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# Standing balance recovery strategies following external perturbations: a multiscale approach with applications to dense crowds

Thomas Chatagnon

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COLLEGE MATHS, TELECOMS

DOCTORAL INFORMATIQUE, SIGNAL

BRETAGNE SYSTEMES, ELECTRONIQUE



école  
normale  
supérieure

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L'ÉCOLE NORMALE  
SUPÉRIEURE RENNES

ÉCOLE DOCTORALE N° 601

*Mathématiques, Télécommunications, Informatique, Signal,  
Systèmes, Électronique*

Spécialité : *Automatique, Productique et Robotique*

Par

**Thomas B. M. CHATAGNON**

**Standing Balance Recovery Strategies Following External Per-  
turbations : A Multiscale Approach With Applications to Dense  
Crowds**

Thèse présentée et soutenue à INRIA Rennes, le 20/12/2023

Unité de recherche : IRISA - UMR 6074

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# INTRODUCTION

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## 1.1 General Context

Human crowds can be experienced by anyone, everywhere in the world. Defining the substantial meaning behind the word “Crowd” is however a real challenge [Le Bon, 1896; Adrian et al., 2019]. This simple word, which we use to describe a phenomenon we may experience on a daily basis, actually covers a complex spectrum of situations. However, a common point seems to apply to any crowd: the presence of inter-individual interactions.

Human crowds, as all kind of social animal formations, come with a wide diversity of interactions between individuals. These interactions occur at a local scale between nearby individuals, but result in important collective motions at larger scales. Interactions in this context are mainly social and based on verbal and non-verbal communication [Volonte et al., 2020; Berton et al., 2022; Raimbaud et al., 2023] as well as culture or habits [Pons and Laroche, 2007]. These social interactions are used as indicators for individuals behavior in crowds, for instance to avoid collisions [Appert-Rolland et al., 2020] or to maintain group formations [Koster et al., 2011]. Occasionally, crowds may also involve physical interactions, i.e. interpersonal contacts. These physical interactions may be voluntary like in particular cultural events and demonstrations involving dancing or other kind of body interactions (e.g. walking arm-in-arm). Voluntary physical interactions appear to be associated with an overall feeling of a collective social identity experienced by individuals of the crowd [Drury and Reicher, 2020; Neville et al., 2022]. However, in other situations physical interactions are involuntary or uncontrolled. Such interactions are often associated with densely crowded events. We define **Dense Crowds** here as tightly packed formations of individuals in which the motion of each individual is limited and likely to result in physical interactions with others. Such a definition still allows an infinite variety of crowd configurations which all share a common feature: physical interactions between individuals. The most common example of circumstances leading to such crowds are large scale cultural events such as sport events, music concerts, festivals or religious rituals. In

this situation, contact forces can accumulate and people within the crowd may experience unpleasant or even dangerous body compression. This phenomenon can lead to anxiety, fainting and even asphyxia [Sieben and Seyfried, 2023]. Physical interactions can also act as external perturbations, throwing people off balance. Such a loss of balance may then lead to additional constraints on neighbours' bodies which can then develop into dangerous collective falls, commonly referred to as crowd collapses [Zhou et al., 2017].

Throughout the last century the recorded number of crowd accident has been constantly growing. These accidents have been associated with numerous physical injuries and deaths each year (see Fig. 1.1) [Feliciani et al., 2023]. In this context the research community employed great efforts to better understand the implications and risks of this common phenomenon. In order to address the underlying complexities of these situations, most studies about human crowds have emerged from collaborations between researchers with multiple backgrounds such as social and computer sciences, physics, mathematics or biomechanics. However, several key elements especially regarding balance and recovery strategy are currently still unclear. These features have to be monitored at local scales, i.e. for an individual and its direct neighbours, but they could play a fundamental role for larger scales motion (e.g. motion propagation, crowd collapses).

In line with the aforementioned challenges, we propose here to study *Standing balance recovery strategies* following external perturbations in the perspective of application for *Dense Crowd* interaction modeling.

The work proposed in this manuscript is embedded in an experimental approach linked to movement sciences, with the biomechanical analysis of recovery strategies following external perturbations. This study was carried out in the context of crowd modelling, with the aim of identifying the recovery characteristics of human standing balance in dense crowd situations. An experimental multiscale approach was used to study standing balance following external perturbations in different environments (see representation in Fig. 1.2). We began our study with the analysis of single individuals' recovery strategies following external perturbations from different directions in a fully controlled laboratory environment. Then, the balance recovery of multiple individuals following external perturbations was investigated in a laboratory-controlled environment replicating dense crowd conditions. Finally, standing balance recovery following physical interactions in an uncontrolled environment was explored for individuals within punk rock concert crowds. The research questions which guided this research were:

1. What are the characteristics of recovery strategies following external perturbations

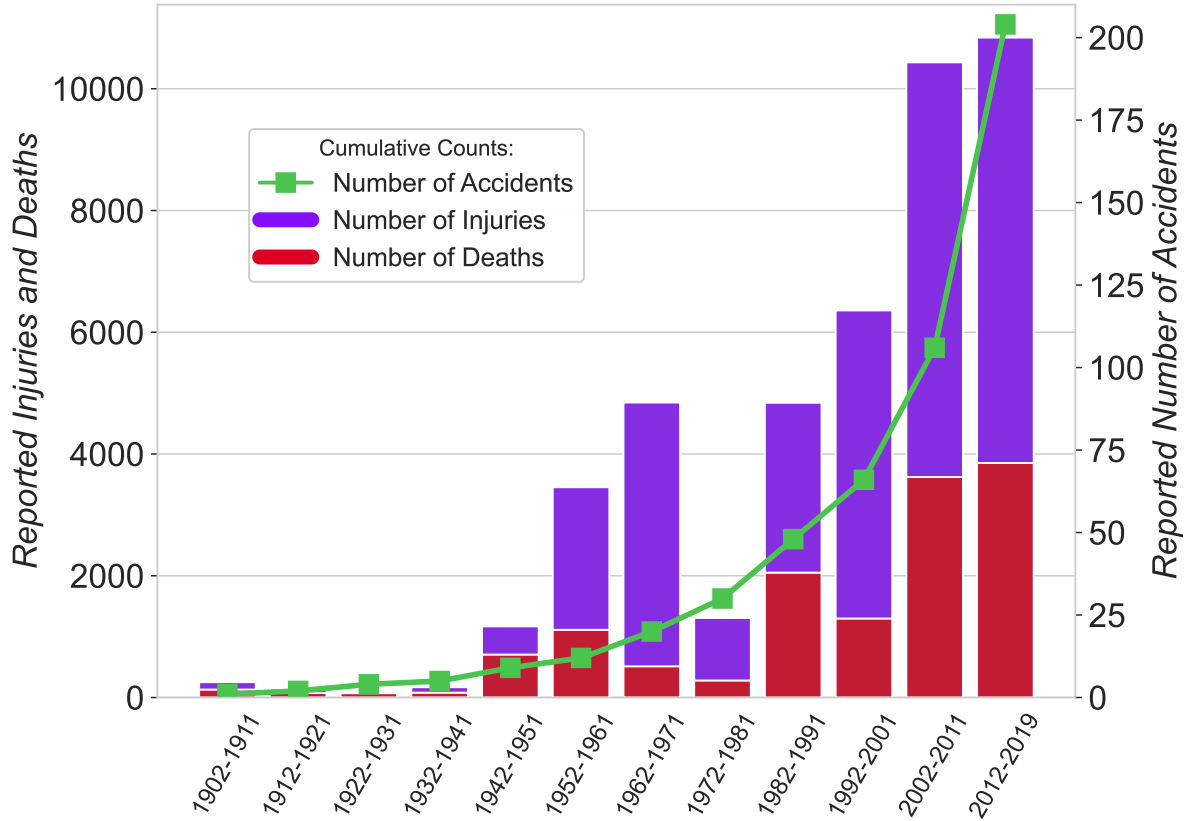


Figure 1.1 – Reported numbers of crowd accidents and resulting casualties for 10-year periods from 1902 to 2019. Figure create from data of [Feliciani et al., 2023].

from different directions? (Chapter 2)

2. How do individuals adapt their recovery strategy following external perturbations in a dense crowd context? (Chapter 3)
3. To which extent recovery strategies observed during laboratory experiments may be compared to recovery strategies recorded in real crowds situations during field studies? (Chapter 4)

## 1.2 Related Work

The studies presented in this thesis are grounded in the context of human movement science and crowd modelling. Our research questions and analyses share common concepts related to standing balance and physical interactions in crowds. We first propose

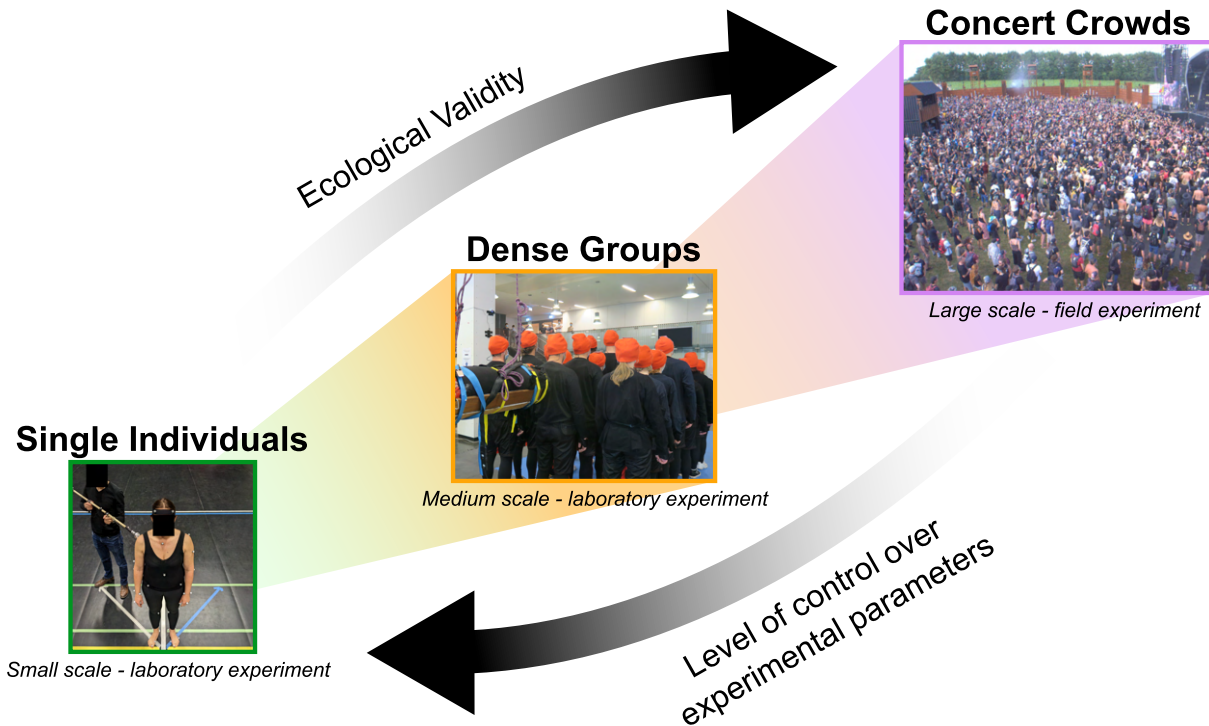


Figure 1.2 – Representation of the multiscale experimental approach proposed in this thesis to study standing balance and balance recovery following external perturbations in the context of static dense crowds.

an overview of the research that has been proposed on these topics. Specific literature related to the three research questions of this thesis are also presented in their respective chapters.

### 1.2.1 Standing Balance and Recovery Following External Perturbations

With more than 684,000 people involved in lethal fall accidents in 2019, falls were estimated to be the second leading cause of unintentional injuries or deaths over the world [Organization et al., 2021]. Fall is currently a major health issue, especially among older populations, and results from a combination of two elements: a perturbation and the inability to recover balance. In this context, research works relative to *human balance* are numerous and very diverse.

In this thesis we are focussing on standing balance following external perturbations. However, perturbations can also be internal, mainly related to symptoms of specific dis-

eases [Winser et al., 2019; Mikos et al., 2021; Vinik et al., 2017; Johnson et al., 2023]. Balance control is also different between static standing situations and locomotion tasks [Hof et al., 2010; Robert et al., 2019; Mierlo et al., 2023; Watier et al., 2023]. In this thesis we only concentrate on static standing situations comparable to what can be experienced in dense crowds [Zhou et al., 2017; Sieben and Seyfried, 2023].

### 1.2.1.1 Standing Balance

Standing balance corresponds to the static or quasi-static upright posture of a person who stands in a state of equilibrium with both feet on the ground [Ramesh and Alan M., 2002]. The standing posture allows static balance, but requires a constant postural control [Forbes et al., 2018]. This postural control is coordinated by the *Central Nervous System* (CNS) which activates muscles based on the available sensory feedback [Peterka, 2002; Maurer et al., 2006; Shanbhag et al., 2023] (see Fig. 1.3). Sensory feedback gives information about both the intrinsic feeling of balance and the surrounding environment. Human sensory feedback can be decomposed into three categories [Shumway-Cook and Woollacott, 1995]. First, visual feedback give information about the head position and velocity, relative to the visible surrounding. Vision also provides information about the surrounding environment e.g. type of terrain, proximity of other static or moving bodies. In addition, proprioceptive or kinesthetic feedback emerging from the body itself (using muscle spindles, Golgi tendon organs or skin mechanoreceptors) allow a relative positioning of every limb in space. Skin mechanoreceptors, particularly under the arches, can also provide information about the surface of the ground and the distribution of body mass during standing balance. Feedback arising from the vestibular organs provide information about head translational and rotational acceleration [Mergner, 2010]. Sensory feedback' information are then processed by the CNS based on personal and environmental constraints such as type or terrain, visibility conditions or other sensory impairments [Peterka, 2002]. CNS itself can also be affected by age, diseases or drugs leading to altered postural control capacities [Melzer et al., 2001; Winser et al., 2019; Westerlind et al., 2019].

Standing balance can also be defined from a mechanical point of view, i.e. the static balance of external forces. Therefore, to achieve balance in an upright posture individuals have to compensate the force of gravity by adjusting their effort on the ground or by using inertia generated through body motion [Horak and Nashner, 1986; Maki and McIlroy, 1997]. The resultant of gravitational forces on the body can be considered as applying only to the *Center of Mass* (CoM) which is the average position of the body mass distribution.

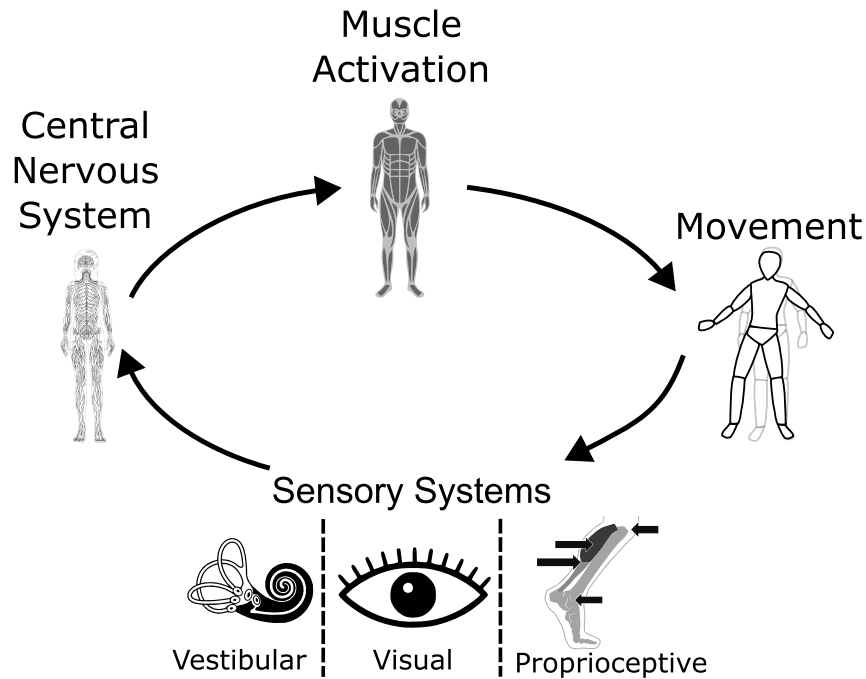


Figure 1.3 – Simplified diagram of the human postural control loop mechanism used to maintain standing balance.

Efforts on the ground can only be located within the *Base of Support* (BoS), defined as the convex area on the ground containing all contact points of the body with the ground. The average location of the resultant efforts with the ground is referred as the *Center of Pressure* (CoP). All the aforementioned variables, are represented in Fig. 1.4.

Standing balance was modelled using an *Inverted Pendulum* (IP) based on these biomechanical reference landmarks.[Pai and Patton, 1997]. This approach was further simplified using *Linear Inverted Pendulums* for which the CoM is assumed to travel at constant height [Kajita and Tani, 1991; Hof et al., 2005]. Most pendulum models are bi-dimensional in the sagittal plan [Vallee et al., 2015; Zelei et al., 2021] (Fig. 1.5), with recent advanced models taking into account mediolateral sway also exist [Hou et al., 2022]. However, a lack of experimental validation remains, experimentally regarding the modeling of recovery out of the sagittal plane.

### 1.2.1.2 Limit of Standing Balance

The *Limit of Standing Balance* (LoSB) or limit of stability [Horak, 2006] is defined as the limit after which individuals trigger strategies involving *Change-in-support* to recover from balance perturbations. If no external support can be used from the environment, the

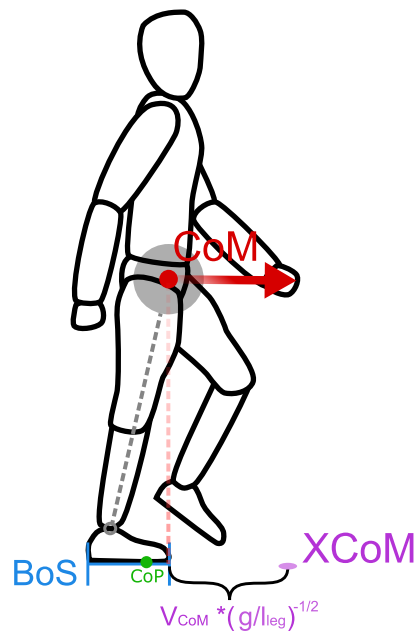


Figure 1.4 – Representation of classical biomechanical variables used to study human standing balance.

