}$ ).

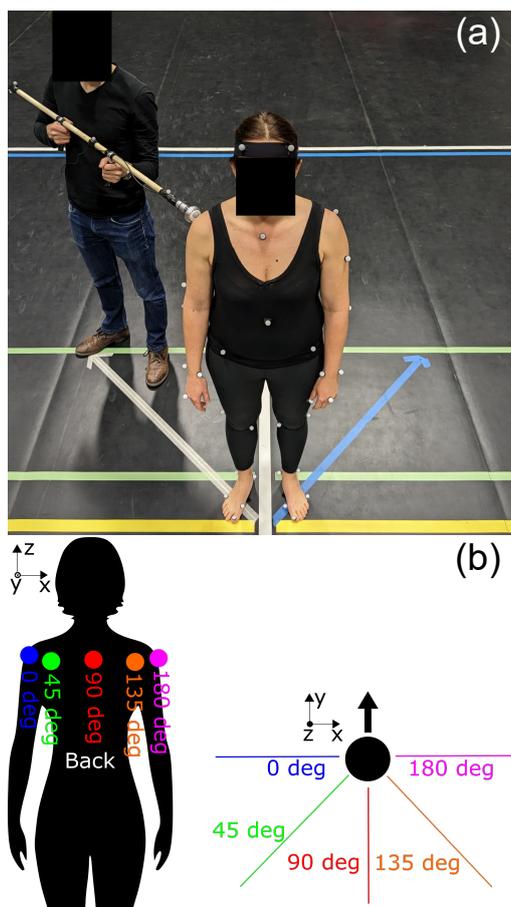


Figure 1: (a) Illustrative picture taken as the participant was about to receive a perturbation with an angle of 45 deg. (b) Angles of application location of the perturbations.

Perturbation angle and intensity were randomised within each block. Participants had no prior indication that a perturbation was coming except from peripheral vision and footstep sounds for NI trials. The following rules were also given to participants before the experiment:

- Stand still and look straight ahead, with feet side by side in a stance not wider than hip width.
- Maintain a stable final position after the perturbation.

Participants' motion was recorded using 45 reflective markers and a 23-camera Qualisys system (200Hz). Markers were placed following standardised anatomical landmarks (Wu et al., 2005). The output signal of the force sensor was processed using a Butterworth (5Hz) without phase shift.

## 2.2. Data Processing

### 2.2.1. Step detection.

Our analysis of stepping behaviour is based on the moment at which a foot initiates the movement to step ( $t_{begin}$ ). This moment arises after the actual step is triggered by the nervous central system, and is closer to what is often referred to as *Toe-off*, which is the moment when the toe loses contact with the ground. Toe-off moment is classically detected using force plates, we propose here a method based only on kinematic data that can be used with any motion captured dataset.

The following three stage method was applied to each foot to detect steps.

1. The distance traveled by the foot during a trial was checked to be higher than a distance threshold  $d_t = 2cm$ , based on the method of Schulz et al. (2006),
2. The transversal speed of the foot was computed and peaks were assumed to correspond to motion induced by steps,
3. For each peak, we selected the closest inflexion points for which the transversal speed value was under 10% of the global maximal speed (ensuring not to find local minimums).

This method returned two inflexion points of the foot transversal speed for each step (see Fig. 2). The first inflexion point (before the transversal speed peak) was considered to be the beginning time of the step  $t_{begin}$ . The second inflexion point (after the transversal speed peak) was considered to be the ending time of the step,  $t_{end}$ . For trials in the sagittal plane, as the participant's legs were not loaded by the perturbation, all steps taken in this configuration were considered as *Front Steps* (FS).

