



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, pp.1-12. 10.1016/j.jbiomech.2023.111703 . hal-04142469v1

HAL Id: hal-04142469

<https://inria.hal.science/hal-04142469v1>

Submitted on 27 Jun 2023 (v1), last revised 21 Aug 2023 (v3)

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^a, Anne-Hélène Olivier^a, Ludovic Hoyet^a, Julien Pettré^a, Charles Pontonnier^a

^a *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.

Email address: thomas.chatagnon@inria.fr (Thomas Chatagnon)

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 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 ± 4.2 years, 70.2 ± 12.1 kg and 1.74 ± 0.08 m respectively. All but one subject were considered having an overall right side preference (laterality test (Coren, 1993) mean: 9.45 ± 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 Angles \times 3 Intensities \times 2 Repetitions).

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). 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.

126 *2.2.2. Limit of Standing Balance (LoSB) in and out of the sagittal plane.*

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

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

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

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

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

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

139 The Ttb is the time required by the projection of the CoM on the ground to reach the BoS boundary
 140 given the current CoM velocity. Ttb is computed as:

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

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

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

143 We also studied the *Distance to Foot boundary* (DtFb) for trials involving steps following lateral per-
 144 turbations. This quantity corresponds to the distance from the CoM ground projection to the boundary
 145 of the polygon created by *Non-Stepping Foot* markers, in the reference linked to the participant's foot
 146 position at the beginning of the foot movement (t_{begin}). The directional vector of the reference used in the
 147 computation was obtained by using the average position of the centroid of each foot marker. This resulted in
 148 the creation of a *Non-Stepping Foot* average position (\mathbf{F}_{NS}), and a *Stepping Foot* average position (\mathbf{F}_S).
 149 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
 150 following definition:

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

151 (7)

152

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

155 *2.3. Analysis*

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

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

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

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

177 3. Results

178 In total, steps were made in 616 trials out of 1260. The recovery did not require steps in 600 trials, and
 179 41 trials were not considered due to their ambiguous nature (leg lifted, but no step). This behavior was
 180 observed for perturbations out of the sagittal plan, and mostly in the mediolateral direction (33 out of 41
 181 trials). Three trials were removed for technical reasons. Table 1 summarises the number of each recovery
 182 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.

183 The models using Ttb or MoS seem to perform similarly in term of accuracy to separate NS trials and
 184 trials with steps. Logistic models based on minimal values of MoS or Ttb kept an overall accuracy above
 185 79% (see Table 2) with a maximum of accuracy for perturbations in the sagittal plane. Separation models
 186 between *Loaded Step* (LS) and *Unloaded Steps* (US) using DtFb keep an accuracy above 97% for all lateral
 187 perturbation angles (see Table 3).

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

192 We observed in Fig. 4 different ranges of minimal values of Ttb and MoS between LSS, UMS and UCS
 193 strategies. The range of values for LSS trials seemed to have a larger overlap with values of NS trials than

194 the US trials (i.e. UMS and UCS). This overlap also depended on the angle of the perturbation, and different
195 overlaps were observed depending on the side of the perturbation (i.e. between 0 deg and 180 deg, or between
196 45 deg and 135 deg). For lateral perturbation trials, minimal values of Ttb or MoS cannot be used to separate
197 LS from US. One way to separate these strategies may therefore be by looking at DtFb (Fig. 5). For all
198 lateral perturbation angles, the logistic models based on the DtFb provide a clear separation between LS and
199 US trials, with an almost perfect accuracy for each angle (see Table 3).

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.

200 4. Discussion

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

205 4.1. Effect of the experimental conditions

206 The perturbation angles had a significant impact on the overlapping range of minimal Ttb and MoS values
207 between Non-Stepping and Stepping recovery strategies. However, almost all the LMMs (except for when
208 using MoS) were not significantly affected by the angle (see Table 4). This resulted in comparable decision
209 boundaries for each logistic model regardless of perturbations angle. One can also notice an asymmetry of
210 stepping strategies used depending on the perturbation angle, with more LSS than UMS for 135deg and
211 180deg, and more UMS than LSS for 0deg and 45deg. This may be linked to the overall right side preference
212 of participants. Further investigations are required to assess the effect of laterality in this situation.