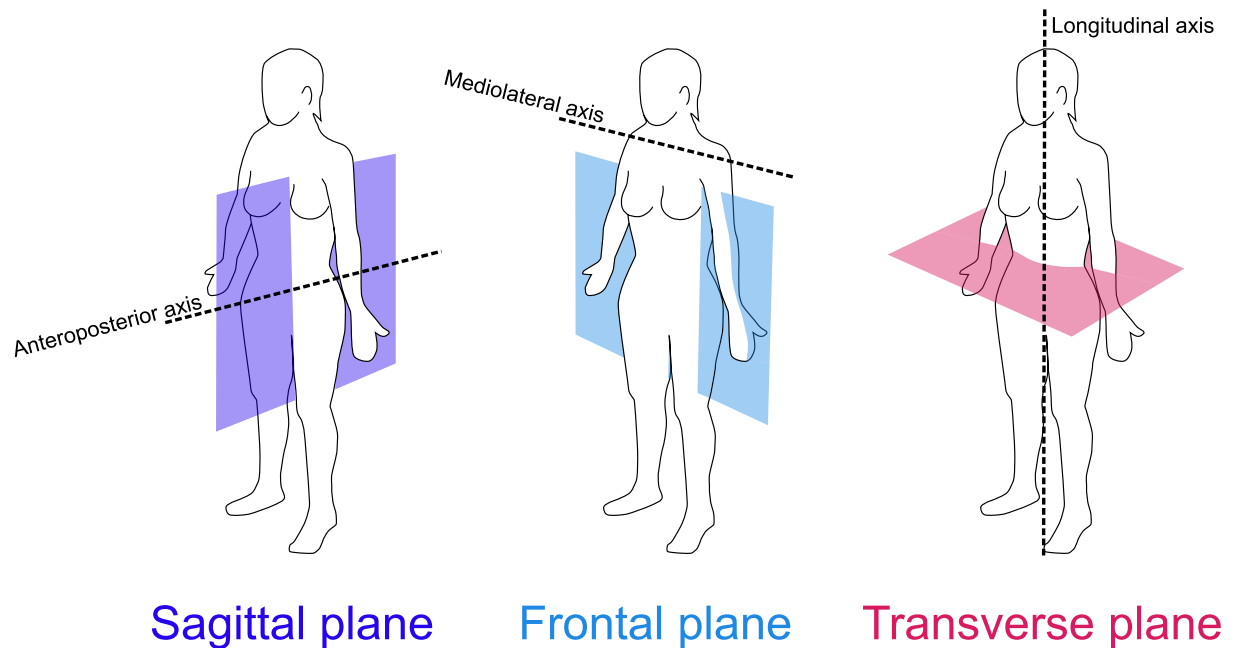


Figure 1.5 – Representation of the anatomical planes and the axes relative to the classical direction associated with the study of the human body.

LoSB corresponds to the limit after which steps are initiated to recover balance [Maki and McIlroy, 1997].



In early work, the moment when the projected *Center of Mass* (CoM) on the ground reaches the boundary of the Base of Support (BoS) was suggested as the functional LoSB [Shumway-Cook and Woollacott, 1995; Winter, 1995]. However, this proposition is only limited to static situations. For dynamic situations the inertia induced by body’s motion has to be taken into account. To do so, the *Zero Moment Point* (ZMP) can be considered [Vukobratović and Borovac, 2004]. The ZMP is defined as the projected point at which reaction forces at the contacts between the feet and the ground do not produce any moment in the ground plane [Vukobratović et al., 2001]. For static situations where the projection of the CoM is contained in the BoS, the ZMP is equal to the CoP. If the ZMP exits the BoS, the body is critically unstable and a modification of the BoS is required to prevent a fall. The LoSB can then be defined as the moment the ZMP exits the BoS.

Using a linearised IP model Hof et al. [2005] proposed to use the concept of *Extrapolated Center of Mass* (XCoM) to study the LoSB. Since XCoM takes the CoM position and velocity into account, it can be used to estimate situations with dynamic instability. This concept 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 moment when the MoS reaches a null value being considered to be the limit of dynamic stability. The actual limit before step initiation for dynamic situations was later demonstrated to be reached before a null MoS occurs [Hof and Curtze, 2016]. One should note that other standing balance models featuring a larger span of fixed support recovery strategies have been developed to determine the LoSB [Pratt et al., 2006; Vallee et al., 2015; Hou et al., 2022]

Another method to assess the limit before initiation of stepping recovery strategy was proposed by Schulz et al. [2006] using the *Time to boundary* (Ttb), i.e. the time for the projected CoM to reach the BoS boundary given its current velocity. Prediction accuracy reaches 80% following perturbations in the sagittal plane, and was later increased using trained neural network models based on kinematics-related features [Emmens et al., 2020]. To the best of our knowledge, this approach has only been used to study the LoSB following perturbation from directions other than anteroposterior.

### 1.2.1.3 Recovery Strategies Overview

Different types of recovery strategies can be adopted by individuals to regain standing balance following perturbations. These recovery strategies can be divided into two main categories, *fixed support* recoveries and recoveries involving a *Change-in-support* [Maki and McIlroy, 1997].

Fixed support recovery strategies include the “ankle strategy”, the “hip strategy” and arm movements. The ankle strategy is defined as the activation of the muscles controlling the ankle rotation. This strategy is limited by muscular capacity of individuals and is thus used for minor perturbations and by younger individuals [King et al., 1994; Melzer et al., 2008]. The hip strategy is characterised by a trunk rotation at hip level [Rietdyk et al., 1999]. In addition to a lower muscle strength requirement for CoM repositioning, the inertia generated by the body rotation helps to damp the CoM velocity [Horak and Nashner, 1986; Maki and McIlroy, 1997]. Both the ankle and the hip strategies have been mainly studied for recovery following perturbations in the anteroposterior direction [Horak and Nashner, 1986]. For lateral perturbations mixtures of ankle and hip strategies were observed together with additional shoulder and upper trunk rotation [Rietdyk et al., 1999]. Arm movements were observed to be used in addition to the ankle and hips strategies [Hof, 2007]. Their effect was reported to be comparable to the hip strategy with inertia generated through arm rotation [Roos et al., 2008; Milosevic et al., 2011].

Recovery strategies involving a *Change-in-support* are defined by a modification of the BoS [Maki and McIlroy, 1997]. This modification can be done either by reaching and using support from elements of the surrounding environment (e.g. walking stick, metro grab bars, other individuals) [Maki et al., 2003], or by stepping to restore a BoS under the CoM and thus be able to compensate the action of the gravitational forces. These strategies are the most effective to recover from external perturbations as they directly increase the available leverage to counter-balance the effect of gravity on the CoM. One should keep in mind that stepping recovery strategies may involve multiple steps [Maki and McIlroy, 1997], especially following lateral perturbations [Borrelli et al., 2021].

The *Leg Abduction* (LA) strategy should also be mentioned in addition to the above recovery strategy. This recovery strategy consists in using one leg as a counterweight to reduce the effect of the perturbation (see Fig. 1.6). The inertia generated by the rotation of the lifted leg is comparable to the one generated during the hip strategy or using arm movements. As one foot is lifted off the ground the BoS is changed using this recovery strategy. However, as the other foot does not move this strategy can be considered as a partially fixed support strategy. Due to their hybrid characteristics LAs were rarely taken into account in previous studies [Borrelli et al., 2021; Bateir et al., 2022].

Although many standing balance recovery models that include step strategies have been proposed [Pratt et al., 2006; Vallee et al., 2015; Zhang and Fu, 2018], experimental data on recovery step characteristics are less numerous. In addition, when considered,

recovery steps characteristics are often averaged with respect to limited sets of external perturbations [McIlroy and Maki, 1996; Mille et al., 2005; Borrelli et al., 2021]. More recently step characteristics have been studied in perspective to external perturbation characteristics [Zhang and Fu, 2018; Li et al., 2021] or to intrinsic quantification of balance disturbance such as CoM displacement and speed [Lai et al., 2022]. It has also been shown that step characteristics depend on the step strategy used [Mille et al., 2005], especially for lateral recovery steps. In line with this finding, Bateir et al. [2022] proposed to study step characteristics in relation to the stepping strategies used after lateral perturbations.

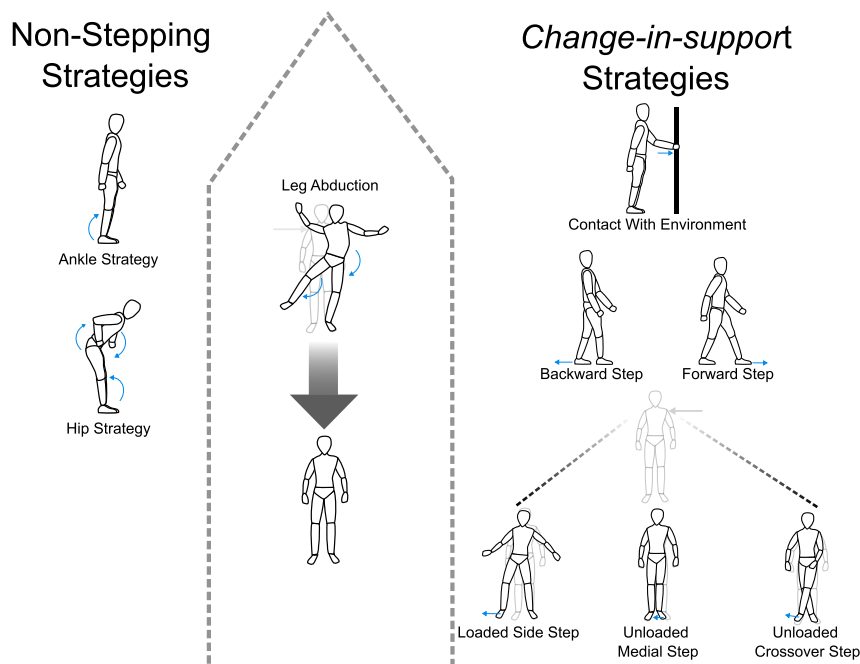


Figure 1.6 – Representation of the different standing balance recovery strategies.

#### 1.2.1.4 Factors Affecting Standing Balance and Recovery

In this section, we will review several factors that have been demonstrated to affect standing balance and recovery following perturbations.

**Direction of Perturbations:** The direction of application of external perturbations was associated with different balance recovery strategies. For fixed support recovery strategies, the main differences between anteroposterior and lateral perturbations are linked to upper body motion [Rietdyk et al., 1999]. Regarding recovery involving *Change-in-support*, different stepping strategies were observed depending on the direction of the perturbation.

For perturbation in the anteroposterior direction, *Forward Step* (FS) and *Backward Step* (BS) were reported [Maki and McIlroy, 1997]. For lateral perturbations, recovery *Side Steps* (SS) can either be *Loaded* or *Unloaded*, depending if the perturbations were loading the body mass onto or away from the stepping leg. For *Unloaded* steps, the unloaded leg can either stay on its original side or cross the other leg resulting in a *Crossover* step. Hence, three main stepping strategies are usually considered: the *Loaded Side Step* (LSS), the *Unloaded Medial Step* (UMS) and the *Unloaded Crossover Step* (UCS) [Mille et al., 2003; Batcir et al., 2020; Batcir et al., 2022].

**Level of Awareness to upcoming perturbations:** The level of Awareness (LoA) to upcoming perturbations can be defined as the degree of knowledge related to the perturbation, e.g. the intensity, the direction or the moment of initiation of given perturbations. A reduced LoA during experiments may be linked to higher levels of anxiety and induce a greater body stiffness [Stins et al., 2011]. Similarly, [Santos et al., 2010] showed that the anticipation of upcoming perturbations has an effect following external perturbation, with larger displacement of the CoM. Regarding the influence of the LoA on the LoSB, unexpected timing has mainly been used in experiments with external perturbations [Emmens et al., 2020; Li et al., 2020a; Robert et al., 2018]. The effect of visual impairment (closed eyes) on standing balance was also used in studies related to standing balance [Hof et al., 2005; van Wegen et al., 2002]. To our knowledge, sensory limitation devices to control the LoA have never been used in studies regarding standing balance following external perturbations. In dense crowds, sensory limitations can be experienced under several conditions. One of the most striking examples may be concert crowds, where individuals may experience both visual and auditory limitations when exposed to loud music and wide variations in lighting. However, visual impairment may also be experienced in spontaneous dense crowds. This was reported in eyewitness testimonies after dense crowds accidents, with some people struggling to see further than their immediate neighbours [Zhen et al., 2008; Sieben and Seyfried, 2023].

**Aging and Age-related Conditions and Diseases:** Another parameter that has been proven to have a strong effect on standing balance and balance recovery is age [McIlroy and Maki, 1996]. As we age, our ability to regain balance changes due to physical and sensorial limitations [Melzer et al., 2001; van Wegen et al., 2002]. On top of those changes, age-related diseases such as Parkinson’s disease [Winser et al., 2019], diabetes

[Vinik et al., 2017] or cardiovascular diseases [Mikos et al., 2021] can increase the risk of falls in the elderly population as its symptoms inhibit proper balance recovery strategies. With regard to dense crowds such as those observed during the Hajj ceremony in Mecca, the population aged over 50 has been observed to represent between 45% and 50% of the total participants [Mushi et al., 2021]. Some pilgrims were reported to be over 85 years old during this event [Azarpazhooh et al., 2013]. The Hajj ceremony is a well monitored event with crowds easily reaching densities that result in non-voluntary physical interactions [Alnabulsi and Drury, 2014]. As the world’s population is aging [United Nations and Affairs, 2019; Organization et al., 2021], we can expect to see a corresponding increase in the number of elderly people participating in dense crowds around the world.

Several other factors not investigated in this manuscript may be added to this list such as the type and slope of the terrain, the mental state or the fatigue. Such factors were pointed out to be involved in several dense crowd accident [Zhou et al., 2017; Sieben and Seyfried, 2023].

#### 1.2.1.5 Experimental Paradigms

Standing balance has been experimentally studied mainly using either moving ground perturbations or external force perturbations [Tokur et al., 2020]. Both experimental methods are referred as using *compliant* perturbations, i.e. perturbations during which the subject’s reaction modifies the induced motion of the perturbation. Other types of experimental paradigms to study recovery strategies use *non-compliant* perturbations which impose unstable body postures to trigger recovery strategies, such as initial release from a static forward leaning angle (“tether-release”) [Thelen et al., 1997; Carty et al., 2011] or imposed body displacement and velocity [Mille et al., 2003].

Standing balance following compliant perturbations has been studied for different perturbation directions. Regarding moving ground perturbations, a wide variety of perturbation directions seem to have been tested including perturbations from anteroposterior directions [Inkol et al., 2018], mediolateral directions [Batcir et al., 2020] and intermediary directions [Moore et al., 1988; Maki and McIlroy, 1997]. Force-controlled perturbations have been, to the best of our knowledge, only investigated for anteroposterior [Schulz et al., 2006; Robert et al., 2018; Emmens et al., 2020; Zelei et al., 2021] and mediolateral directions [Rietdyk et al., 1999].

Different characteristics can be given to describe experimental compliant perturbations. For linear moving ground perturbation, the displacement offset of the moving

ground and the speed or duration of the perturbation were considered in early works [Diener et al., 1988; Horak et al., 1989]. Then more importance was given to the acceleration and jerk (i.e. variation of acceleration over time), as these parameters were shown to have the strongest effect on standing balance [Maki and Ostrovski, 1993; Powell and Palacín, 2015]. For force-controlled perturbations the characteristics are the perturbation duration and intensity, the force profile over time, as well as the application location on the body and the delivering method used, i.e., whether the perturbation was delivered by a pushing or a pulling mechanism [Robert et al., 2018; Rietdyk et al., 1999]. In studies involving non-repeatable perturbation delivery methods, such as manual pushing perturbations, a combination of the duration and the intensity can be used to characterise the perturbations. This has been done using the perturbation impulse, i.e., the integral of the delivered force intensity over time [Rietdyk et al., 1999; Li et al., 2021; Feldmann and Adrian, 2023].

## 1.2.2 Contact and Physical Interactions in Dense Crowds

By definition physical interactions may be experienced by any individual in a dense crowd. These interactions generate body compression which can accumulate and lead to dramatic outcomes [Sieben and Seyfried, 2023]. Physical contacts in dense crowds may also act like external perturbations leading to a loss of standing balance and even falls [Zhou et al., 2017]. In this context, modeling physical interactions and their consequences (e.g. discomfort, compression, falls) became one of the major challenges in the research community since the beginning of the century.

In this section are reviewed the main contributions regarding physical interactions in the context of dense crowds. Along this review, we try to identify the remaining gaps in the knowledge concerning standing balance and falls in dense crowds.

### 1.2.2.1 Reports of Falling Accidents in Dense Crowds

According to dense crowd accident reports, the deadly consequences are emerging from thoracic compressions or as people on the ground were being stepped on by others [Lee and Hughes, 2005; Feliciani et al., 2023]. The second category of these fatal consequences is directly linked to the fall of individuals in dense crowd contexts. However, the original cause of falling may be extremely difficult to identify.

In 1993, during the New Year's accident of Lan Kwai Fong (Hong-Kong) people falling

resulted in “a five layer human pile-up” [Lee and Hughes, 2005]. The cause of this accident what investigated by a special commission but “No single witness has been able so far to provide a single clear account of precisely what happened.” [Balsari et al., 2017; Bokhary, 1993]. The commission however emphasizes that “The tragedy [...] occurred not simply because people fell but because they were so densely packed that a massive, crushing human pile-up resulted when they fell. That dreadful result was due to extreme overcrowding. The other factors (such as the gradient, the slippery surface, the drunkenness, the spraying, the jostling, the pushing, the convergence at the cross-road and people coming upward) or any one or more of them might have caused many people to fall”. This statement highlights the complex and multifactorial threat to standing balance one may be exposed in dense crowds.

[Zhou et al., 2017] reported about people falling following the break of a police cordon during the accident at Shanghai Bund on the 31.12.2014. Although the conditions of the falls were not clear, the external perturbations generated by a “crowd wave” were identified as the triggering element of the accident.