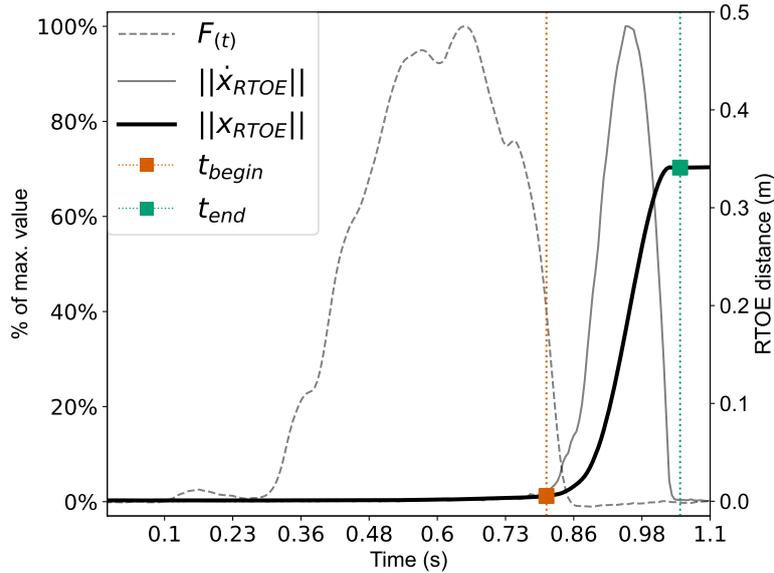


Figure 2: Transversal speed ( $||\dot{x}_{RTOE}||$ ) and distance ( $||x_{RTOE}||$ ) from the origin of the marker placed on the right toe (RTOE) of a participant for a representative trial.  $t_{begin}$  is the moment at which the step is initiated,  $t_{end}$  is the moment at which the considered foot stops moving. The shape of the recorded perturbation force ( $F(t)$ ) is represented with a dashed line.

To determine whether the step was a *Side* (LSS or UMS) or *Crossover* (UCS) step, the vectors from the left to the right toe markers  $\mathbf{L}_{toe}\mathbf{R}_{toe}$ , and from the left to the right heel markers  $\mathbf{L}_{heel}\mathbf{R}_{heel}$ , were considered. A step was considered to be a *Side Step* if both following inequality were true:

$$\mathbf{L}_{toe}\mathbf{R}_{toe}|_{t_{begin}} \cdot \mathbf{L}_{toe}\mathbf{R}_{toe}|_{t_{end}} \geq 0, \quad (1)$$

$$\mathbf{L}_{heel}\mathbf{R}_{heel}|_{t_{begin}} \cdot \mathbf{L}_{heel}\mathbf{R}_{heel}|_{t_{end}} \geq 0 \quad (2)$$

In some trials, the participants swung one leg to keep balance without stepping. This behaviour fulfilled all stages of the step detection method; however we did not consider them as *recovery steps*. Trials involving this behaviour were manually discarded.

### 2.2.2. Limit of Standing Balance (LoSB) in and out of the sagittal plane.

Two quantities were used to assess the stepping likelihood following external perturbations: the *Margin of Stability* (MoS) (Hof et al., 2005) and the *Time-to-boundary* (Ttb) (Schulz et al., 2006). Both quantities involve the position of the CoM and the BoS in time. The CoM was computed by using inverse kinematics of an osteoarticular model fitted to the filtered motion capture data. This computation was performed using the CusToM library (Muller et al., 2019).

The MoS relies on the concept of XCoM which is defined as:

$$\mathbf{XCoM} = \mathbf{x}_{CoM} + \frac{\dot{\mathbf{x}}_{CoM}}{\omega_0}, \quad (3)$$

where  $\mathbf{x}_{CoM}$  is the instantaneous position of the projection of the CoM on the ground and  $\omega_0 = \sqrt{g/l}$ , with  $l$  the participant's leg length and  $g$  the acceleration of gravity. Using this quantity, MoS is computed as:

$$MoS = (\mathbf{u}_{max} - \mathbf{XCoM}) \cdot \frac{\dot{\mathbf{x}}_{CoM}}{\|\dot{\mathbf{x}}_{CoM}\|}, \quad (4)$$

where  $\mathbf{u}_{max}$  is the closest point to the CoM on the BoS in the direction of the CoM velocity. This definition allows negative values for MoS, when  $\mathbf{XCoM}$  is outside the BoS and  $\dot{\mathbf{x}}_{CoM}$  is oriented away from the BoS. Such a situation is depicted in Fig. 3.a where the CoM and  $\mathbf{XCoM}$  are represented at  $t_{begin}$  for two representative trials.