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

219 4.2. Modeling approach

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

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

235 After making the aforementioned choices some of our results may still be comparable to the literature,
236 with some differences remaining in the shape of the perturbations applied to participants. Following the
237 method of Hof and Curtze (2016) and regarding perturbations in the sagittal plane, the mean distance
238 before the LoSB in our experiment would have been $5cm \pm 1cm$. Here we found a smaller limit around
239 $3cm$. Similarly, Schulz et al. (2006) observed a critical Ttb of $0.52s$ with a prediction accuracy of 94%
240 for a population of young, old unimpaired and old with balance-impairment. This value is comparable to
241 the one observed under the same conditions in our study ($0.44s$ and 99% accuracy). The main differences
242 in the results may be explain by the methodological variation (e.g. for step detection) and differences in
243 experimental protocols (e.g. participants asked to avoid stepping as much as possible in previous studies).

244 4.3. Step Characterisation

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

254 4.4. Limitations

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

266 The geometric BoS boundaries were approximated in our experiment using the location of the external
267 markers placed on the outer part of each foot of participants, therefore slightly over estimating the BoS.
268 Thus, the actual boundaries may vary up to 1cm (based on the size of the marker used) towards the CoM
269 ground projection at rest.

270 5. Conclusion

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

279 Acknowledgement

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

282 This project has received funding from the European Union's Horizon 2020 research and innovation pro-
283 gramme under grant agreement No 899739 (CrowdDNA).

284

285 Figures

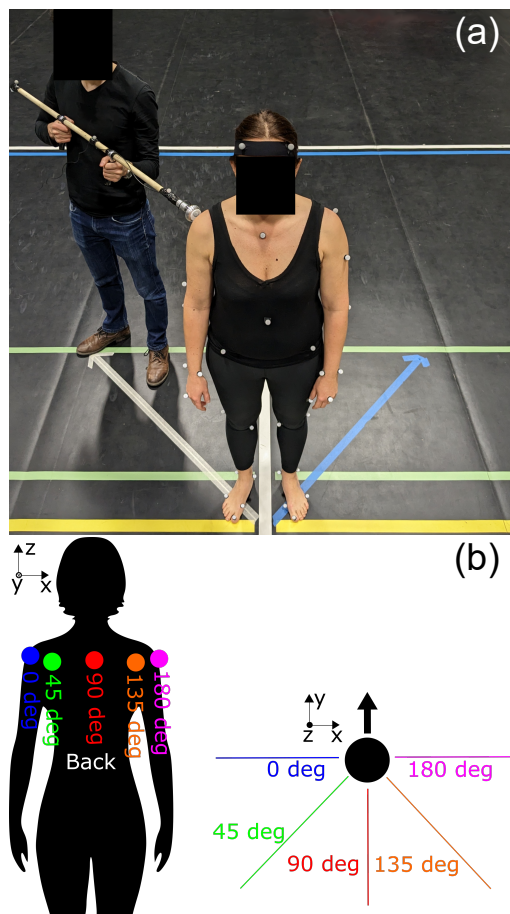


Figure 1: (a) Illustrative picture taken as the participant was about to receive a perturbation with an angle of 45 deg. (b) Angles of application location of the perturbations.