Sensorial impairment of individuals within the crowd was also reported during the Miyun bridge accident which happened in 2004 in Mihong (China). During this accident an overcrowded bridge was being evacuated in emergency. This evacuation resulted in people falling on top of each other. [Zhen et al., 2008] reported that “One of the survivors said that he was so eager to leave the bridge, that he did not hear any racket around him, when he run out of the entrance he felt collapsed”. Another eyewitness reported: “[...] suddenly, I found several people piled up in front of me, I wanted to keep away but I could not control my feet, it was too late ...”. These testimonies bring to light the sensory limitations and the physical constraints that can be experienced by individuals in this context.

Eventually, falls in dense crowds were for a long time only considered happening when individuals of the crowd were moving [Lee and Hughes, 2005; Zhen et al., 2008]. Recently [Sieben and Seyfried, 2023], has shown that during the Love Parade accident which happened in 2010 in Duisburg (Germany), falling was experienced by individuals of an almost static crowd. Some people also claim to have experienced challenging standing balance circumstances including having “someone standing on a foot or leg so that it cannot be moved anymore, losing a shoe because it got stuck, a leg being trapped, no room to put down a foot, and fear that a leg could have been broken. There were also reports of difficulties staying on one’s feet. Some people describe stumbling, others state that they did

not have contact with the ground anymore.”

In conclusion, based on the aforementioned testimonies, falls can be considered as a serious threat to people in dense crowds. Therefore, standing balance and recovery strategies should be considered to understand and model the complexity of such situations.

### 1.2.2.2 Contact and Physical Interactions Modelling in Crowd Simulations

To the best of our knowledge the first explicit consideration of physical interactions for crowd modelling was proposed by Helbing et al. [2000] using simple repulsion forces, reproducing a *Discrete Element Method* used for granular medium modeling [Cundall, 1971; Cundall and Strack, 1979]. This approach was then further developed. Rigid body contact models have been developed to avoid overlapping of the simulated bodies [Maury, 2008; Pécol et al., 2011; Faure and Maury, 2015]. Friction between individuals have also been proposed to the collision terms of the models [Lin et al., 2016].

All the aforementioned models are referred as “Microscopic” models, i.e., models for which each individual is represented by an agent with specific body characteristics and defined by individual state variables such as position, velocity and orientation. However, other kinds of models can be used to model dense crowds, and especially “Macroscopic” models [Yang et al., 2020]. This kind of models can be associated with the Eulerian approach to model flow fields. In this approach the state variable of a given field (e.g., velocity, density) is estimated for every discrete regions of the considered space. For these models, physical interactions can be modeled using stress tensor to represent interpersonal repulsion and friction forces [Golas et al., 2014].

All the presented models can be associated with quantitative estimations of interpersonal contact effort or estimated level of discomfort [Golas et al., 2014] or frustration [Maury and Reda, 2021]. Although, none of them could be used to assess the level of standing balance of the modelled individuals. Pelechano et al. [2007] proposed a simulation allowing numerical agents to fall following external pushes. However, no information regarding standing balance of the simulated characters nor any precise criterion leading to falls are provided. Later on, models were created to take into account balance recovery processes following external perturbations [Kim et al., 2015] and evaluate risks of falls [Li et al., 2023]. These models however are based on very simple rules applied on approximated bi-dimensional disc-like agents to represent individuals in the crowd. A lack of consideration regarding recovery strategies and in particular regarding stepping strategies is common to all these models. In particular, to the best of our knowledge, reactions



following physical interactions have only been modelled using isotropic laws whereas it has been shown that balance recovery strategies differ depending on the angle and location of the perturbations [Maki and McIlroy, 1997; Rietdyk et al., 1999; Batair et al., 2022].

Therefore, balance recovery strategies and the risks of falling in dense crowds remain unclear. One can highlight the recent suggestion of a “human domino” model ([Wang et al., 2019]) as a first approach to introduce standing balance for crowd modelling. However, this model remains limited, with highly simplified stepping strategies, and no consideration for other formations than one-dimensional lines of individuals.

### 1.2.2.3 Experimental Knowledge of Physical Interactions in Dense Crowds

The lack of representation of balance recovery strategies in dense crowd models is associated with a lack of experimental data on this matter. To our knowledge, most experimental studies of such crowds focused on the static load [Wang and Weng, 2018; Wang et al., 2020] and external forces [Li et al., 2020b] experienced by individuals in dense formations. These studies were carried out as asphyxia and fainting due to chest compression appeared to be one of the main causes of death in dense crowds [DeAngelo et al., 1998; Sieben and Seyfried, 2023; Feliciani et al., 2023].

Kinetic information extracted from video recording of dense crowds can also be extracted using computer vision based methods. These data can be head trajectories [von Krüchten and Schadschneider, 2017; Sundararaman et al., 2021], or local average velocity fields [Silverberg et al., 2013; Bottinelli and Silverberg, 2018]. Estimation of the level of velocity changes due to physical interaction can then be extracted. These methods are however limited and does not provide information about the whole body motion of individuals within the considered crowds.

Recently, the development of commercially available IMU-based motion capture solutions has made it possible to capture the full body motion of individuals in group formation [Feldmann and Adrian, 2023]. Such a technology was used in the present work to investigate standing balance and stepping recovery strategies for both dense formation and real crowd situations.

## 1.3 Chapter Conclusion and Present Contributions

In the light of the aforementioned related work, we have seen that human standing balance results of a constant postural control performed by the *Central Nervous System*

(CNS) through the muscles, based on different sensory feedback. This balance control has however limits and thus standing balance may be lost following perturbations. Several methods have been proposed to estimate the *Limit of Standing Balance* (LoSB) based on different assumptions. Beyond this limit, a large range of possible recovery strategies have been observed. In addition, standing balance and recovery following perturbations are affected by several parameters such as the direction of the perturbation, the *Level of Awareness* (LoA) to the upcoming perturbation and the personal capabilities of the considered person.

Regarding physical interactions and standing balance in dense crowds, multiple cases of falls have been reported following crowd accidents in the past decades. However, existing dense crowd models currently only focus on contact efforts linked to physical interaction rather than individual's stability. This limited consideration is also linked to the scarcity of available data regarding standing balance in such context.

In line with these conclusions, we propose here to investigate the standing balance and the recovery strategies of individuals in different situations in order to fill the existing knowledge gap in the context of dense crowds. First the Limit of Standing Balance and the recovery strategies of single individuals following external perturbations for different directions are studied in Chapter 2. Then, experimental information about recovery behaviors following external perturbations for individuals within densely populated groups are reported in Chapter 3. The finding of the two first studies are compared and discussed with standing balance recovery strategies observed during real crowded events involving physical interactions between individuals in Chapter 4. Finally, discussions and general conclusions regarding the results obtained in the frame of this thesis will be presented. Particular attention will be given to the research perspectives in the light of the current limitations of the proposed work.

## Contributions

All the contributions presented in this thesis and the associated chapters are detailed in this section.

### Separation Method for Recovery Strategies of Single Individuals Following External Perturbations, Chapter 2

In this study we proposed separation models the separate recovery strategies of single individuals following external perturbations.

In particular, we used logistic regressions on kinematic variables associated with individuals' intrinsic level of balance (namely, the *Margin of Stability* and the *Time to boundary*) to separate reactions to external perturbations requiring the use of recovery steps from the other recovery strategies. Decision boundaries were then deduced from these regressions, providing quantitative limits based in kinematic variables beyond which participants were more likely to initiate stepping recovery strategies following external perturbations. The novelty of the present results lies in the consideration of several experimental parameters in the creation of these models, including the *Level of Awareness* to the upcoming perturbation and a large variety of perturbation angles. These models were published in [Chatagnon et al., 2023].

We also proposed a method to the separate recovery strategies following lateral perturbations for which the first recovery steps were *Loaded* or *Unloaded*. This method is based only on kinematic information prior to the step initiation and showed excellent separation capabilities. The novelty of the method is related with the study of *Distance to Foot boundary* defined as the distance between the *Center of Mass* at step initiation and the boundary of the non-stepping foot. This method was presented in [Chatagnon et al., 2023].

Eventually, we proposed a model to separate all stepping recovery strategies based on the perturbation angle and the *Distance to Foot boundary*. This model is composed of regions in which specific recovery strategies were more likely used by participants during experiment involving recovery of single individuals to external force-controlled perturbations. The model is based on estimations of the perturbation angles using kinematic information prior to the step initiation. Therefore, this model can be used to predict recovery strategies of single individuals based only on kinematic variables prior to step initiation. The novelty of this model consists in its predictive ability and its possible

integration for general human balance recovery simulations.

### ***Unified Classification Method for Recovery Strategies Following External Perturbation From Any Possible Direction, Chapter 2***

A new classification method has been proposed in order to label the different types of recovery strategies regardless of the perturbation angle. The proposed *Unified* classification method relies on a protocol for which each possible recovery strategy is associated with a specific trajectory of the projection of the *Center of Mass* in the original *Base of Support* of the considered individual. This method has been proposed due to an existing gap in the knowledge regarding this matter. Previous studies, to the best of our knowledge, were using classification with prior knowledge of the perturbation angles. In these studies, the difference between *Forward Steps* and *Side Steps* was based only on the already known direction of the perturbation. No prior knowledge of the perturbation direction is required to label recovery strategies using the proposed method.

### **Study of the Recovery Strategies of Young Adults in Dense Group Formations Following External Perturbations, Chapter 3**

A novel experimental paradigm was considered in this study. This paradigm is a variation of the classical “Push-Recovery” paradigm but involving multiple participants in dense group formation. Several original results were revealed through the analysis of this new type of experiment. We showed that the limit of standing balance beyond which participants initiated recovery steps seemed to be different depending on the experimental interpersonal distancing conditions. Recovery steps were observed to be initiated for a more restrictive level of balance when participants were not initially in physical contact with their neighbours. Finally, we found that hand raising was more frequently initiated prior to step initiation when both behaviours were observed.

### **Proof of Concept: Study of the Recovery Strategies Following Physical Interactions in a Context of Punk Rock Concert Crowd, Chapter 4**

Another novel experimental paradigm has been proposed for field experiments on balance recovery in crowded environments. Here we proposed to use full-body motion capture to study balance recovery following physical interactions in the context of punk rock concert crowds. The analysis of the experimental data obtained in the frame of this study

bring to light new information relative to standing balance in such a context. In particular, perturbations for all possible directions were observed. Results also suggest that stepping recovery strategies were triggered for lower levels of standing balance perturbation in this context.

### **Characterisation of First Recovery Step Following External Perturbations for Individuals in Different Crowded Environments, Chapter 2, Chapter 3 and Chapter 4**

First, the characteristics of the first recovery steps of single individuals following external perturbation were studied for each of stepping recovery strategy observed during the considered experiment. The step length and average speed were compared with the momentum of the *Center of Mass*, defined as the speed of the *Center of Mass* multiplied by the mass of the considered participant. New insights regarding recovery steps were exposed, particularly regarding the different characteristics of the recovery steps depending on the recovery strategy used.

We then compared the findings obtained with the single individuals experiments with two other experiments involving recovery strategies in crowded environments. In particular, we showed that, smaller and slower steps were used for equivalent perturbation intensities by participants within densely populated environment involving interpersonal contacts, compared to the response of single individuals. We also observed that individuals in punk rock concert crowds used smaller and faster recovery steps in this situation than single individuals or individuals in dense formations. All of these results are, to the best of our knowledge, original and provide a further understanding of standing balance in human crowds.

### **Creation of Experimental Datasets Including Novel Experimental Paradigms, Chapters 2 and 4**

Two datasets based on original experimental paradigms have been created in the frame of this thesis.

The first dataset is composed of the full-body motion capture recordings of single individuals' balance recovery strategies following external force-controlled perturbations. The novelty of this dataset lies in the proposed experimental parameters and, in particular, in the different directions of the perturbations investigated.

The second dataset is composed of full-body motion capture recordings of individual's balance recovery strategies following physical interactions while being part of the crowd during punk rock concerts. On the one hand, the recording of full-body motion capture during crowded events is a new approach to study balance recovery in real complex environments. On the other hand, this paradigm uses a hybrid approach involving recruited participants with a defined protocol immersed in a real uncontrolled environment. To the best of our knowledge, such an approach has never been used to study balance recovery or physical interactions in human crowds.



# LIMIT OF STANDING BALANCE AND RECOVERY STRATEGIES OF SINGLE INDIVIDUALS

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In this chapter are reported the results of experiments conducted on single individuals in a fully controlled laboratory environment.

Particularly, we investigate here the *Limit of Standing Balance* (LoSB), the stepping strategies and the step characteristics of individuals following sudden external perturbation arising from different directions with and without sensory impairment.

After providing an in-depth overview of the collected data and the general methods used in this work, the study is then divided into two sections in which different hypotheses are made.

Here are the main scientific questions at stake in this chapter and the associated section in which those questions are considered:

- What is the limit after which people use stepping recovery strategies following an external force controlled perturbation?  
(Sections 2.2 and 2.3)
- Do the angle of perturbation and the Level of Awareness have an impact on the individual LoSB? (Section 2.2)
- Can we anticipate the nature of a stepping strategy based on kinematics information prior to the step? (Sections 2.2 and 2.3)
- What are the characteristics of the first recovery step? (Section 2.3)

Elements of discussion and conclusions regarding the results presented here are proposed at the end of this chapter.



## 2.1 Materials and Methods

### 2.1.1 Experimental Data Collection

The experiment presented in this chapter received approval from our national French ethics committee (*Comité de Protection des Personnes EudraCT: 2021-A01378-33*). All participants signed an informed consent form relative to the processing of their data.

Twenty-one young adults with no physical disabilities participated in this study (10 females, 11 males). Their average age, mass and height were  $27.2 \pm 4.2$  yo,  $70.2 \pm 12.1$  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:  $9.45 \pm 3.28$ ). Mass, height, gender and laterality repartition can be seen in Fig. 2.1 and all demographic details are provided in Fig. 2.2.

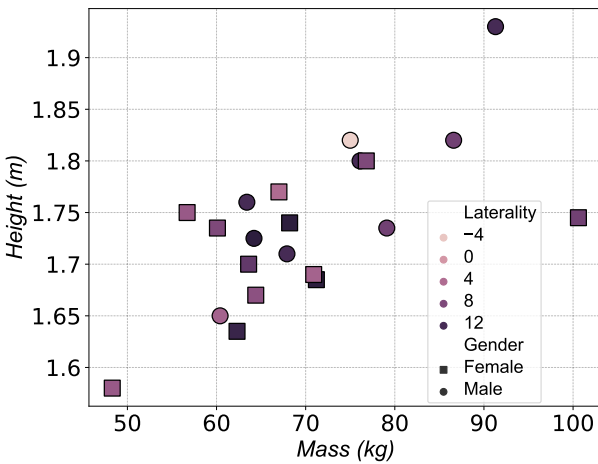


Figure 2.1 – Graphical representation of participants mass, height, gender and laterality distribution.

Gender	Age	Mass	Height	Laterality
Female	25	67	1.77	4
Male	27	75	1.82	-5
Female	24	63.6	1.7	10
Female	38	100.6	1.745	9
Male	26	60.4	1.65	5
Female	20	48.3	1.58	6
Female	36	71.2	1.685	14
Male	25	91.3	1.93	12
Female	25	64.4	1.67	7
Male	26	64.2	1.725	14
Female	25	56.7	1.75	6
Male	24	63.4	1.76	12
Female	25	62.3	1.635	13
Female	30	70.9	1.69	5
Female	24	68.2	1.74	14
Male	31	76.1	1.8	12
Female	24	76.8	1.8	8
Male	28	86.6	1.82	9
Male	28	79.1	1.735	9
Female	28	60.1	1.735	8
Male	32	67.9	1.71	12

Figure 2.2 – Demographic details and laterality characteristics of the participants.

To assess the effect of the *Level of Awareness* (LoA) to upcoming perturbations on

stepping strategies, the experiment was divided into two blocks: one using *Sensory Impairment* (SI) and one with *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 (see Fig. 2.3). We used a latin square design to randomise the conditions across participants to avoid any ordering effect.

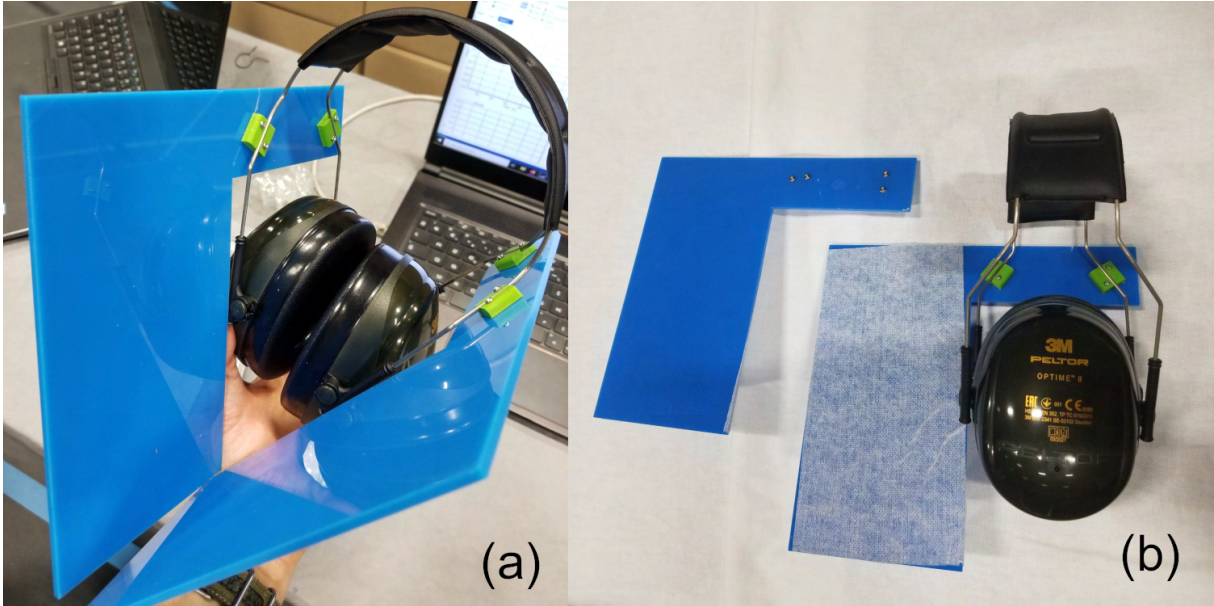


Figure 2.3 – (a) Front view of the sensory impairment device. (b) Side view of the sensory impairment device.