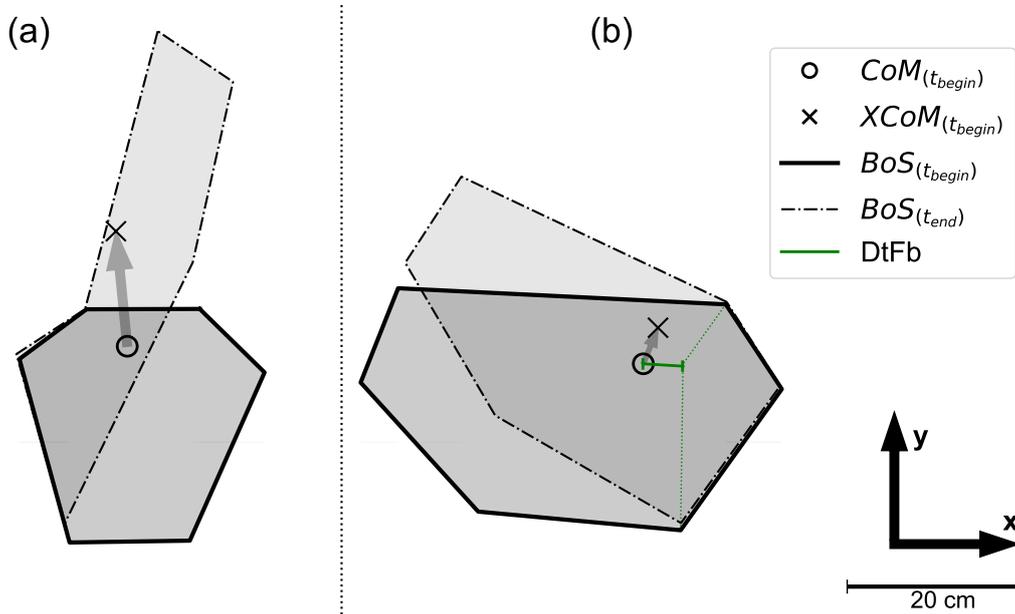


Figure 3: Spatial representation of the reaction of two participants for perturbations at 90 deg (a) and 135 deg (b). By definition, the arrow between the CoM and the XCoM represents  $\frac{\dot{\mathbf{x}}_{CoM}}{\omega_0}$ .

The Ttb is the time required by the projection of the CoM on the ground to reach the BoS boundary

given the current CoM velocity. Ttb is computed as:

$$Ttb = \frac{Dtb}{\|\dot{\mathbf{x}}_{CoM}\|}, \quad (5)$$

$$Dtb = (\mathbf{u}_{max} - \mathbf{x}_{CoM}) \cdot \frac{\dot{\mathbf{x}}_{CoM}}{\|\dot{\mathbf{x}}_{CoM}\|} \quad (6)$$

with the *Distance to boundary* (Dtb) being the distance between the CoM and the closest point on the BoS in the direction of the CoM velocity.

We also studied the *Distance to Foot boundary* (DtFb) for trials involving steps following lateral perturbations. This quantity corresponds to the distance from the CoM ground projection to the boundary of the polygon created by *Non-Stepping Foot* markers, in the reference linked to the participant's foot position at the beginning of the foot movement ( $t_{begin}$ ). The directional vector of the reference used in the computation was obtained by using the average position of the centroid of each foot marker. This resulted in the creation of a *Non-Stepping Foot* average position ( $\mathbf{F}_{NS}$ ), and a *Stepping Foot* average position ( $\mathbf{F}_S$ ). The directional vector linked to the participants feet position at  $t_{begin}$  is then  $\mathbf{F}_S \mathbf{F}_{NS}|_{t_{begin}}$ , leading to the following definition:

$$DtFb = \left( (\mathbf{u}_{NS} - \mathbf{x}_{CoM}) \cdot \frac{\mathbf{F}_S \mathbf{F}_{NS}}{\|\mathbf{F}_S \mathbf{F}_{NS}\|} \right) \Bigg|_{t_{begin}}, \quad (7)$$

With  $\mathbf{u}_{NS}$  being the closest point on the *Non-Stepping Foot* boundary in the direction of  $\mathbf{F}_S \mathbf{F}_{NS}|_{t_{begin}}$ . Negative values of DtFb indicate that the CoM was inside the *Non-Stepping Foot* boundary at  $t_{begin}$ .

### 2.3. Analysis

We used *logistic models* based on the minimal value of the MoS and Ttb obtained during each trial to estimate the limit after which steps were initiated by participants. If a participant took a step during one trial, the minimal value of MoS and Ttb before step beginning was considered.

In particular, we monitored the accuracy, sensitivity and specificity of the models. Accuracy corresponds to the number of correct estimations of the model divided by the total number of trials. Sensitivity is the number of step trials correctly detected divided by the total number of trials with steps, i.e. a high sensitivity is linked to a high efficiency of the model at detecting step trials. Specificity is the number of *Non-Step* (NS) trials correctly estimated divided by the total number of NS trials, i.e. a high specificity is linked to a high efficiency at detecting NS situations. *Decision boundaries* (DB) of the models are also given in the results section. They represent the critical value after which the model estimated that steps were initiated by participants.

To assess the effect of the experimental conditions (i.e. the angle of the perturbation and LoA), we also built four *Logistic Mixed Models* (LMMs) upon our dataset. These models are general logistic models assessing the probability of taking a step for a given minimal value of Ttb or MoS, and considering the angle of the perturbation and the sensory state of the participant as factors. The different participants were considered in the models as a random effect due to specific reaction each participant might have. The LMMs and all related analyses were created and performed using the Jamovi software suite (Jamovi, 2022).

We also propose to use the DtFb to separate *Loaded Step* (LSS) and *Unloaded Steps* (UMS and UCS) following lateral perturbations. To perform this characterisation we also used logistic models based on the value of the DtFb. A *Logistic Mixed Model* (LMM) was also created to assess the effect of experimental conditions on separation of the data.