286 References

- 287 Borrelli, J., Creath, R., Gray, V., Rogers, M., 2021. Untangling biomechanical differences in perturbation-induced stepping
 288 strategies for lateral balance stability in older individuals. *Journal of Biomechanics* 114, 110161. doi:[https://doi.org/10.](https://doi.org/10.1016/j.jbiomech.2020.110161)
 289 [1016/j.jbiomech.2020.110161](https://doi.org/10.1016/j.jbiomech.2020.110161).
- 290 Bressel, E., Yonker, J.C., Kras, J., Heath, E.M., 2007. Comparison of static and dynamic balance in female collegiate soccer,
 291 basketball, and gymnastics athletes. *J Athl Train* 42, 42–46.
- 292 Coren, S., 1993. The lateral preference inventory for measurement of handedness, footedness, eyedness, and earedness: Norms
 293 for young adults. *Bulletin of the Psychonomic Society* 31, 1–3. doi:[10.3758/BF03334122](https://doi.org/10.3758/BF03334122).
- 294 Emmens, A.R., F. van Asseldonk, E.H., Prinsen, V., der Kooij, H.v., 2020. Predicting reactive stepping in response to
 295 perturbations by using a classification approach. *Journal of NeuroEngineering and Rehabilitation* 17, 84. doi:[10.1186/](https://doi.org/10.1186/s12984-020-00709-y)
 296 [s12984-020-00709-y](https://doi.org/10.1186/s12984-020-00709-y).
- 297 Fujimoto, M., Bair, W.N., Rogers, M.W., 2017. Single and multiple step balance recovery responses can be different at
 298 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>.
- 299
- 300 Gray, V.L., Yang, C.I., McCombe Waller, S., Rogers, M.W., 2017. Lateral perturbation-induced stepping: Strategies and
 301 predictors in persons poststroke. *Journal of Neurologic Physical Therapy* 41.
- 302 Hof, A., Gazendam, M., Sinke, W., 2005. The condition for dynamic stability. *Journal of Biomechanics* 38, 1–8. doi:[10.1016/j.](https://doi.org/10.1016/j.jbiomech.2004.03.025)
 303 [jbiomech.2004.03.025](https://doi.org/10.1016/j.jbiomech.2004.03.025).
- 304 Hof, A.L., Curtze, C., 2016. A stricter condition for standing balance after unexpected perturbations. *Journal of Biomechanics*
 305 49, 580–585. doi:<https://doi.org/10.1016/j.jbiomech.2016.01.021>.
- 306 Jamovi, 2022. The jamovi project. Retrieved from <https://www.jamovi.org/>. (Version-2.3), Accessed: 2022-09.
- 307 Li, X., Song, W., Xu, X., Zhang, J., Xia, L., Shi, C., 2020. Experimental study on pedestrian contact force under different
 308 degrees of crowding. *Safety Science* 127, 104713. doi:[10.1016/j.ssci.2020.104713](https://doi.org/10.1016/j.ssci.2020.104713).

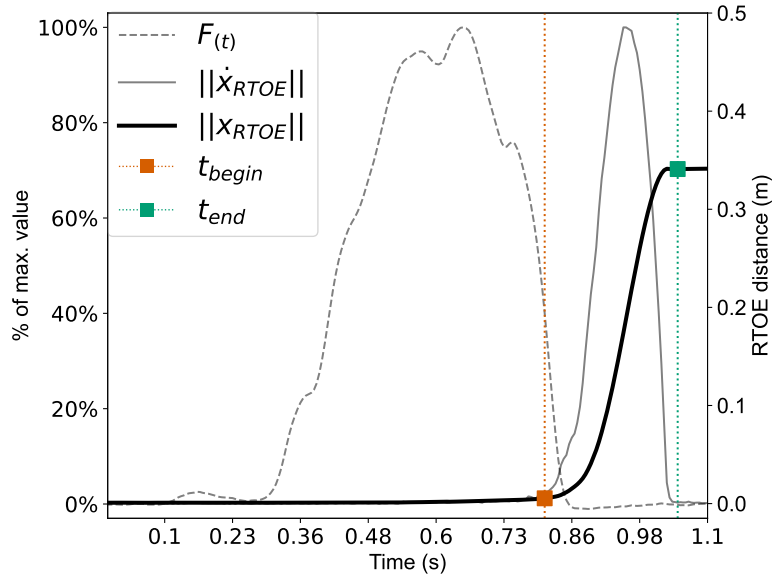


Figure 2: Transversal speed ($\|\dot{x}_{RTOE}\|$) and distance ($\|x_{RTOE}\|$) from the origin of the marker placed on the right toe (RTOE) of a participant for a representative trial. t_{begin} is the moment at which the step is initiated, t_{end} is the moment at which the considered foot stops moving.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