The perturbation was applied using a pole equipped with a 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 different angles, with intensities divided into three ranges (‘Low’, ‘Medium’, ‘High’). We investigated the effect of direction of perturbation using five different angles, detailed in Fig. 2.4. A trial corresponded to a single reaction to a single external perturbation. 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. The distribution of perturbation impulse (integral over time of the perturbation force) can be seen in Fig. 2.5. 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).

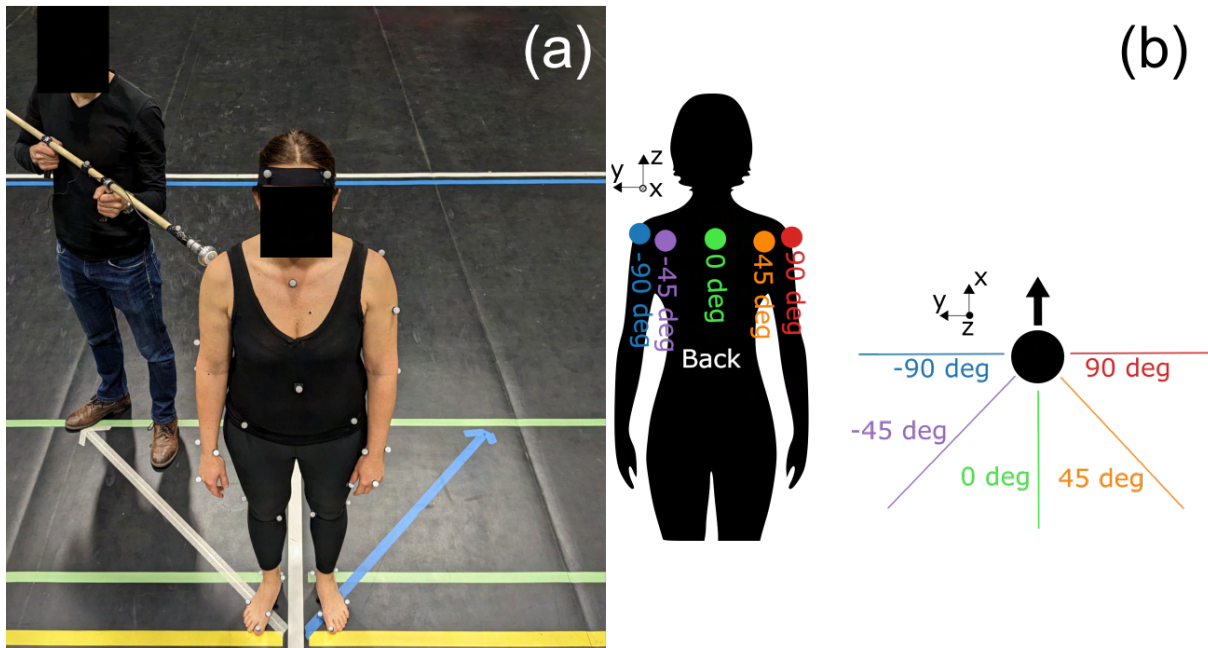


Figure 2.4 – (a) Illustrative picture taken as the participant was about to receive a perturbation with an angle of  $45\text{ deg}$ . (b) Angles of application location of the perturbations.

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 recovering from the perturbation.

Participants were intentionally not provided explicit instruction to actively sustain their balance to the utmost extent. This decision was made in order to encourage a behaviour that participants would naturally adopt and feel at ease with in a real-world situation. However, some participants exhibited unexpected recovery strategies such as large leg abduction to regain balance following 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] (see Fig. 2.6).

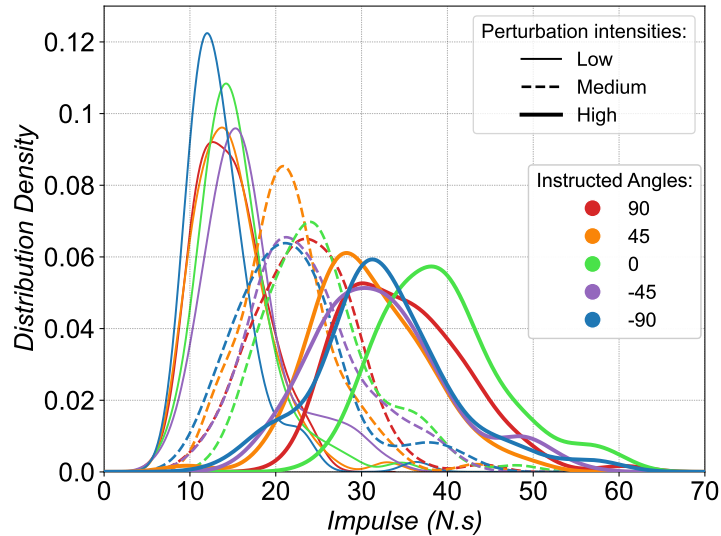


Figure 2.5 – Distribution of perturbation impulse depending on their intensity level and angle. The perturbation impulse is computed following [Feldmann and Adrian, 2023] as the integral of the perturbation force over time.

## 2.1.2 Data Processing

### 2.1.2.1 Computation of Biomechanical Quantities

Most of the results presented in this manuscript rely on biomechanical quantities such as the *Center of Mass* (CoM) or the *Base of Support* (BoS). While some quantities (e.g. marker positions, and velocities) can be directly derived from motion capture recordings (see Fig. 2.7), the computation of the CoM requires the use of a biomechanical model. This model is used to estimate the position of each limb in time. The estimation is completed by taking the filtered position of the recorded markers as input and fitting a whole human body model using an optimisation method (here the Levenberg–Marquardt algorithm [Livet et al., 2023]). This process is called Inverse Kinematic. By knowing the position of each limb in time, we can then assign a mass distribution to all body parts using anthropometric tables [Dumas et al., 2007]. The position of the CoM is then obtained by averaging the mass position of each body part. The inverse kinematics process and the computation of the position of the CoM in time for each participant were achieved using the Matlab CusToM library [Muller et al., 2019]. The human body model used here was composed of 18 segments and 42 degrees of freedom.

Two quantities were used to assess standing balance and the stepping likelihood fol-

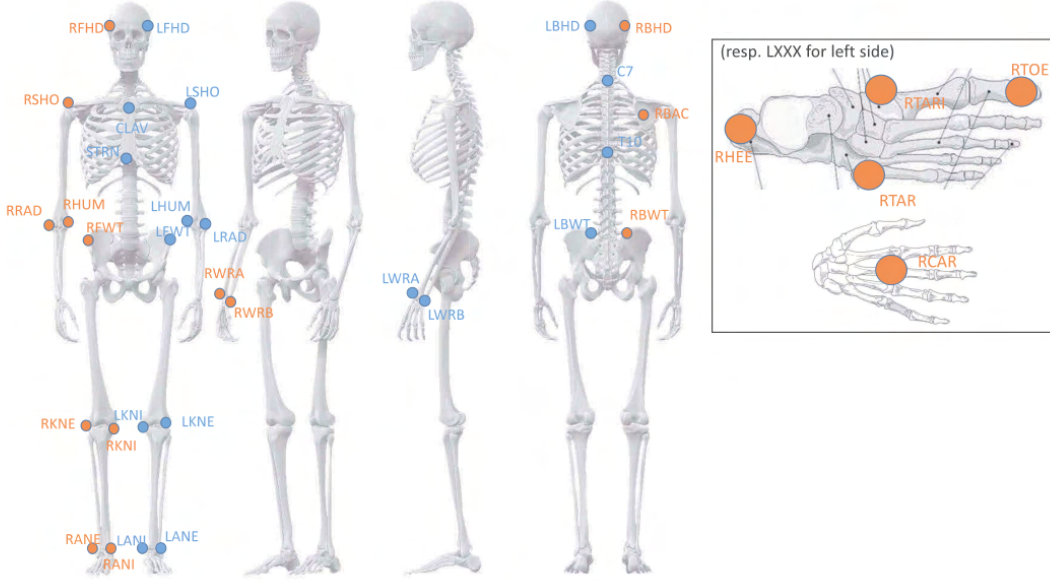


Figure 2.6 – Anatomical position of the reflective markers used for motion capture during the experiments. Figure from the Matlab CusToM library documentation [Muller et al., 2019].

lowing 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 and velocity of the CoM and the BoS position in time.

The MoS is based on the concept of *Extrapolated Center of Mass* (XCoM) proposed by Hof et al. [2005].

The XCoM is defined as:

$$\mathbf{XCoM} = \mathbf{x}_{CoM} + \frac{\dot{\mathbf{x}}_{CoM}}{\omega_0}, \quad (2.1)$$

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:

$$MoS = (\mathbf{u}_{max} - \mathbf{XCoM}) \cdot \frac{\dot{\mathbf{x}}_{CoM}}{\|\dot{\mathbf{x}}_{CoM}\|}, \quad (2.2)$$

where  $\mathbf{u}_{max}$  is the crossing point of the half-line from the XCoM in the direction of the CoM velocity and the BoS. This definition is valid if the ground projection of the XCoM is within the BoS polygon. If XCoM is past the boundary of the BoS,  $\mathbf{u}_{max}$  is defined as the



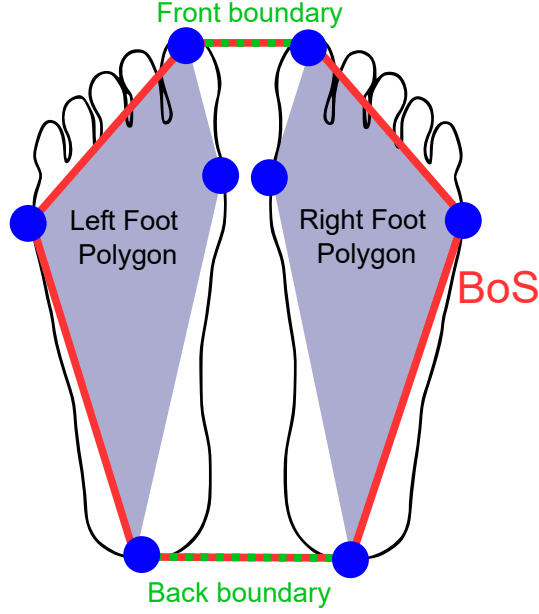


Figure 2.7 – Representation of the BoS, defined as the enclosed polygon linking all external foot markers, here in red. Blue dots represent the motion capture marker positions.

crossing point of the half-line from the XCoM in the opposite direction of the CoM velocity and the BoS. This definition leads to negative values for MoS. Such a situation is depicted in Fig. 2.8.a where the CoM and XCoM are represented at  $t_{begin}$  for two representative trials. By definition the MoS Eq. (2.2) may be used to determine the LoSB, as a null or negative value of the MoS indicates a critical unstable state for the inverted pendulum model representing the Human body.

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:

$$Ttb = \frac{Dtb}{\|\dot{\mathbf{x}}_{CoM}\|}, \quad (2.3)$$

$$Dtb = (\mathbf{u}_{max} - \mathbf{x}_{CoM}) \cdot \frac{\dot{\mathbf{x}}_{CoM}}{\|\dot{\mathbf{x}}_{CoM}\|} \quad (2.4)$$

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.

In addition to the MoS and Ttb we studied the *Distance to Foot boundary* (DtFb). This quantity corresponds to the shortest distance from the ground projection of the CoM to the boundary of the polygon created by *Non-Stepping Foot* markers at step initiation. If the ground projection of the CoM is within the Non-Stepping Foot polygon

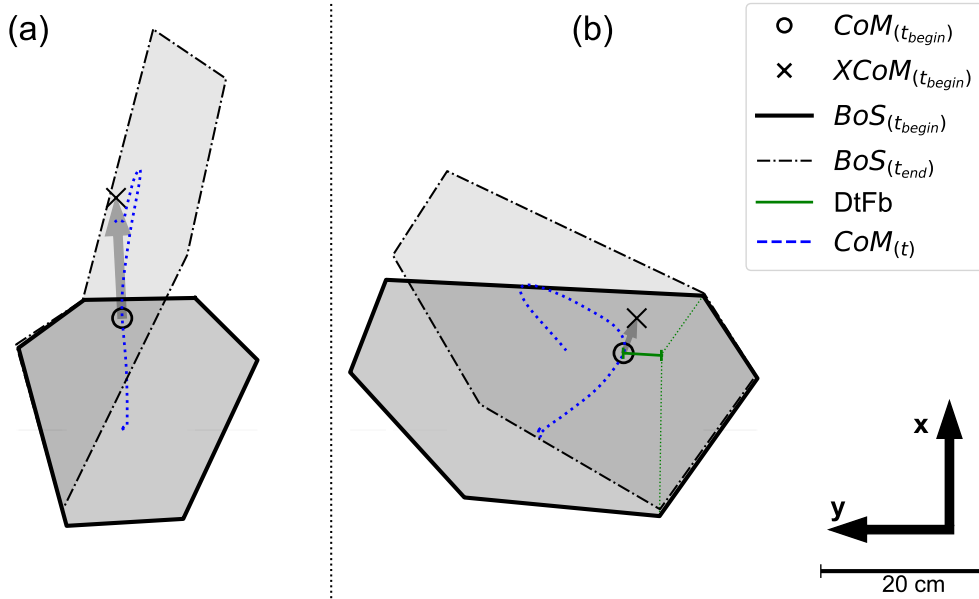


Figure 2.8 – Spatial representation of the reaction of two participants for perturbations at  $0\ deg$  (a) and  $-45\ deg$  (b). By definition, the arrow between the CoM and the XCoM represents  $\frac{\dot{\mathbf{x}}_{CoM}}{\omega_0}$ .

at step initiation, the DtFb is considered as negative. By definition the DtFb can only be computed when a step was taken. We 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.

This definition slightly differs from the one proposed in [Chatagnon et al., 2023] especially regarding the value of the DtFb when the center of mass is out of the BoS at step initiation. With this definition the DtFb is negative only if the CoM is within the non-stepping foot polygon at step initiation. This definition was modified to be relevant in all situations observed during experiments described in Chapter 3 and Chapter 4.

### 2.1.2.2 Step Detection and Classification

Our analysis of stepping behaviours is based on the moment when a foot initiates the movement to step ( $t_{begin}$ ). This moment occurs 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. While *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 fall into local minimums).

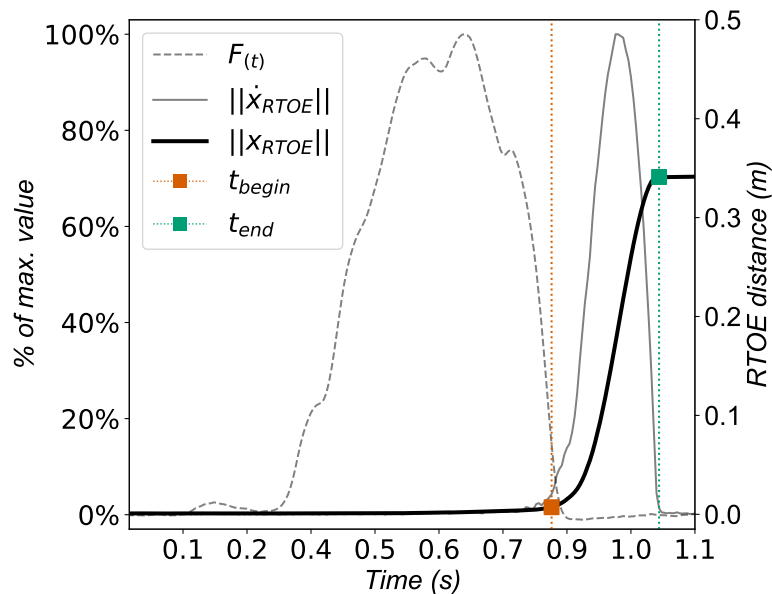


Figure 2.9 – Transversal speed ( $||\dot{x}_{RTOE}||$ ) and distance from initial position ( $||x_{RTOE}||$ ) of the marker placed on a participant’s right toe (RTOE) following a perturbation.  $t_{begin}$  is the moment at which the step is initiated,  $t_{end}$  is the moment at which the considered foot stops moving. The shape of the recorded perturbation force ( $F(t)$ ) is represented with a dashed line.

This method returned two inflexion points of the foot transversal speed for each step (see Fig. 2.9). 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,  $t_{end}$ .

Once a step is detected the stepping strategy may be classified depending on several step characteristics. Stepping strategies following perturbations in the anteroposterior



direction are often considered as *Forward Steps* (FS) in the literature [McIlroy and Maki, 1996] for perturbations coming from the posterior direction, or *Backward Steps* (BS) for perturbations coming from the anterior direction.

Lateral recovery strategies can be divided into three categories according to the classification of [Mille et al., 2005], *Loaded Side Steps* (LSS), *Unloaded Medial Steps* (UMS), and *Unloaded Crossover Step* (UCS). To determine whether the step was a *Crossover 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 *Crossover Step* if one of the following inequality was true:

$$\mathbf{L}_{toe}\mathbf{R}_{toe}|_{t_{begin}} \cdot \mathbf{L}_{toe}\mathbf{R}_{toe}|_{t_{end}} < 0, \quad (2.5)$$

$$\mathbf{L}_{heel}\mathbf{R}_{heel}|_{t_{begin}} \cdot \mathbf{L}_{heel}\mathbf{R}_{heel}|_{t_{end}} < 0 \quad (2.6)$$

*Side step* can either be a *Loaded Side Step* (LSS) or an *Unloaded Side Step* (USS) depending on whether the mass of the participant was respectively moving toward or away from the stepping foot. For instance, if no crossover of the feet was detected and the step was made with the foot which has been unloaded by the perturbation, then this stepping strategy is an *Unloaded Medial Step* (UMS).

On top of these stepping strategies, another recovery strategy often referred as *Leg Abduction* (LA) [Bacir et al., 2022], has been observed during the experiment. During LA, participants used one leg as a counterweight to reduce the effect of the perturbation. If this recovery strategy was successful, the participant’s foot returned to the original position as if no step was taken.