### 3. Results

In total, steps were made in 616 trials out of 1260. The recovery did not require steps in 600 trials, and 41 trials were not considered due to their ambiguous nature (leg lifted, but no step). This behavior was observed for perturbations out of the sagittal plan, and mostly in the mediolateral direction (33 out of 41 trials). Three trials were removed for technical reasons. Table 1 summarises the number of each recovery type used by participants for each experimental condition.

Angle	No Step		FS		LSS		UMS		UCS	
	NI	SI	NI	SI	NI	SI	NI	SI	NI	SI
0 deg	60	64	0	0	8	5	5	8	41	42
45 deg	65	63	0	0	6	6	18	21	37	35
90 deg	35	31	91	94	0	0	0	0	0	0
135 deg	66	72	0	0	20	7	7	8	29	36
180 deg	68	76	0	0	16	7	7	4	26	32

Table 1: Number of trials in which the following strategies were used : *No Step*, *Front Step* (FS), *Loaded Side Steps* (LSS), *Unloaded Medial Steps* (UMS), *Unloaded Crossover Steps* (UCS). Perturbation angles (0 deg to 180 deg) and the LoA (NI, SI) were counted separately.

The models using Ttb or MoS seem to perform similarly in term of accuracy to separate NS trials and trials with steps. Logistic models based on minimal values of MoS or Ttb kept an overall accuracy above 79% (see Table 2) with a maximum of accuracy for perturbations in the sagittal plane. Separation models between *Loaded Step* (LS) and *Unloaded Steps* (US) using DtFb keep an accuracy above 97% for all lateral perturbation angles (see Table 3).

The distribution of data in Figs. 4 and 5 shows no prior effect of the LoA on data distribution. This observation was validated by our statistical analysis using LMMs (see Table 4). A minor effect of the angle of the perturbation is visible only on the LMM using the Minimal values of MoS. Given this information, SI and NI trials were considered to be comparable and all of them are used in the following logistic models.

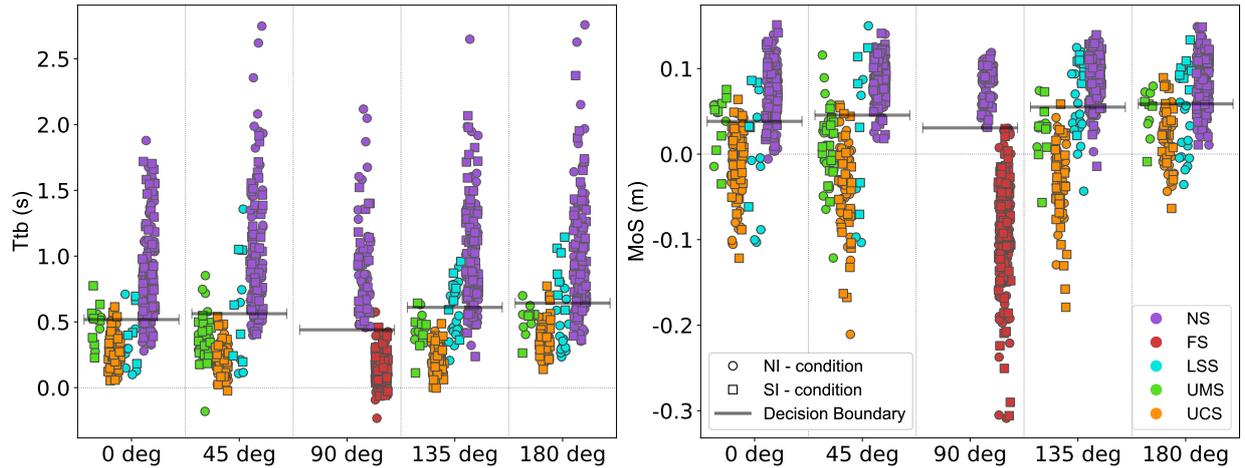


Figure 4: Separation between Non-Step (NS) trials and trials with steps (FS, LSS, UMS, UCS). NI trials are marked with round dots and SI trials with square dots. Each dot represents the minimal value of Ttb or MoS during one single trial. Minimal value was computed before step initiation for trials involving a step.