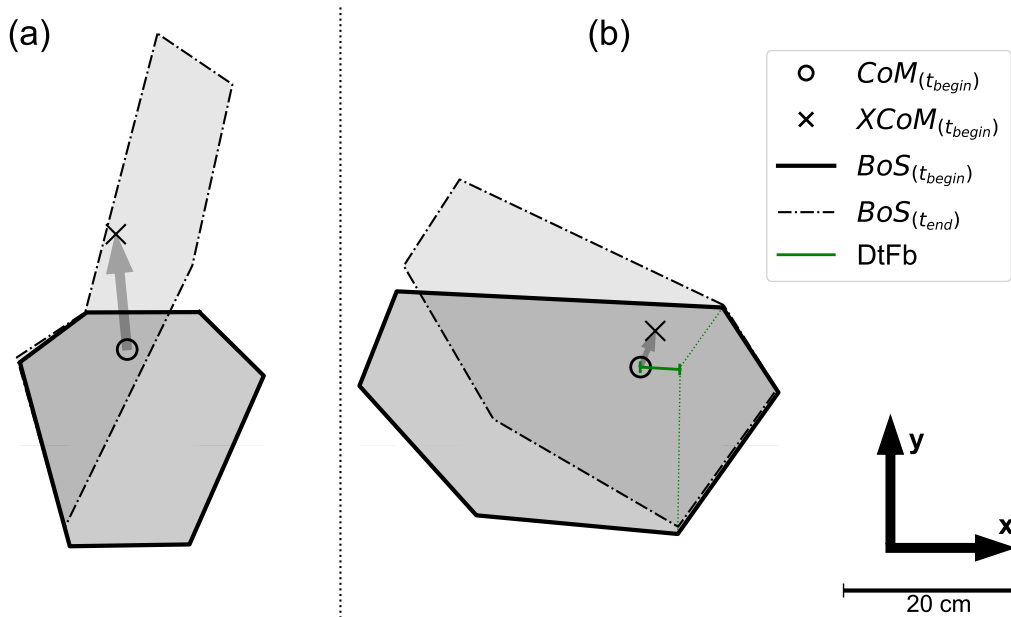


Figure 3: Spatial representation of the reaction of two participants for perturbations at 90 deg (a) and 135 deg (b). By definition, the arrow between the CoM and the XCoM represents $\frac{\dot{x}_{CoM}}{\omega_0}$.

309 Maki, B.E., McIlroy, W.E., 1997. The Role of Limb Movements in Maintaining Upright Stance: The “Change-in-Support”
 310 Strategy. *Physical Therapy* 77, 488–507. doi:10.1093/ptj/77.5.488.
 311 Mille, M.L., Johnson, M.E., Martinez, K.M., Rogers, M.W., 2005. Age-dependent differences in lateral balance recovery through

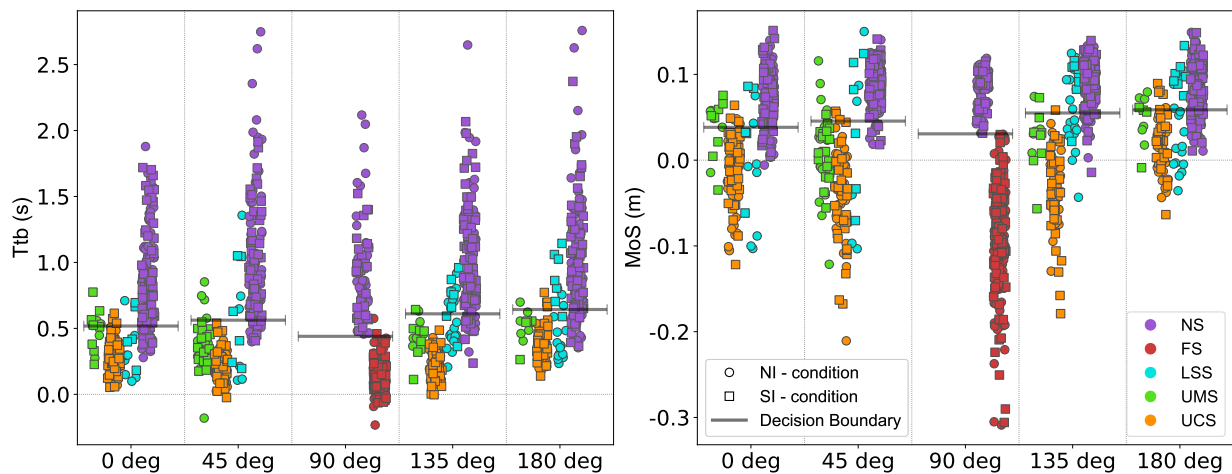


Figure 4: Separation between Non-Step (NS) trials and trials with steps (FS, LSS, UMS, UCS). NI trials are marked with round dots and SI trials with square dots. Each dot represents the minimal value of Ttb or MoS during one single trial. Minimal value was computed before step initiation for trials involving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