Because of the momentaneous one leg support and the involved leg motion, the LA strategy lays in between a stepping and a non-stepping strategy. For this reason, these strategies were often not considered [Bacir et al., 2020; Bacir et al., 2022; Chatagnon et al., 2023]. Here we include LA as a specific recovery strategy. LA were detected if the maximal distance traveled by the foot during a trial exceeded the final position of the foot during this trial by  $3cm$ . LA were considered successful only if the final position of the foot was within the  $5cm$  perimeter around the foot original position. A non-successful abduction was considered as a US. Threshold parameters were selected following a sensitivity analysis of these parameters on the number of LA and stepping strategies detected.

In total, steps were taken in 642 trials. Successful LA strategies were observed in 47 trials. Recovery required no steps in 568 trials. Out of 1260 trials recorded, 3 were

discarded due to technical issues.

## 2.2 Limit of Standing Balance Relative to the Instructed Angles of Perturbation

In this section we studied the recovery strategies used by participants undergoing perturbations from five different directions under two *Levels of Awareness* (LoA), and present the major findings that have been published in Chatagnon et al. [2023]. More specifically, we tried to find the limit after which participants initiated stepping strategies based on kinematic information. For lateral perturbations, we also tried to find a criteria based on the DtFb to predict if the initiated step would be a *Loaded Side Step* (LSS) or an *Unloaded Side Step* (USS). The following assumptions are used in this section:

- The angle of the delivered perturbation is assumed to be equal to the instructed angle given to the experimenter before applying the perturbation.
- Stepping recovery strategies following intermediary perturbation angles ( $-45\text{ deg}$  and  $45\text{ deg}$ ) were only considered to be lateral stepping strategies (LSS, UMS, UCS), i.e. not as FS.

Following these assumptions, stepping strategies are here considered to either follow anteroposterior perturbations and lead to *Forward Steps* (FS) or to followed lateral perturbations (out of the sagittal plane) and lead to *Side Steps* (LSS, UMS, UCS). Due to its definition this stepping strategy classification is then referred as *Bi-modal*.

### 2.2.1 Analysis Methods

In addition to the method presented previously in this chapter, the following statistical analysis methods are used in this section.

We worked here with logistic regressions to study the limit after which participants were more likely to initiate a stepping recovery strategy following the perturbations. These regressions were created using the minimal values of MoS and Ttb before step initiation for each trial. If a participant did not initiate a step to recover from the perturbation, the overall minimal values of MoS and Ttb during the trial were considered. The logistic regressions were then used to create separation models between two recovery strategies. If a logistic regression value is above 0.5 the model indicates that a stepping strategy is

more likely to be used, under 0.5 a strategy not involving step is more likely to be used. The threshold value for which the regression is equal to 0.5 is referred as the *Decision Boundary* (DB).

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 *No 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.

To assess the effect of the experimental conditions (i.e. the angle of the perturbation and LoA), we also built *Logistic Mixed Models* (LMMs) upon our dataset. These models are general logistic models assessing the probability for participants 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 the specific reactions 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 Steps*, i.e. LSS, and *Unloaded Steps*, i.e. 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.

Trials with successful LA strategies were not considered in any logistic model due to their specific nature (between stepping and non-stepping strategies).

## 2.2.2 Results

### 2.2.2.1 Limit of Standing Balance for Every Stepping Recovery Strategies

In this section, we present the results of the Logistic models depicted in Section 2.2.1 to study the LoSB (see Fig. 2.10)

The logistic models using Ttb or MoS seem to perform similarly in terms of accuracy to separate NS trials and trials with steps. Both models keep an overall accuracy above 80% (see Table 2.1) with a maximum of accuracy for perturbations in the anteroposterior

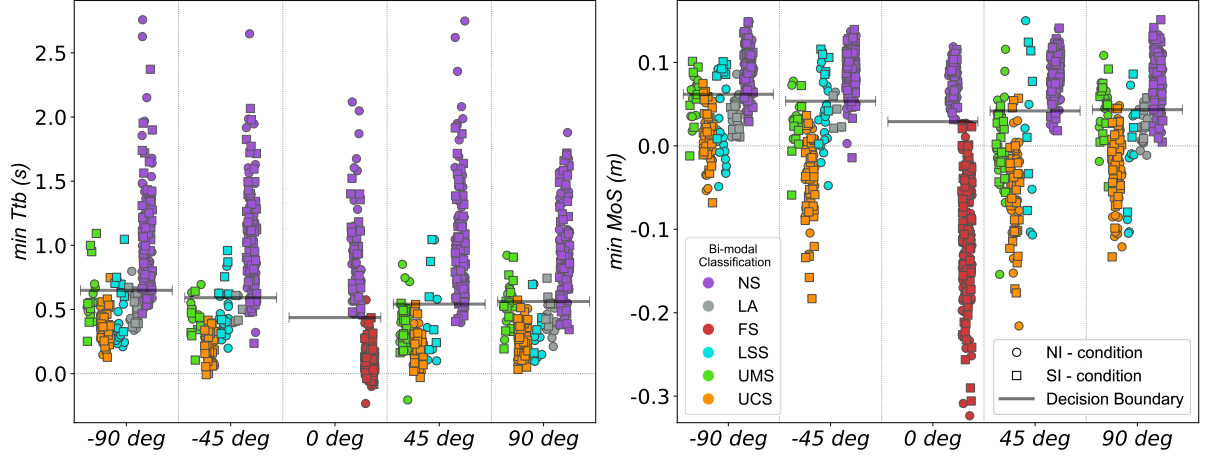


Figure 2.10 – Separation between *No Step* (NS) trials and trials with steps (FS, LSS, UMS, UCS) for each instructed angle of perturbation. Trials with *No Impairment* (NI) are marked with round dots, trials with *Sensory Impairment* (SI) are marked with square dots. Each dot represents the minimal value of Ttb or MoS during one single trial. Minimal value was computed before step initiation for trials involving a step. Decision boundaries of the logistic regression are represented by vertical bars. *Leg Abduction* (LA) strategies are represented in grey in the graphic but are not taken into account in the logistic models.

direction.

Angle	NS/Step - Min. MoS				NS/Step - Min. Ttb			
	DB (cm)	Accuracy (%)	Sensitivity (%)	Specificity (%)	DB (s)	Accuracy (%)	Sensitivity (%)	Specificity (%)
−90 deg	6.2	83	79	85	0.65	88	88	88
−45 deg	5.4	89	87	90	0.59	88	89	87
0 deg	2.9	100	100	100	0.44	99	99	100
45 deg	4.2	90	89	93	0.54	93	93	93
90 deg	4.3	84	83	85	0.56	87	89	84

Table 2.1 – Characteristics of the logistic models to separate NS trials and trials with steps using minimal values of MoS or Ttb for each perturbation angle (−90 deg to 90 deg). An angle of 0 deg corresponds to perturbation in the sagittal plane.

As one can see in Fig. 2.10 no prior effect of the LoA can be seen on data distribution. This observation was validated by our statistical analysis as none of the LLMs is significantly affected by LoA changes (see Table 2.2). 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 regressions.

	$R^2_{conditional}$	$R^2_{marginal}$	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
LSS/USS - DtFb	0.999	0.419	0.991	0.713	<.001

Table 2.2 – Characteristics of the *Logistic Mixed Models* (LMMs) between NS trials and trials with steps, and between *Loaded Side Steps* (LSS) and *Unloaded Side Steps* (USS). The covariate is the quantity on which the regression is based, respectively here: minimal values of MoS, minimal values of Ttb, and DtFb.

We observed in Fig. 2.10 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 USS 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  $90\ deg$  and  $-90\ deg$ , or between  $45\ deg$  and  $-45\ deg$ .

### 2.2.2.2 Separation of Stepping Strategies Following Lateral Perturbations

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 the DtFb (Fig. 2.11). For all lateral perturbation angles, the logistic regressions based on the DtFb were created. These regressions have a clear separation between LSS and USS trials, with a perfect accuracy for each angle (see Table 2.3).

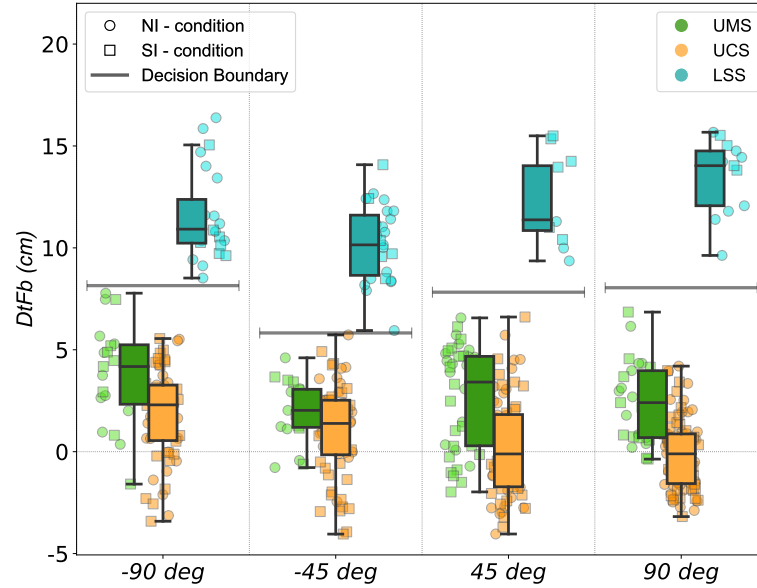


Figure 2.11 – Separation between trials with *Loaded Steps* (LSS) and *Unloaded Steps* (UMS and UCS) using the DtFb for lateral perturbations. A negative DtFb indicates a CoM within the polygon of the foot markers at  $t_{begin}$ .

Angle	LS/US - DtFb			
	DB (cm)	Accuracy (%)	Sensitivity (%)	Specificity (%)
-90 deg	8.1	100	100	100
-45 deg	5.8	100	100	100
0 deg	-	-	-	-
45 deg	7.8	100	100	100
90 deg	8.0	100	100	100

Table 2.3 – Characteristics of the logistic models to separate trials involving *Loaded Side Steps* (LSS) or *Unloaded Side Steps* (USS) based on the DtFb for lateral perturbation angles.

### 2.2.3 Discussions

Results shown in Fig. 2.10 and Table 2.1 demonstrate that minimal values of MoS and Ttb are good estimations to draw the limits after which participants initiate steps to regain balance. Thanks to the LMMs (Table 2.2), one can observe that these limits do not significantly change with the angle of perturbation nor with LoA to the upcoming

perturbation.

The lack of effect of the LoA to upcoming perturbation on recovery strategies 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 investigations are required to draw any conclusion on that matter.

The angles of perturbation have however an impact on the accuracy of the logistic model to determine the LoSB, as overlaps of minimal values of MoS and Ttb increase with the laterality of the perturbations. One can also notice an asymmetry of stepping strategies used depending on the perturbation angle, with more LSS than UMS for  $-45deg$  and  $-90 deg$ , and more UMS than LSS for  $45 deg$  and  $90 deg$ . 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.

Very different step characteristics were observed whether the perturbation was coming from the anteroposterior direction or from the other lateral directions. Lateral perturbations also result in a larger range of recovery strategies (LA, LSS, UMS, UCS). The LA strategies was used at the boundary between stepping and non-stepping recovery strategies. A non-symmetrical repartition of data reveals that this strategy may be preferred for some perturbation directions depending on the laterality of participant. However, are required to draw any conclusion as a limited number of occurrences were recorded along the experiment.

For lateral perturbations, a stepping strategy classification method was proposed using logistic regressions of the DtFb. We 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. The proposed method has an excellent accuracy to separate LS and US. As one can see in Fig. 2.11, there is a difference between LSS and USS strategies with overall smaller and negative values of DtFb when a UMS or a UCS was used.

Regarding logistic regressions, 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 LSS and USS

as different stepping strategies were preferred depending on the perturbation direction.

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 average distance before the LoSB in our experiment would have been  $5\text{cm} \pm 1\text{cm}$ . Here we found a smaller limit around  $3\text{cm}$ . Similarly, [Schulz et al., 2006] observed a critical Ttb of  $0.52\text{s}$  with a prediction accuracy of 94% for a population of young and older adults unimpaired or with balance-impairment. This value is comparable to the one observed under the same conditions in our study ( $0.44\text{s}$  and 99% accuracy). The main differences in the results may be explained by the mediolateral 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).

## 2.2.4 Preliminary Conclusion

In the section we proposed a first approach to estimate the Limit of Standing Balance (LoSB) of young adults following external perturbation from different directions. We proposed to use the *Distance to Foot boundary* (DtFb) to characterise the stepping strategies used following lateral perturbations. All the results presented in this section rely on two assumptions, as presented in the introduction of this section:

- The angle of the delivered perturbation is assumed to be equal to the instructed angle given to the experimenter before applying the perturbation during the experiment.
- Stepping recovery strategies following intermediary perturbation angles ( $-45\text{ deg}$  and  $45\text{ deg}$ ) were only considered to be lateral stepping strategies, i.e. LSS, UMS or UCS.

However, the validity of these assumptions might be questioned. On the one hand, due to the nature of the perturbation application (experimenter manually applying the perturbation with a leveled pole) the *actual perturbation angle* may slightly differ from the *instructed angles* given to the experimenter. On the other hand perturbations with *instructed angles* of  $-45\text{ deg}$  and  $45\text{ deg}$  appeared to trigger stepping strategies similar to what was observed for anteroposterior and mediolateral perturbations. For these instructed angles of perturbation, we observed steps taken to the front. However, given the *Bi-Modal* classification for stepping strategies used in this section, steps were considered



to be either *Loaded Side Steps* (LSSs) or *Unloaded Medial Steps* (UMSs). The main frontal component of the steps was thus completely ignored.

These two elements are further studied in the following section: Additional methods are proposed to classify recovery strategies regardless of the perturbation angle, and characteristics of first recovery steps of each stepping strategy are analysed.

## 2.3 Unified Stepping Strategy Classification and First Recovery Step Characteristics

Two main lines of research emerge from the conclusions proposed in Section 2.2. One of these lines is relative to the perturbation angles. As discussed in the previous section the actual perturbation angles were likely to differ from the *instructed angles* of perturbation, i.e. the angles of perturbation instructed to the experimenter who applied the perturbation. As such, the perturbation directions may actually not be distributed over five angles but through a whole spectrum of angles with a centered repartition around these five *instructed angles* of perturbation. Following this idea one could wonder how to characterise these perturbation angles.

The second line of research regards the stepping recovery strategies. One can consider the *Bi-Modal* classification as an acceptable approach given the assumption proposed in the previous sections. However, when considering a full spectrum of potential perturbation directions, perturbations from the anteroposterior and the mediolateral directions only represent a limited fraction of these possibilities. Hence, in order to study stepping recovery strategies following perturbations from any direction one should seek to classify stepping strategies not based on the angle of perturbation but rather on the actual characteristics of the steps used to recover balance.

In this section, a *Unified* stepping strategy classification is introduced, which does not depend on the perturbation angle. The following research axes are then investigated. First, a characterisation of the perturbation angle is proposed as well as a way to estimate this angle only based on kinematic information. Based on the *Unified* stepping strategy classification we then propose a clustering of the different stepping strategies using kinematic information. Eventually, we present the characteristics of the first recovery steps for each stepping strategy in relation with the momentum of the participant.

## 2.3.1 Additional Methods

### 2.3.1.1 Unified Recovery Strategy Classification

We propose here a classification method in order to label recovery strategies following external perturbations from any direction. This classification method relies on the trajectory of the center of mass and the position of the feet before step initiation. The main assumption of this method is that the projection of the CoM on the ground before the perturbation is within the BoS and strictly in between the feet, i.e. the projection of the CoM is out of both feet polygons. The main variables for this method are the trajectory of the CoM during the trial, the feet polygons (see Fig. 2.7) and the frontal and rear boundaries of the BoS (defined by the position of the toes and the heels respectively, see Fig. 2.7)

The proposed *Unified* recovery stepping strategy classification is obtained through the algorithm detailed in the following flowchart (Fig. 2.12).

This classification method relies on the detection of feet crossing exposed in Section 2.1.2.2. If no feet crossing is detected, the trajectory of the projection of the center of mass on the ground together with the initial BoS (BoS before step initiation) are then used for the stepping strategy labeling. *Forward Step* and *Backward Step* strategies are labeled as such if the CoM crossed respectively the front or the back boundary (Fig. 2.7) of the initial BoS. *Side Step* strategies which do not involve leg-crossover can be labeled by knowing whether the stepping leg was *Loaded* or *Unloaded* during the step. To do so the method considers that the loaded foot is the one which polygon initial position is crossed first by the CoM trajectory (Fig. 2.7). Eventually, if a step was made during the trial but the CoM trajectory did not cross the BoS nor any of the feet initial polygons then the step is labeled as *Sub-Critical Step* (SCS). During this kind of stepping strategy to projection of the CoM did not travel out of the original BoS and stayed in between both feet polygon.

The proposed classification method only gives information on the first recovery step. However, follow-up steps can also be classified especially after *Side Step* strategies [Borrelli et al., 2021].