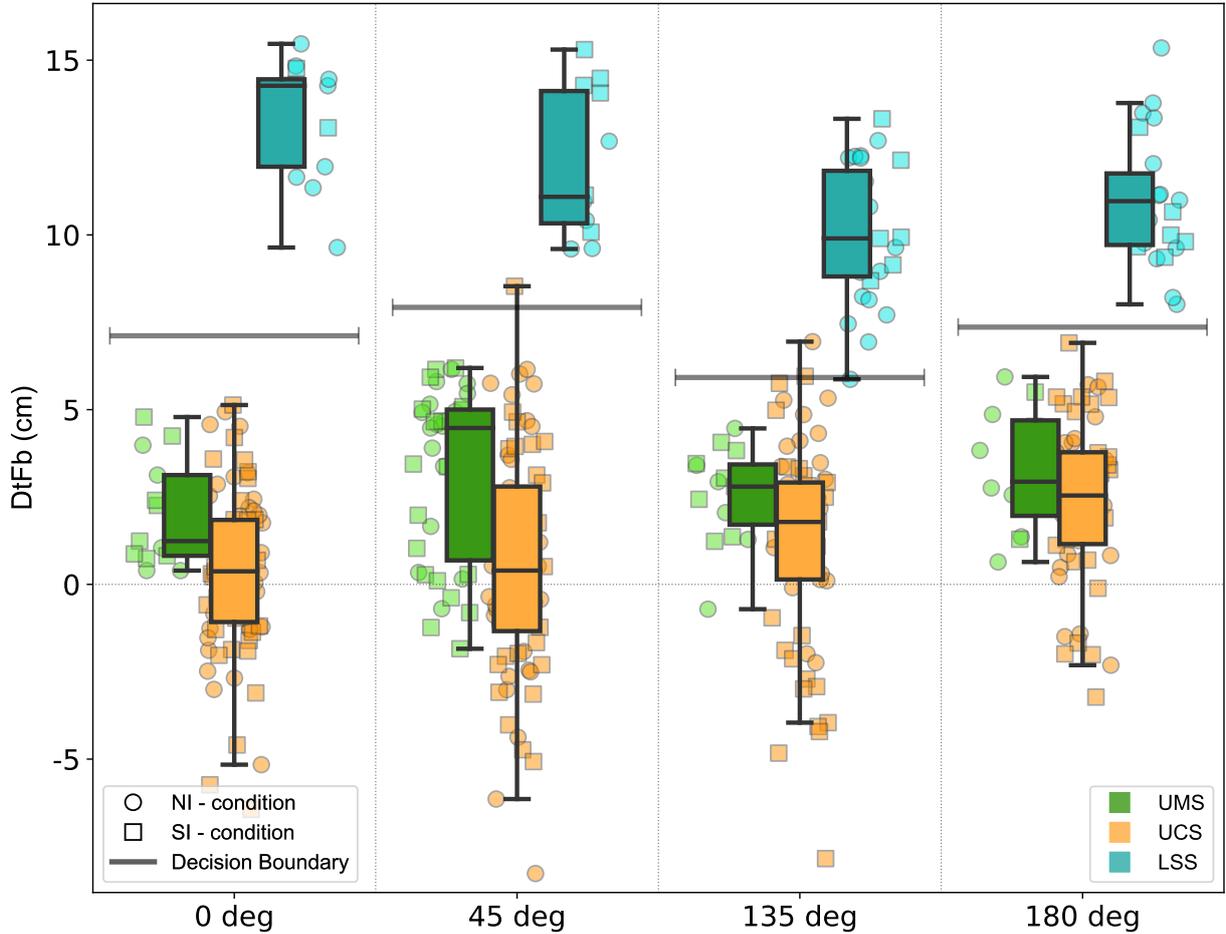


Figure 5: Separation between trials with *Loaded Steps* (LSS) and *Unloaded Steps* (UMS and UCS) using the DtFb for lateral perturbations. A negative DtFb indicates a CoM within the polygon of the foot markers at  $t_{begin}$ .

We observed in Fig. 4 different ranges of minimal values of Ttb and MoS between LSS, UMS and UCS strategies. The range of values for LSS trials seemed to have a larger overlap with values of NS trials than the US trials (i.e. UMS and UCS). This overlap also depended on the angle of the perturbation, and different overlaps were observed depending on the side of the perturbation (i.e. between 0 deg and 180 deg, or between 45 deg and 135 deg). For lateral perturbation trials, minimal values of Ttb or MoS cannot be used to separate LS from US. One way to separate these strategies may therefore be by looking at DtFb (Fig. 5). For all lateral perturbation angles, the logistic models based on the DtFb provide a clear separation between LS and US trials, with an almost perfect accuracy for each angle (see Table 3).

#### 4. Discussion

In this paper, we investigated stepping strategies while undergoing perturbations from five different directions under two levels of awareness, using classical methods (Mos, Ttb) to estimate the LoSB. A new method to discriminate *Loaded* and *Unloaded* steps following lateral perturbations using only kinematic quantities was also proposed.

Angle	NS/Step - Min. MoS				NS/Step - Min. Ttb			
	DB (cm)	Accuracy (%)	Sensitivity (%)	Specificity (%)	DB (s)	Accuracy (%)	Sensitivity (%)	Specificity (%)
0 deg	3.83	83	83	84	0.52	85	88	81
45 deg	4.55	90	89	92	0.56	90	91	89
90 deg	3.07	100	100	100	0.44	99	99	100
135 deg	5.50	85	83	87	0.61	87	87	85
180 deg	5.87	79	76	81	0.64	82	85	81

Table 2: Characteristics of the logistic models to separate NS trials and trials with steps using minimal values of MoS or Ttb for each perturbation angle (0 deg to 180 deg). Perturbations with an angle of 90 deg corresponds to situation in the sagittal plane.