- 312 protective stepping. *Clinical Biomechanics* 20, 607–616. doi:<https://doi.org/10.1016/j.clinbiomech.2005.03.004>.
- 313 Muller, A., Pontonnier, C., Puchaud, P., Dumont, G., 2019. Custom: a matlab toolbox for musculoskeletal simulation. *Journal*
- 314 *of Open Source Software* 4, 927. doi:10.21105/joss.00927.
- 315 Robert, T., Vallee, P., Tisserand, R., Buloup, F., Bariatinsky, D., Vercher, J., Fitzpatrick, R., Mille, M., 2018. Stepping
- 316 boundary of external force-controlled perturbations of varying durations: Comparison of experimental data and model
- 317 simulations. *Journal of Biomechanics* 75, 89–95. doi:10.1016/j.jbiomech.2018.05.010.
- 318 Santos, M.J., Kanekar, N., Aruin, A.S., 2010. The role of anticipatory postural adjustments in compensatory control of posture:
- 319 2. biomechanical analysis. *Journal of Electromyography and Kinesiology* 20, 398–405. doi:10.1016/j.jelekin.2010.01.002.
- 320 Scholz, J.P., Schöner, G., 1999. The uncontrolled manifold concept: identifying control variables for a functional task.
- 321 *Experimental Brain Research* 126, 289–306. doi:10.1007/s002210050738.
- 322 Schulz, B.W., Ashton-Miller, J.A., Alexander, N.B., 2006. Can initial and additional compensatory steps be predicted in young,
- 323 older, and balance-impaired older females in response to anterior and posterior waist pulls while standing? *Journal of*
- 324 *Biomechanics* 39, 1444–1453. doi:10.1016/j.jbiomech.2005.04.004.
- 325 Shumway-Cook, A., Woollacott, M.H., 1995. *Motor control: theory and practical applications*. Baltimore (Md.): Williams and
- 326 Wilkins.
- 327 Stins, J.F., Roerdink, M., Beek, P.J., 2011. To freeze or not to freeze? affective and cognitive perturbations have markedly
- 328 different effects on postural control. *Human Movement Science* 30, 190–202. doi:10.1016/j.humov.2010.05.013. basic
- 329 Mechanisms underlying Balance Control under Static and Dynamic Conditions.
- 330 Sturnieks, D.L., Menant, J., Delbaere, K., Vanrenterghem, J., Rogers, M.W., Fitzpatrick, R.C., Lord, S.R., 2013. Force-
- 331 controlled balance perturbations associated with falls in older people: a prospective cohort study. *PLoS One* 8, e70981.
- 332 doi:10.1371/journal.pone.0070981.
- 333 Tokur, D., Grimmer, M., Seyfarth, A., 2020. Review of balance recovery in response to external perturbations during daily
- 334 activities. *Human Movement Science* 69, 102546. doi:10.1016/j.humov.2019.102546.
- 335 van Wegen, E., van Emmerik, R., Riccio, G., 2002. Postural orientation: Age-related changes in variability and time-to-boundary.
- 336 *Human Movement Science* 21, 61–84. doi:10.1016/S0167-9457(02)00077-5.
- 337 Winter, D., 1995. *ABC of Balance During Standing and Walking*. Waterloo Biomechanics. Waterloo, CA.
- 338 Wu, G., van der Helm, F.C., (DirkJan) Veeger, H., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade,
- 339 K., Wang, X., Werner, F.W., Buchholz, B., 2005. Isb recommendation on definitions of joint coordinate systems of various
- 340 joints for the reporting of human joint motion—part ii: shoulder, elbow, wrist and hand. *Journal of Biomechanics* 38, 981–992.
- 341 doi:10.1016/j.jbiomech.2004.05.042.