### 2.3.1.2 Perturbation Angles, CoM Momentum and Step Characteristics

**Perturbation angle** · During the experiment, participants undergone compliant perturbations i.e. “perturbations during which a subject’s response modifies the body dis-

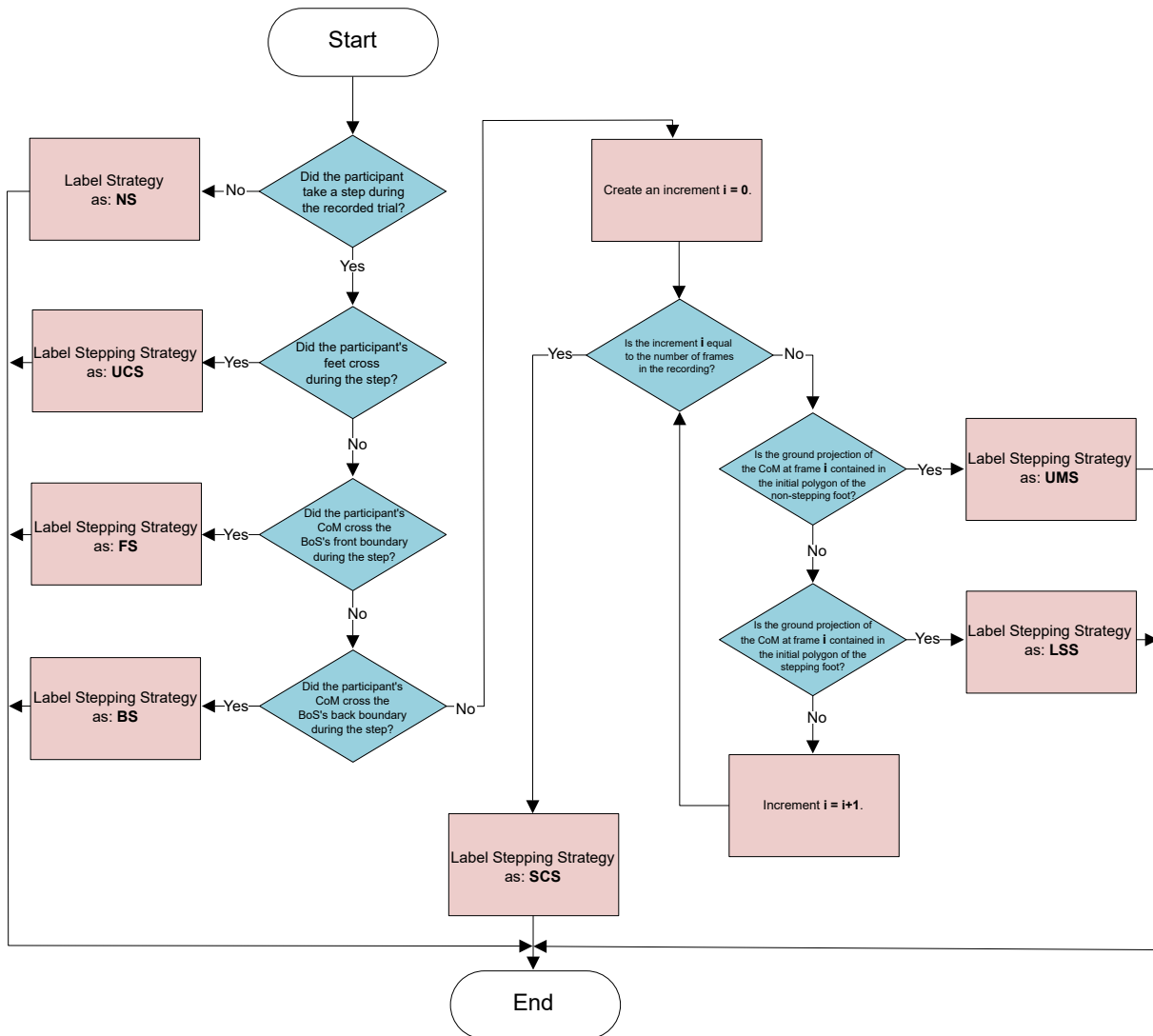


Figure 2.12 – Flowchart of the *Unified* classification method to label recovery strategies. This method allows a classification of stepping strategies without prior knowledge of the perturbation angle.

placement induced by the perturbation” [Robert et al., 2018]. Thus, we chose to use the direction of the CoM velocity of the participant at the maximum of perturbation intensity as the *Ground Truth* (GT) angle of perturbation (see Fig. 2.13). To estimate the perturbation direction based only on kinematic information we used the direction of the CoM velocity at the moment of minimal Ttb of the considered trial. Both GT and estimated angles were computed between the CoM velocity and the normal vector to participant’s shoulder in the direction of sight. The *Estimated* angle of perturbation enable to evaluate the direction of a perturbation only based on intrinsic kinematic information. This method is then used in all the following studies as no quantitative measure of the actual angles of perturbation was possible.

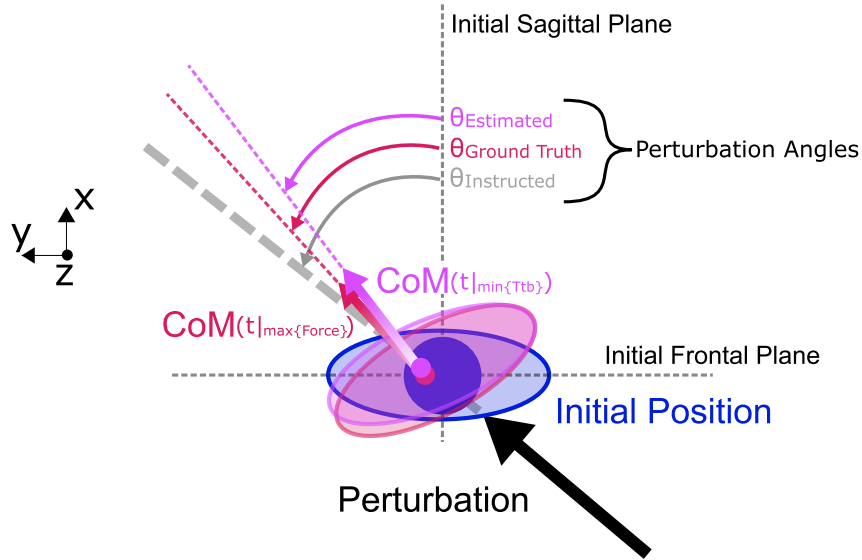


Figure 2.13 – Representation of the different perturbations angles. The *Instructed* perturbation angles, in grey, correspond to the angle between the initial sagittal plane and the direction given to the experimenter who applied the perturbation. The *Ground Truth* angle, in red, correspond to the angle between the initial sagittal plane and direction of the CoM velocity of the participant at the maximum of perturbation intensity. The *Estimated* angle of perturbation, in purple, correspond to the angle between the initial sagittal plane and direction of the CoM velocity of the participant at the moment of minimal Ttb during the considered trial.

**CoM momentum** · Classically, balance recovery and step characteristics have also been studied with regard to the applied perturbation [Vallee et al., 2015; Robert et al., 2018; Li et al., 2020b; Batcir et al., 2022]. In the following, we decided to rather consider

the CoM momentum as a relevant quantification of the intensity of the perturbation. This quantity was chosen over force sensor measurement as it could be easily computed only from kinematic information and thus be compared with results from other studies in which perturbation forces could not be obtained. The CoM momentum is defined as the mass of the participant multiplied by the speed of the participants' CoM at a given moment.

**Step Characteristics** · Regarding the characteristics of the steps, three main aspects were monitored: the length, the average speed and the angular deviation. The step length corresponds to the norm of the step vector, the step vector being defined as the vector from the position of the Toe marker at  $t_{begin}$  and its position at  $t_{end}$ . The step average speed is the step length divided by the step duration between  $t_{begin}$  and  $t_{end}$ . The step angle deviation is the oriented angle between the step vector and the estimated perturbation direction, i.e. the direction of the CoM velocity at the moment of minimal Ttb. All aforementioned step characteristics are represented in Fig. 2.14.

### 2.3.1.3 Analysis ·

Linear regressions were used to study the relationship between the step length, the average speed, and the CoM momentum at step initiation. The linear regressions were obtained using a Least-Squares method [Pedregosa et al., 2011]. The quality of the regression was assessed using the Coefficient of Determination ( $R^2$ ), the Root-Mean-Square Deviation (RMSE), and Shapiro-Wilk tests over the residual.  $R^2$  represents the proportion of the total variation of the considered quantities accounted for by the regression model. The RMSE is the root-mean-square of the average squared difference between the experimental data and the regression model. Shapiro-Wilk test assesses the normality of a distribution, here used to study the distribution of the residuals, i.e. the difference between the experimental data and regression models.

## 2.3.2 Results

### 2.3.2.1 Estimation of Perturbation Angles

The estimated perturbation angle using the direction of the CoM at the moment of minimal Ttb is shown in Fig. 2.15. This approximation seems to be more accurate for perturbations which triggered a stepping strategy (see Fig. 2.15 and appendix: Fig. A.1)

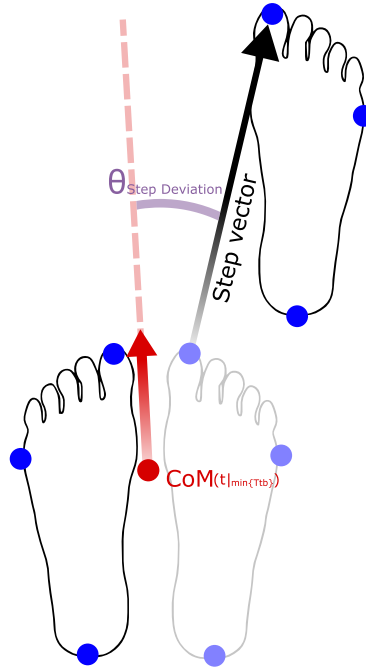


Figure 2.14 – Representation of the step vector (black arrow) and deviation angle (purple line). Step vector is defined as the displacement of the reconstructed stepping toe marker between the beginning and the final time of the first recovery step. Deviation angle is defined as the angle between the step vector and the direction of the CoM velocity at the moment of minimal Ttb.

with a difference of  $7 \pm 8 \text{ deg}$  between the estimated and the *Ground Truth* perturbation angles. For perturbations not triggering stepping strategies the mean difference is  $12 \text{ deg}$ , but the standard deviation reaches  $34 \text{ deg}$  due to some approximations being almost at the diametral opposite of the *Ground Truth* (see Fig. 2.15).

### 2.3.2.2 Recovery Strategy Separation

Stepping recovery strategies labeled with the proposed *Unified* classification are displayed by perturbation angle and DtFb in Fig. 2.16. This representation allows the visualisation of stepping strategy regions. *Forward Step* strategy were mainly used for perturbations with a GT angle between  $-34 \text{ deg}$  and  $34.3 \text{ deg}$ , or between  $-29 \text{ deg}$  and  $30.4 \text{ deg}$  using the estimated perturbation angles. This region is then referred as the *Centered - Forward Step* (C-FS) region.

For *Side Step* strategies, *Loaded* and *Unloaded* steps can be separated regardless of the perturbation angle with a DtFb under  $6 \text{ cm}$  for *Unloaded* strategies. In total four regions

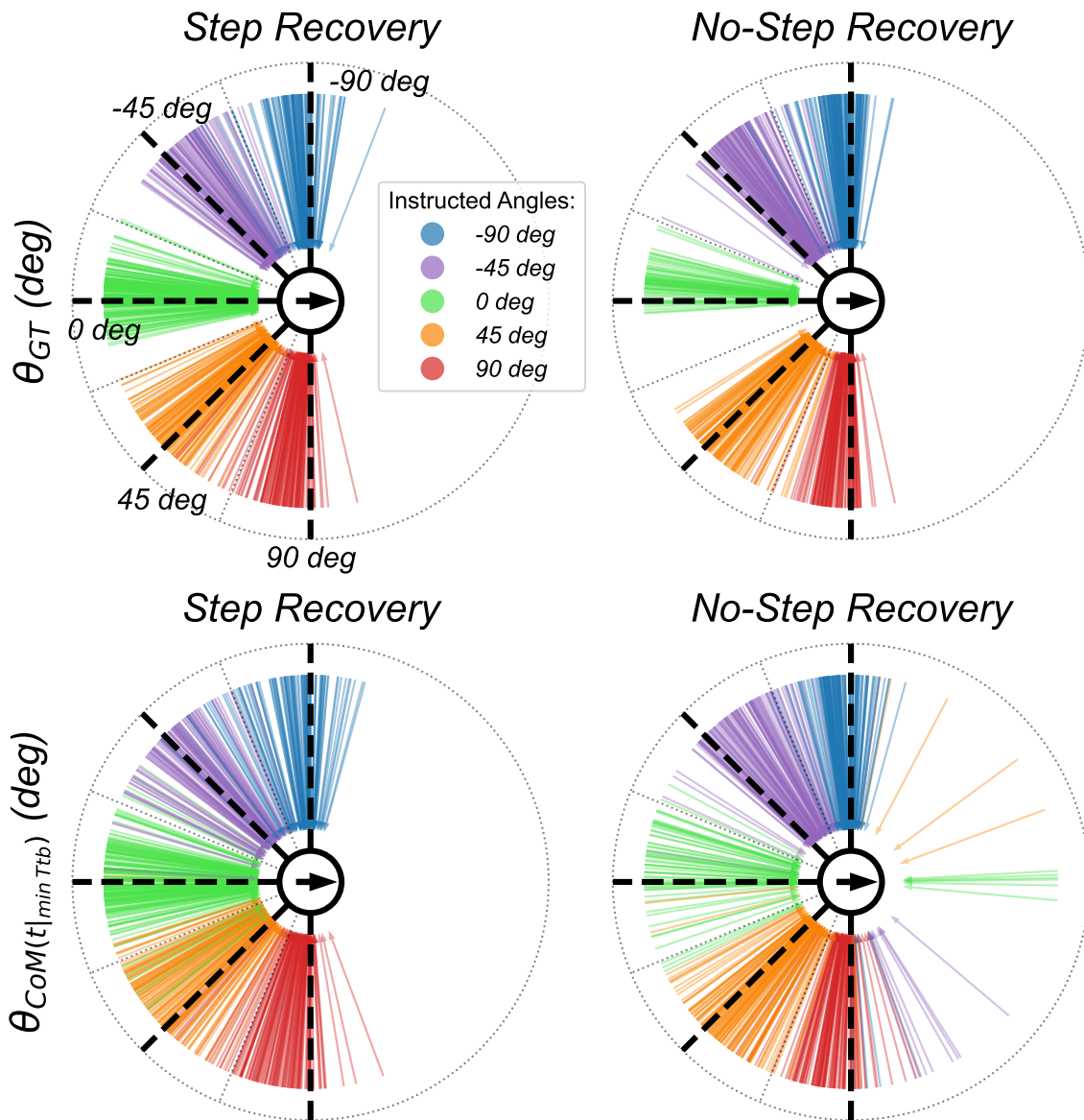


Figure 2.15 – Representation of the estimated perturbation angle based on the direction of the CoM velocity at the moment of minimal Ttb compared to the *Ground Truth* (GT) perturbation angle given by the direction of the CoM velocity at the moment of maximal perturbation intensity. The angles of perturbation are separated by recovery strategies, respectively *with* or *without* step. Trials are coloured by *instructed angles* given to the experimenter who applied the perturbation.

emerge from this separation.

Trials out of the C-FS region which occurred after perturbations with positive angles are contained in *Positive - Side Step* (P-SS) regions. This group of regions is composed of the *Positive - Loaded Step* (P-LS) region, containing trial with a DtFb higher than 6 cm, and the *Positive - Unloaded Step* (P-US) region, featuring trials with a DtFb lower than 6 cm. Similarly, for trials out of the C-FS following perturbations with negative perturbation angles trials are contained in *Negative - Side Step* (N-SS) regions, i.e. either in the *Negative - Loaded Step* (N-LS) or the *Negative - Unloaded Step* (N-US) regions depending on the value of the DtFb.

Characteristics of all logistic separations between regions are presented in Table 2.4.

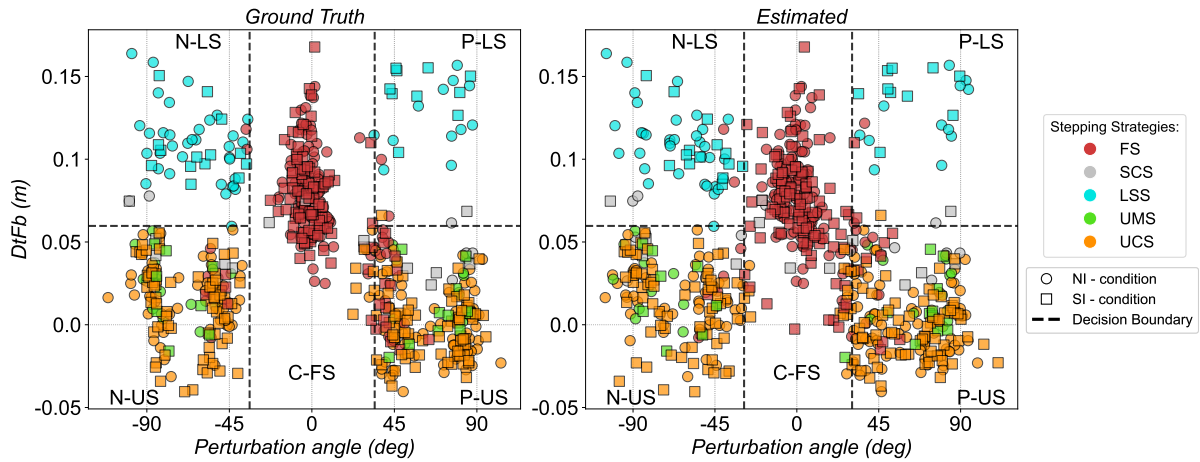


Figure 2.16 – *Distance to Foot boundary* (DtFb) in relation with the perturbation angle (left-hand side: Ground Truth, right-hand side: Estimated) for every trial involving stepping recovery strategies. Data are coloured using the *Unified* classification method. Dashed lines represent the decision boundaries of the proposed stepping strategy clustering model.

The *Limit of Standing Balance* (LoSB) have also been studies for the N-SS, C-FS and P-SS regions defined using GT and the *Estimated* angles of perturbation. The separation between trials involving recovery strategies with or without steps are represented in Fig. 2.17. The logistic separation models obtained an accuracy above 89% regardless of the method used to compute the angles of perturbation. All the characteristics of the models are visible in Table 2.5.



Region Separations	Decision Boundaries	Accuracy (%)	Sensitivity (%)	Specificity (%)
C-FS/P-SS (Ground Truth)	34.3 deg	91	88	95
C-FS/P-SS (Estimated)	30.4 deg	97	97	98
C-FS/N-SS (Ground Truth)	-34.0 deg	97	95	100
C-FS/N-SS (Estimated)	-29.0 deg	92	91	94
LS/US	6.0 cm	99	99	99

Table 2.4 – Characteristics of the logistic regressions used to create the separation between all clusters visible in Fig. 2.16. Separations were created between the *Centered - Forward Step* (C-FS) cluster and *Side Steps* (SS) clusters, i.e. either N-SS clusters following negative perturbation angles or P-SS following positive perturbation angles, based on the *Ground Truth* or *Estimated* angles of perturbation. Separation between *Loaded Step* (LS) and *Unloaded Step* (US) clusters was created using the *Distance to Foot Boundary* (DtFb).