Angle	LS/US - DtFb			
	DB (cm)	Accuracy (%)	Sensitivity (%)	Specificity (%)
0 deg	7.11	100	100	100
45 deg	7.93	100	100	100
90 deg	-	-	-	-
135 deg	5.92	97	96	97
180 deg	7.36	100	100	100

Table 3: Characteristics of the logistic models to separate trials involving *Loaded Steps* (LS) or *Unloaded Steps* (US) based on the DtFb for lateral perturbation angles.

	$R^2_{conditional}$	$R^2_{marginal}$	p-value : Fixed Effect Omnibus tests		
			Angle	Level of awareness	covariate
NS/Step - Min. MoS	0.905	0.810	0.022	0.761	<.001
NS/Step - Min. Ttb	0.932	0.858	0.117	0.900	<.001
LS/US - DtFb	0.999	0.419	0.991	0.713	<.001

Table 4: Characteristics of the *Logistic Mixed Models* (LMMs) between NS trials and trials with steps, and between *Loaded Steps* (LS) and *Unloaded Steps* (US). The covariate is the quantity on which the regression is based, respectively here: minimal values of MoS, minimal values of Ttb, and DtFb.

#### 4.1. Effect of the experimental conditions

The perturbation angles had a significant impact on the overlapping range of minimal Ttb and MoS values between Non-Stepping and Stepping recovery strategies. However, almost all the LMMs (except for when using MoS) were not significantly affected by the angle (see Table 4). This resulted in comparable decision boundaries for each logistic model regardless of perturbations angle. One can also notice an asymmetry of stepping strategies used depending on the perturbation angle, with more LSS than UMS for 135deg and 180deg, and more UMS than LSS for 0deg and 45deg. This may be linked to the overall right side preference of participants. Further investigations are required to assess the effect of laterality in this situation.

No significant effect of the level of awareness (LoA) was observed in the statistical models (see Table 4), suggesting that participants reacted similarly to the perturbations independently of this condition. This may be explained by the fact that participants knew that they were about to be pushed at any moment, regardless of the imposed LoA. For populations comparable to the one studied here, stepping strategies may remain the same independently of the LoA to upcoming perturbations. However, further studies are required to draw any conclusion on that matter.

#### 4.2. Modeling approach

Regarding logistic models, we decided to weight our models to normalise data repetition. Therefore, we did not give more importance to the most used recovery strategies. This choice was made as the protocol of our experiment did not ensure a fixed ratio between non-step and step trials. However, this may have had a slight impact on the decision boundary for the separation models, especially for those between LS and US as different stepping strategies were preferred depending on the perturbation direction.

We also chose to define the Dtb as the distance between the CoM and the BoS in the direction of the CoM velocity (Schulz et al., 2006) and not as the shortest distance between the CoM and the BoS (Hof et al., 2005). This choice impacted the computation of both MoS and Ttb, especially when the CoM velocity had a strong tangential component to boundary of the BoS. Regarding the influence of the perturbation angle and of the direction of the CoM velocity, this definition of Dtb allowed for a stronger impact of the CoM velocity direction on the results. Conversely, DtFb was defined relative to the foot position as the CoM velocity at  $t_{begin}$  could be directed towards none of the foot boundaries, especially after lateral perturbations at 45 deg and 135 deg (see Fig. 3). We also chose to use DtFb (over other classical quantities like the *Center of Pressure*) in our study as it only involves kinematic quantities and can be used on any motion captured dataset.

After making the aforementioned choices some of our results may still be comparable to the literature, with some differences remaining in the shape of the perturbations applied to participants. Following the method of Hof and Curtze (2016) and regarding perturbations in the sagittal plane, the mean distance before the LoSB in our experiment would have been  $5cm \pm 1cm$ . Here we found a smaller limit around  $3cm$ . Similarly, Schulz et al. (2006) observed a critical Ttb of  $0.52s$  with a prediction accuracy of 94% for a population of young, old unimpaired and old with balance-impairment. This value is comparable to the one observed under the same conditions in our study ( $0.44s$  and 99% accuracy). The main differences in the results may be explain by the methodological variation (e.g. for step detection) and differences in experimental protocols (e.g. participants asked to avoid stepping as much as possible in previous studies).