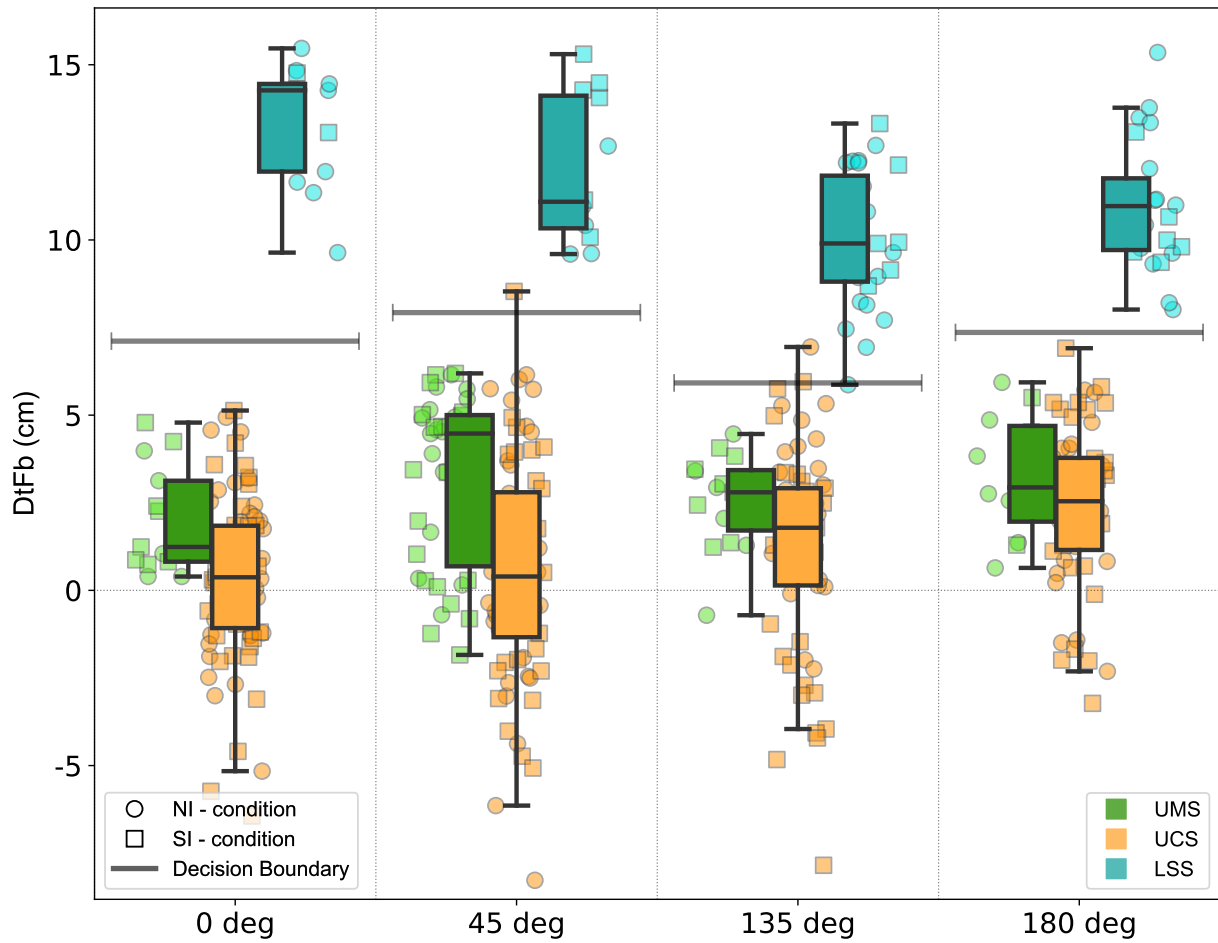


Figure 5: Separation between trials with *Loaded Steps* (LSS) and *Unloaded Steps* (UMS and UCS) using the DtFb for lateral perturbations. A negative DtFb indicates a CoM within the polygon of the foot markers at t_{begin} .