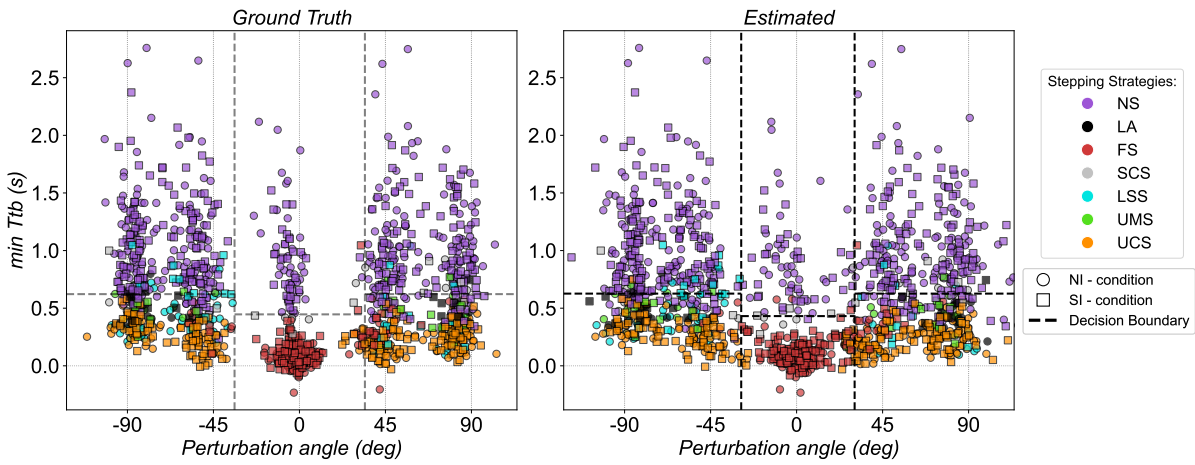


Figure 2.17 – Minimal *Time to boundary* (Ttb) for every trial in relation to perturbation angle (left-hand side: Ground Truth, right-hand side: Estimated). Minimal Ttb value was computed before step initiation for trials involving a step. Data are coloured using the *Unified* classification method. Horizontal dashed lined represent the decision boundaries of the proposed separations between trials with and without steps for every range of perturbation angles. The range of perturbation angles delimited by vertical dashed lines are associated with the stepping strategy clusters visible in Fig. 2.16.

Separation NS/Step - Estimated Perturbation Angle Regions					
Considered Region	Angles Range	Decision Boundaries (s)	Accuracy (%)	Sensitivity (%)	Specificity (%)
P-SS (Ground Truth)	$[-180 \text{ deg} ; -34 \text{ deg}]$	0.62	88	89	89
C-FS (Ground Truth)	$[-34 \text{ deg} ; 34.3 \text{ deg}]$	0.44	98	97	100
N-SS (Ground Truth)	$[34.3 \text{ deg} ; 180 \text{ deg}]$	0.55	89	91	88
P-SS (Estimated)	$[-180 \text{ deg} ; -29 \text{ deg}]$	0.63	89	89	88
C-FS (Estimated)	$[-29 \text{ deg} ; 30.4 \text{ deg}]$	0.43	97	97	99
N-SS (Estimated)	$[30.4 \text{ deg} ; 180 \text{ deg}]$	0.56	89	91	88

Table 2.5 – Characteristic of the logistic separation models between trial with and without steps for different the different recovery strategy clusters defined in Fig. 2.16 created using the *Ground Truth* or the *Estimated* angles of perturbation.

### 2.3.2.3 First Recovery Step Characteristics

The first recovery step length and average speed are compared to the CoM momentum and to each other in Figs. 2.18 to 2.20. First recovery step length seems to have a linear relationship with the CoM momentum when FS is used as recovery strategy. Such a relationship is also found (with lower coefficient of determinations) between the average speed of the first recovery steps and the CoM momentum. Eventually the strongest linear relationships appear when looking at the first recovery step’s average speed compared to step length. In addition to the linear relationships, one could observe that different stepping strategies are used for different ranges of CoM momentum. The relations between average speed and step length also significantly changed between stepping strategies, with faster FS and USS than UCS or UMS for the same distance traveled by the stepping foot. One can also see that steps classified as SCS are made for smaller values of CoM momentum and have characteristics close to UMS. Characteristics of all linear regressions are reported in the appendix, Table A.3

The direction of the step seems to get closer to the estimated direction of the perturbation as the CoM momentum increases. This is shown in Fig. 2.21 where one can see that the step deviation angle gets closer to zero as CoM momentum increases. For low

CoM momentum the deviation increases with a preferred direction which depends on the side of the recovery strategy (see Fig. 2.21 and Table A.4). Median deviations are shifted to negative for strategies following disturbance with negative perturbation angles and to positive for strategies following disturbance with positive perturbation angles.

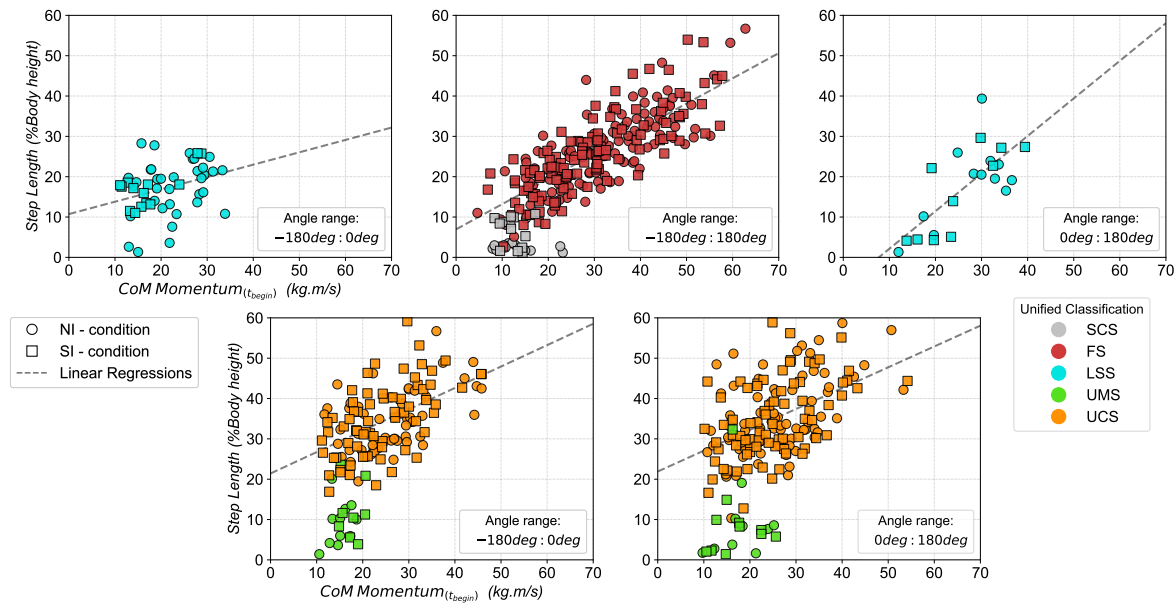


Figure 2.18 – Representation of the length of the first recovery step compared to the CoM momentum at step initiation for each stepping recovery strategy (labeled using the *Unified* classification). Dashed lines represent the linear regressions based on data repartition.

2.3. Unified Stepping Strategy Classification and First Recovery Step Characteristics

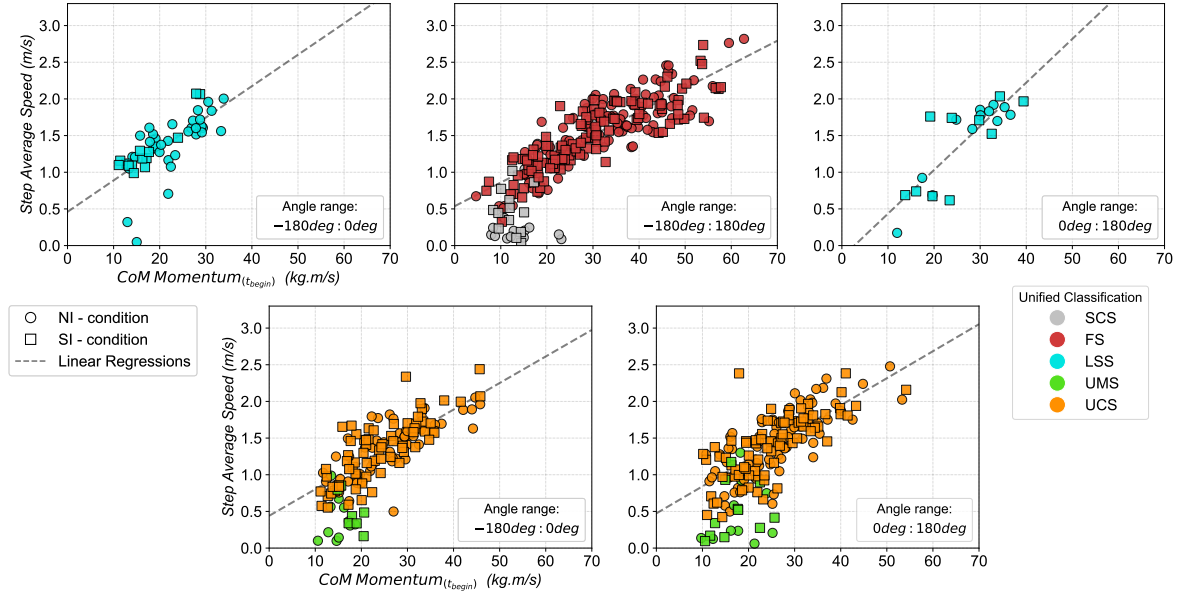


Figure 2.19 – Representation of the average foot speed during the first recovery step compared to the CoM momentum at step initiation for each stepping recovery strategy (labeled using the *Unified* classification). Dashed lines represent the linear regressions based on data repartition.

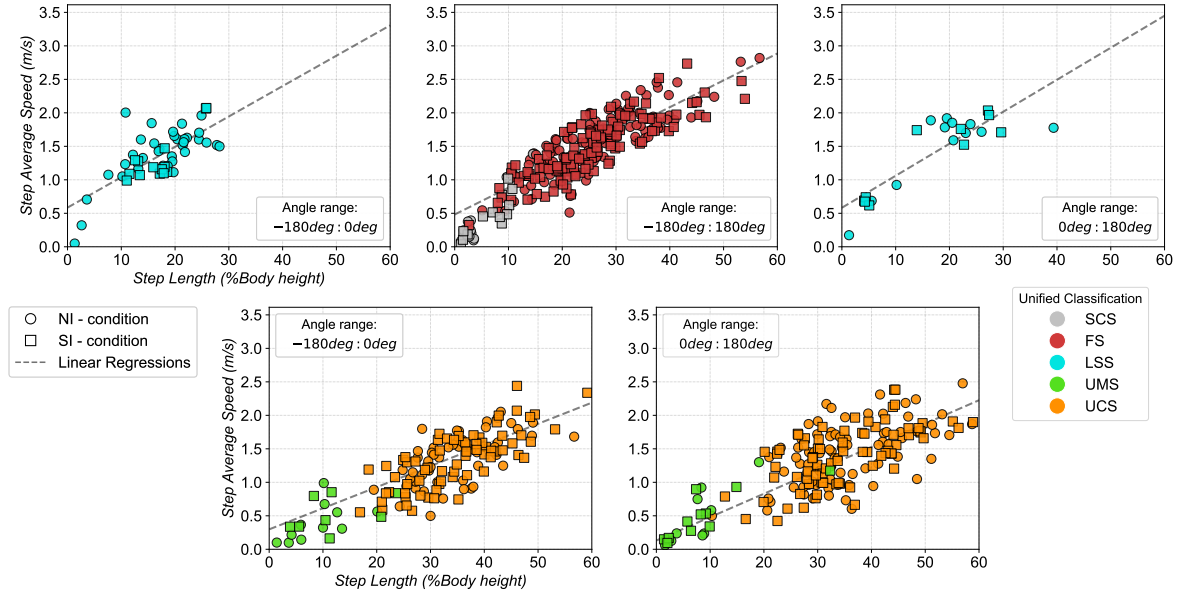


Figure 2.20 – Representation of the average foot speed during the first recovery step compared to the step length for each stepping recovery strategy (labeled using the *Unified* classification). Dashed lines represent the linear regressions based on data repartition.

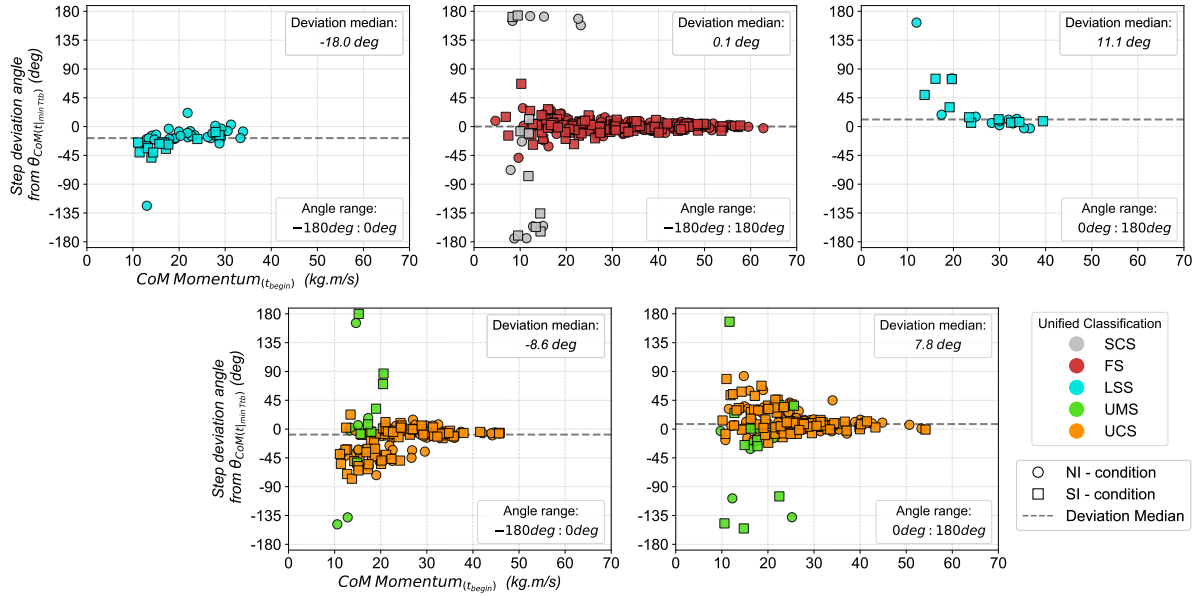


Figure 2.21 – Representation of the step deviation angle compared to the CoM momentum at step initiation for each stepping recovery strategy (labeled using the *Unified* classification). Dashed lines represent the linear regressions based on data repartition.

### 2.3.3 Discussions

We have seen with Fig. 2.15 that the perturbation angle can be estimated using the direction of the CoM velocity at the moment of minimal Ttb. The difference between GT and the estimated angle stays limited with some exception for several trials with perturbations which did not lead to stepping recovery strategies. For these trials the estimated angle was almost the diametral opposite of the actual perturbation angle. This indicates that the minimal Ttb was reached during the recovery, when the CoM was travelling back from the perturbation.

Following the study of the perturbation angle, we proposed a separation model that predict stepping strategies based on kinematic information prior to step initiation. In total, five regions were considered, with three groups of region (N-SS, C-FS, P-SS) emerging from a separation using the angles of perturbation. The boundary between these groups of regions changes whether separation was based on the GT angles or the estimated angles of perturbation. However, the difference between the boundary decisions of the separation models (at most 5 deg) remains lower than the average difference between GT and the estimated angles when a stepping strategy is used, i.e. 7 deg (see appendix: Fig. A.1).

For each of these group of regions (N-SS, C-FS, P-SS), the LoSB was studies using

a separation models between trials involving stepping recovery strategies and recovery without step based on the minimal Ttb. The separation models proposed with this method appear to be comparable in terms of accuracy to the one proposed in Section 2.2.2.1.

Eventually, the DtFb was used to separate *Loaded* and *Unloaded* steps in the regions containing *Side Steps*, i.e. N-SS and P-SS. This separation was performed with an almost perfect accuracy, comparable to was obtained using the *intructed* perturbation angles in Section 2.2.2.2.

Regarding the first recovery steps characteristics, we observed linear relationships with the CoM momentum. These relationships were especially clear when a FS strategy was used. One can notice that a relationship between the CoM momentum and *Unloaded* step (UMS, UCS) characteristics seems to appear for perturbations leading to a CoM momentum over  $20 \text{ kg.m/s}$ . This threshold echos with the one observed to mark the end of the overlapping between non-stepping and stepping strategies (see appendix: Fig. A.2). The most distinct linear relationships were visible between step length and average step speed. These correlations appeared for every stepping strategy but with different coefficients. Therefore, one can see in Fig. 2.20 that FS and LSS were executed with a higher average stepping speed than the UMS and UCS. This effect may be explained by the greater DtFb observed for these strategies. By having a greater distance from the CoM to the non-stepping foot at step triggering participants using LSS or FS are more unstable and need to react faster to prevent falling [Maki and McIlroy, 1997; Mille et al., 2005]. Considering the significant overlaps between NS and LSS strategies (see appendix: Figs. 2.17 and A.2), one may infer that the LSS strategy was used for less 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 LSS were associated with a less complex stepping trajectory resulting in shorter execution time.

We also studied the direction of the first recovery step and especially the deviation angle between the first recovery step direction and the estimated direction of perturbation. We observed that the deviation angle decreases as the CoM momentum at step initiation increases. This link may once more be induced by the state of balance in which the participants were during the trial. We can see in Fig. 2.21 that the largest deviation angle occurred for stepping strategies associated with less challenging recovery (SCS, LSS, UMS) and for lower values of CoM momentum. The side of the deviation also appears to

be influenced by the side of the perturbation. For LSS and UCS stepping strategies, we observed that at lower CoM momentum the step deviation angles was more likely to be negative for strategies following disturbance with negative perturbation angles and more likely to be positive for strategies following disturbance with positive perturbation angles. This suggests that in this situation the first recovery step vectors were more directed towards the back of the participants.