#### 4.3. Step Characterisation

We tried to characterise the stepping strategies based on kinematic information. For that matter we proposed to use the DtFb which appears to be a relevant indicator to separate LS and US trials. As one can see in Fig. 5, there is a difference between LS and US trials with overall smaller and negative values of DtFb when a UMS or a UCS was used. Considering the significant overlaps between NS and LSS strategies in Fig. 4, one may assume that the LSS strategy was used for less critical/challenging situations out of the sagittal plane, i.e. when the CoM (travelling away from the perturbation) is still away from the BoS limit of the loaded foot, allowing the latter to be used. However, further investigation is required to validate this hypothesis as Borrelli et al. (2021) showed that side steps were less complex trajectories resulting in shorter excursion times.

#### 4.4. Limitations

The LoSB is highly dependent on the intrinsic proprioception of each participant. During the experiment many behaviours were observed, with some participants making a step at nearly each trial, while others almost never made a step. The present results and models were based on the overall results of the considered population only, and would benefit from being validated on a larger population in the future. Similarly, we observed ambiguous behaviours in a few trials (41 out 1260), where participants only swung their leg without making a step. Such behaviours, not considered in our panel of strategies (NS, FS, LSS, UMS, UCS), would benefit from being explored separately in the future. The effect of the shape of the external perturbation was also not investigated in this work, which may have an impact on the type of recovery strategy used, and our study would benefit from further analysis on that matter. Similarly, studying perturbations which would trigger a reaction in posterior directions (Hof and Curtze, 2016; Schulz et al., 2006) would also be a nice addition to the proposed work.

The geometric BoS boundaries were approximated in our experiment using the location of the external markers placed on the outer part of each foot of participants, therefore slightly over estimating the BoS.

Thus, the actual boundaries may vary up to  $1\text{cm}$  (based on the size of the marker used) towards the CoM ground projection at rest.

## 5. Conclusion

This study demonstrated that the concepts of Ttb and MoS are good indicators to estimate the *Limit of Standing Balance* (LoSB) following perturbations from different directions. Our results also suggest that an imposed level of awareness does not influence participants' stepping strategies. We finally proposed to study the DtFb to characterise the stepping strategies following lateral perturbations. Data collected in the frame of this work could be used to analyse the characteristics of the steps induced by sudden perturbations. The main body parts used to regain standing balance may also be studied using more specific motion analysis (Scholz and Schöner, 1999). This dataset may as well be used as a comparison baseline to understand how stepping behaviour changes following external perturbations when being surrounded by other individuals.

## Acknowledgement

We would like to thank the reviewers who contributed to this work through insightful and constructive comments.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 899739 (CrowdDNA), as well as French government ANR CONTINUUM project under grant agreement No ANR-21-ESRE-0030.

## References

- Borrelli, J., Creath, R., Gray, V., Rogers, M., 2021. Untangling biomechanical differences in perturbation-induced stepping strategies for lateral balance stability in older individuals. *Journal of Biomechanics* 114, 110161. doi:<https://doi.org/10.1016/j.jbiomech.2020.110161>.
- Bressel, E., Yonker, J.C., Kras, J., Heath, E.M., 2007. Comparison of static and dynamic balance in female collegiate soccer, basketball, and gymnastics athletes. *J Athl Train* 42, 42–46.
- Coren, S., 1993. The lateral preference inventory for measurement of handedness, footedness, eyedness, and earedness: Norms for young adults. *Bulletin of the Psychonomic Society* 31, 1–3. doi:[10.3758/BF03334122](https://doi.org/10.3758/BF03334122).
- Emmens, A.R., F. van Asseldonk, E.H., Prinsen, V., der Kooij, H.v., 2020. Predicting reactive stepping in response to perturbations by using a classification approach. *Journal of NeuroEngineering and Rehabilitation* 17, 84. doi:[10.1186/s12984-020-00709-y](https://doi.org/10.1186/s12984-020-00709-y).
- Fujimoto, M., Bair, W.N., Rogers, M.W., 2017. Single and multiple step balance recovery responses can be different at first step lift-off following lateral waist-pull perturbations in older adults. *Journal of Biomechanics* 55, 41–47. doi:<https://doi.org/10.1016/j.jbiomech.2017.02.014>.
- Gray, V.L., Yang, C.I., McCombe Waller, S., Rogers, M.W., 2017. Lateral perturbation-induced stepping: Strategies and predictors in persons poststroke. *Journal of Neurologic Physical Therapy* 41.
- Hof, A., Gazendam, M., Sinke, W., 2005. The condition for dynamic stability. *Journal of Biomechanics* 38, 1–8. doi:[10.1016/j.jbiomech.2004.03.025](https://doi.org/10.1016/j.jbiomech.2004.03.025).
- Hof, A.L., Curtze, C., 2016. A stricter condition for standing balance after unexpected perturbations. *Journal of Biomechanics* 49, 580–585. doi:<https://doi.org/10.1016/j.jbiomech.2016.01.021>.
- Jamovi, 2022. The jamovi project. Retrieved from <https://www.jamovi.org/>. (Version-2.3), Accessed: 2022-09.
- Li, X., Song, W., Xu, X., Zhang, J., Xia, L., Shi, C., 2020. Experimental study on pedestrian contact force under different degrees of crowding. *Safety Science* 127, 104713. doi:[10.1016/j.ssci.2020.104713](https://doi.org/10.1016/j.ssci.2020.104713).
- Maki, B.E., McIlroy, W.E., 1997. The Role of Limb Movements in Maintaining Upright Stance: The “Change-in-Support” Strategy. *Physical Therapy* 77, 488–507. doi:[10.1093/ptj/77.5.488](https://doi.org/10.1093/ptj/77.5.488).
- Mille, M.L., Johnson, M.E., Martinez, K.M., Rogers, M.W., 2005. Age-dependent differences in lateral balance recovery through protective stepping. *Clinical Biomechanics* 20, 607–616. doi:<https://doi.org/10.1016/j.clinbiomech.2005.03.004>.
- Muller, A., Pontonnier, C., Puchaud, P., Dumont, G., 2019. Custom: a matlab toolbox for musculoskeletal simulation. *Journal of Open Source Software* 4, 927. doi:[10.21105/joss.00927](https://doi.org/10.21105/joss.00927).
- Robert, T., Vallee, P., Tisserand, R., Buloup, F., Bariatsinsky, D., Vercher, J., Fitzpatrick, R., Mille, M., 2018. Stepping boundary of external force-controlled perturbations of varying durations: Comparison of experimental data and model simulations. *Journal of Biomechanics* 75, 89–95. doi:[10.1016/j.jbiomech.2018.05.010](https://doi.org/10.1016/j.jbiomech.2018.05.010).
- Santos, M.J., Kanekar, N., Aruin, A.S., 2010. The role of anticipatory postural adjustments in compensatory control of posture: 2. biomechanical analysis. *Journal of Electromyography and Kinesiology* 20, 398–405. doi:[10.1016/j.jelekin.2010.01.002](https://doi.org/10.1016/j.jelekin.2010.01.002).
- Scholz, J.P., Schöner, G., 1999. The uncontrolled manifold concept: identifying control variables for a functional task. *Experimental Brain Research* 126, 289–306. doi:[10.1007/s002210050738](https://doi.org/10.1007/s002210050738).
- Schulz, B.W., Ashton-Miller, J.A., Alexander, N.B., 2006. Can initial and additional compensatory steps be predicted in young, older, and balance-impaired older females in response to anterior and posterior waist pulls while standing? *Journal of Biomechanics* 39, 1444–1453. doi:[10.1016/j.jbiomech.2005.04.004](https://doi.org/10.1016/j.jbiomech.2005.04.004).
- Shumway-Cook, A., Woollacott, M.H., 1995. *Motor control: theory and practical applications*. Baltimore (Md.): Williams and Wilkins.
- Stins, J.F., Roerdink, M., Beek, P.J., 2011. To freeze or not to freeze? affective and cognitive perturbations have markedly different effects on postural control. *Human Movement Science* 30, 190–202. doi:[10.1016/j.humov.2010.05.013](https://doi.org/10.1016/j.humov.2010.05.013). basic Mechanisms underlying Balance Control under Static and Dynamic Conditions.
- Sturnieks, D.L., Menant, J., Delbaere, K., Vanrenterghem, J., Rogers, M.W., Fitzpatrick, R.C., Lord, S.R., 2013. Force-controlled balance perturbations associated with falls in older people: a prospective cohort study. *PLoS One* 8, e70981. doi:[10.1371/journal.pone.0070981](https://doi.org/10.1371/journal.pone.0070981).
- Tokur, D., Grimmer, M., Seyfarth, A., 2020. Review of balance recovery in response to external perturbations during daily activities. *Human Movement Science* 69, 102546. doi:[10.1016/j.humov.2019.102546](https://doi.org/10.1016/j.humov.2019.102546).
- van Wegen, E., van Emmerik, R., Riccio, G., 2002. Postural orientation: Age-related changes in variability and time-to-boundary. *Human Movement Science* 21, 61–84. doi:[10.1016/S0167-9457\(02\)00077-5](https://doi.org/10.1016/S0167-9457(02)00077-5).
- Winter, D., 1995. *ABC of Balance During Standing and Walking*. Waterloo Biomechanics. Waterloo, CA.
- Wu, G., van der Helm, F.C., (DirkJan) Veeger, H., Makhssous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., Buchholz, B., 2005. Isb recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—part ii: shoulder, elbow, wrist and hand. *Journal of Biomechanics* 38, 981–992. doi:[10.1016/j.jbiomech.2004.05.042](https://doi.org/10.1016/j.jbiomech.2004.05.042).