### 2.3.4 Preliminary Conclusion

In this section a *Unified* stepping strategy classification method was proposed. This classification does not depend on the perturbation angle like the *Bi-modal* classification used in Section 2.2. After exposing this method we study the actual perturbation angle and tried to estimate it using the *Center of Mass* (CoM) velocity direction at the moment of minimal *Time to boundary* (Ttb). A separation model of the different recovery strategies was then proposed using only kinematic information prior to the moment of step initiation. This model relies on logistic regressions based on the *Time to boundary* (Ttb), the *Distance to Foot boundary* (DtFb) and the estimated perturbation angle. Finally, relationships between the CoM momentum and first recovery step length and average speed were exposed for *Forward Step* strategies. Linear relationships were also found between first recovery step length and average speed for all stepping recovery strategies. The direction of the first recovery step appears to be related to the estimated perturbation angle. This relation depends however on the stepping strategy used and the CoM momentum at step initiation, with a decreasing deviation angle between step direction and estimated direction of perturbation as the CoM momentum increases.

## 2.4 Limitations of the Study

The proposed study also comes with limits that have to be acknowledged in order to fully grasp the context of validity of the previous conclusions.

First, 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.

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.

Another element which may have an impact on our results is the way the BoS was approximated. In this study, the geometric BoS boundaries were approximated in using the location of the external markers placed on the outer part of each foot of participants. This approximation may lead to a slightly larger BoS. The actual boundaries may vary up to 1cm (based on the size of the marker used) towards the CoM ground projection at rest.

The proposed *Unified* method for step classification comes with hypotheses which need to be validated in order to correctly estimate the stepping strategy used during a trial. The main hypothesis is that the projection of the CoM on the ground is within the BoS and remains strictly in between the foot polygons before the perturbation. Due to the variety of postures one may demonstrate depending on the context (e.g. loading a leg to rest the other) this hypothesis may not be verified at all time in other experimental conditions.

Eventually, stepping strategies involving more than one step have been observed during the experiment. However, only the first recovery step was considered in this study. The overall objective of this work is to gather information about critical standing balance situations in order to understand the risk of falling in dense crowds. Therefore, this study focuses on the standing balance limit and the first actions taken to recover balance following an external perturbation. Here, the first step is the most critically affected by the perturbation. Follow-up steps are relative to the individual balance control and the adopted stepping strategy [Li et al., 2020a; Borrelli et al., 2021].

## 2.5 Chapter Conclusion

Throughout this chapter we studied the reaction of single individuals, to external force-controlled perturbations, in a fully controlled lab environment and for different level of awareness of the participants to the upcoming perturbation. In particular, we demonstrated that the *Limit of Standing Balance* could be characterised using either the *Time to boundary* or the *Margin of Stability* with no significant effect of the level of awareness of participants of the upcoming perturbations.



Three new methods were proposed in this chapter. First the *Distance to Foot boundary* was suggested as a relevant quantity to assess the nature of side steps based on kinematic information at the moment of step initiation. Then we suggested using the direction of the *Center of Mass* velocity at the moment of minimal *Time to boundary* to estimate the actual angle of the external perturbation. Eventually, we exposed a *Unified* classification method to label recovery strategies without prior knowledge of the perturbation angle. These three methods enabled us to create separation models of all the recovery strategies used by participants in the context of this experiment. These models are based only on kinematic information prior to the step initiation and could t. Eventually, the first recovery step characteristics of the different classified stepping recovery strategies were studied and compared with the CoM momentum at the moment of step initiation.

Using this dataset one may study in more details recovery strategies involving multiple steps following sudden external perturbations. The main body parts used to regain standing balance may also be studied using more specific motion analysis [Scholz and Schöner, 1999].

Data collected in the frame of this study could also be used as a comparison baseline to understand how stepping behaviours change following external perturbations when being surrounded by other individuals. This is *the force of* the following chapters of this manuscript.

# RECOVERY STRATEGIES OF MULTIPLE INDIVIDUALS TO EXTERNAL PERTURBATIONS

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In this chapter are reported the results of experiments conducted on young adults within dense group formations in a fully controlled laboratory environment. The notion of dense group here refers to tightly packed formations of individuals in which the motion of a considered participant is limited and is likely to result in physical interaction with other individuals.

In particular, we investigate in this context the *Limit of Standing Balance* (LoSB) and the recovery strategies including the characteristics of the first recovery steps and the initiation of hand raising following sudden external perturbations. The recovery strategies used by participants in this context of dense groups are studied in relation to the interpersonal distancing observed for different group formations. All results are also compared with the models developed during the study of the single individuals experiment of Chapter 2.

After providing a detailed overview of the data collected and the general methods used in this work, the study is then articulated to investigate the following scientific questions addressed in this chapter.

- Does interpersonal distancing have an effect on the LoSB of participants within dense groups? (Sections 3.2.2 and 3.2.3)
- What are the recovery strategies used by participants in dense groups to recover from external perturbations? (Sections 3.2.3 to 3.2.5)
- To what extent recovery strategies of participants in dense crowd-like situations can be compared to the response of single individuals following external perturbations? (Sections 3.2.1, 3.2.3 and 3.2.4)

Elements of discussion and conclusions regarding the results presented here are proposed at the end of this chapter.

## 3.1 Materials and Methods

### 3.1.1 Experimental Data Collection

The data used in this study are part of a larger experimental dataset created by recording the full body motion and tracking the head trajectory of 80 people throughout a variety of push-recovery activities in dense group formations. These experiments received ethical approval from the University of Wuppertal in April 2021 (Reference: *MS/BBL 210409 Seyfried*) and all participants signed an informed consent form relative to the processing of their data. These experiments have been directed by the Institute for Advanced Simulation, IAS-7: Civil Safety Research of the Forschungszentrum Jülich. The work presented here results from a collaboration which took place in the frame of the CrowdDNA H2020 European research project.

Many parameters were varied during the experiment, including the number of participants, the spatial configurations of the groups, the level of awareness of the upcoming perturbation, and the interpersonal distances between participants. In this study, a trial refers to a single push-recovery cycle of an entire group of participants. Out of the 27 group configurations tested during the experiments we selected here trials from four different group configurations. Specifically, we selected a line configuration (4A11) and three packed configurations with different relative position of neighbours (4B55, 4C55, 4D–) as illustrated in Fig. 3.1. The selected trials were composed of the same participants. We selected these group configurations to maximise the number of observable possible interactions between individuals. Two interpersonal distancing conditions have been studied: the *No Distance* condition, i.e. with direct physical contact between participants and the *Elbow Distance* condition, i.e. an approximated distance of one elbow length was set between participants.

All participants were facing the same direction at the beginning of each trial. Participants had no prior indication about the upcoming perturbations, and they were asked, before each trial, to count backwards from 100 to 0 in a quiet voice. The perturbation could happen at any time during this period. Perturbations were manually delivered using a hanging punching bag in the anteroposterior direction at shoulder height on the

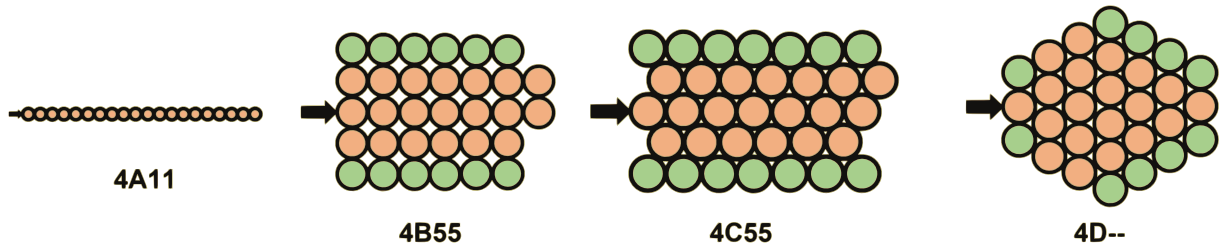


Figure 3.1 – Representation of the selected group configurations. Participants wearing motion capture suits are represented by orange discs. Additional participants at the boundaries (without motion capture suits) are represented by green discs. The external perturbation location and direction is represented by the black arrow.

back of the rearmost participant (see Fig. 3.2). All perturbation intensities were recorded using a pressure pad with the same experimental setup as in the work of Feldmann and Adrian [2023].

For each trial, the motions of twenty participants (8 females, 12 males) were recorded using Xsens MVN Link suits (IMMU-based motion capture, 240Hz). The average age, mass and height of the participants were  $24.8 \pm 3.7$  yo,  $75.8 \pm 14.9$  kg and  $1.79 \pm 0.08$  m respectively. All demographic information are available in Table 3.1. Twelve additional participants were added at the boundaries during the packed configuration trials (see green discs in Fig. 3.1). The trials were also recorded using a top-view video camera (GoPro 9, 25Hz). All participants wore a coloured hat with an attached ArUco code linked to demographic information such as body height and mass.

In total, all the 20 participants wearing motion capture suits performed 6 trials for each of the investigated group formations. This resulted in a dataset of 24 trials composed of 20 full body motion recordings. Only recordings with a CoM speed above the minimal CoM speed due to external perturbations observed during the single individuals experiment were analysed. Hence, out of the 480 experimental recordings considered, only 330 recording for which participants received external perturbations were used in our study.

## 3.1.2 Data Processing

### 3.1.2.1 Video Recordings

The top-down view recordings of the experiment provided a clear vision of participants' head trajectories during the experiments. These trajectories were extracted from the video recordings using the PeTrack software from [Boltes and Seyfried, 2013; Boltes



Figure 3.2 – Picture of the experiments for a group formation close to the 4B55 formation studied here. In this picture, the group is only composed of participants wearing motion capture suits. For the 4B55 formation, additional participants without motion capture suits were placed on the side boundaries of the group formation.

Gender	Mass (kg)	Height(m)	Gender	Mass (kg)	Height(m)
Female	81	1.77	Male	67	1.81
Female	56	1.75	Male	75	1.84
Female	56	1.69	Male	120	1.87
Female	77	1.74	Male	87	1.84
Female	65	1.73	Male	84	1.9
Female	60	1.64	Male	87	1.88
Female	65	1.64	Male	75	1.82
Female	87	1.84	Male	69	1.78
Male	69	1.77	Male	89	1.89
Male	64	1.85	Male	82	1.82

Table 3.1 – Demographic details of the considered participants of the dense groups experiment wearing motion capture suits.

et al., 2021]. This software automatically detects the participant’s coloured hat and ArUco code and calculates the participant’s actual trajectory based on pixels trajectories of the

video recordings (see Fig. 3.3). Using this software, we were able to reconstruct the relative head positions of participants during the experiments. We could then compute an approximate local density and interpersonal distance of each participant to their up-front neighbour. Both variables were computed for the initial position, using the first frame of the recordings, before the perturbation occurred.

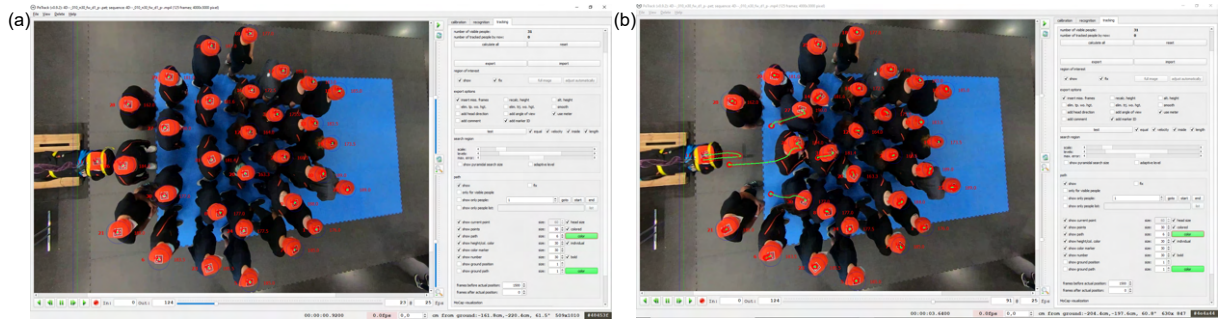


Figure 3.3 – Screenshots of the PeTrack software ([Boltes and Seyfried, 2013; Boltes et al., 2021]) while processing one of the trial with the 4D– configuration. (a) The head tracking is visible before the external perturbation happened. (b) The head tracking is visible after the perturbation. The green lines represent the tracked head trajectories.

The distance to the up-front neighbour was computed relative to the head distance between a considered participant and the closest neighbour up-front. For staggered configuration, by definition, the neighbours up-front were not aligned with the considered participant. In order to be able to compare all trials together, only the distance in the direction of participants’ sight was considered. This distance can also be seen as the distance to the up-front row, as illustrated in Fig. 3.4.

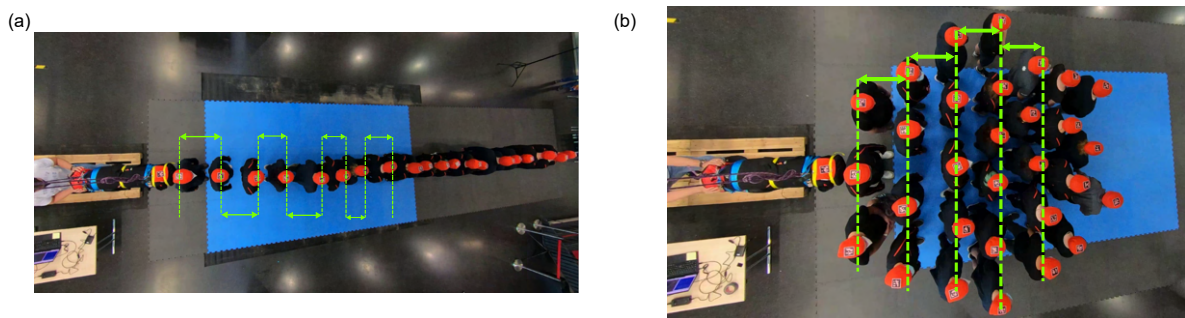


Figure 3.4 – Representation of the interpersonal distance (green arrows) for two representative examples: (a) 4A11, line formation, (b) 4D–, staggered group formation.

To compute the local density of participants, two different methods were used depending on the group configuration. For the Single row configuration (4A11), a 1D definition

of the density was used. Local density in this condition was computed as the multiplicative inverse of the half interpersonal distances between the considered participant and the direct neighbours [Cao et al., 2016]. The definition of density can then be expressed as :

$$\rho_i = \max \left\{ \left( \frac{\|\mathbf{X}_i - \mathbf{X}_{i-1}\|}{2} + \frac{\|\mathbf{X}_{i+1} - \mathbf{X}_i\|}{2} \right)^{-1}, 1 \right\}, \quad (3.1)$$

with  $\rho_i$  being the local density of the considered participant indexed  $i$  and  $X_i, X_{i+1}, X_{i-1}$  being the position of the considered participant and the immediate neighbours up-front and behind respectively.

For group configurations (4B55, 4C55, 4D–), local density was computed using a method based on Voronoi diagrams called Voronoi density, as in Steffen and Seyfried [2010]. These diagrams are created using seeds and composed with cells around the seeds created so that every point within the cell is closer to its seed than to any other seed (see Fig. 3.5). To compute the Voronoi density, a diagram is computed using the head position of participants as seeds. The density is then defined as the multiplicative inverse of the intersecting area of the Voronoi cell and a circle centered on the participant with a  $1m^2$  area. This intersection prevents the Voronoi density from falling below  $1ppl/m^2$  for unbounded cells at the edge of the group.

### 3.1.2.2 Motion Capture Recordings

The classical optical motion capture technique used in Chapter 2 could not be used in a context of dense groups due to its high sensitivity to visual occlusion. To solve this matter a method based on *Inertial Measurement Units* (IMUs) was used. This technology does not require any optical information and can thus be used in dense crowd situations. IMUs can measure linear acceleration and angular velocity (using accelerometers and gyroscopes). During the experiments, a commercial solution from Xsens company was used (MVNlink). This solution uses *Inertial and Magnetic Measurement Units* (IMMUs) which improve the accuracy of body segment position estimation [Fang et al., 2018]. The whole dataset was then processed using the Xsens MVN 2020.2 software, and virtual markers were reconstructed from the raw recordings. These markers are reconstructed anatomical landmarks determined by the relative position of IMMUs in the suit and the body measurements of each participant’s limbs. The virtual reconstructed markers used here are comparable to the one used in Section 2.1.2.1.



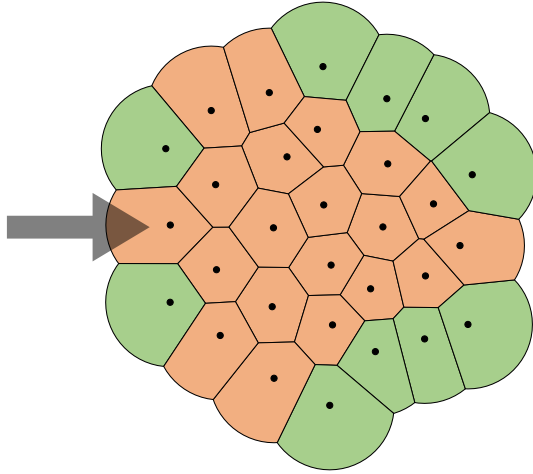


Figure 3.5 – Representation of the Voronoi diagram for using participants initial head positions as seeds (black dots). This example has been created using a trial with the 4D-group formation (also visible in Fig. 3.3). For participants wearing motion capture suits the Voronoi cells are orange. Cells of additional participants at the boundaries (without motion capture suits) are colored in green. The external perturbation location and direction is represented by the black arrow.

One should keep in mind that systems using these motion capture methods require to be calibrated in order to compute the positions of the limbs from the information of the sensors. Thus, only *estimations* of the limb positions are reconstructed using this technique and reconstruction method relies greatly on the quality of the calibration. This can be problematic if a sensor placed on a participant’s body moves during the experiments leading to a drift of the reconstructed limb position in the recorded data. To mitigate this issue two calibration protocols were performed before and after the experiments.

Furthermore, for each trial, a few participants were not affected by the external perturbation. This was usually the case for participants in the front rows who benefit from the energy dissipation of the perturbation by previous participants [Feldmann and Adrian, 2023]. Without perturbation, their CoM remained static or with a very low velocity throughout the entire recorded trial. This causes issues with the numerical computation of the *Time to boundaries* (Ttb) which is by definition infinite for a static CoM. To prevent any numerical artefact, we removed the recording of all participants whose CoM speed did not exceed  $0.05\text{ m/s}$ . This threshold was chosen to ensure no computational error and



remains below the lowest maximum CoM speed value observed after perturbations during previous single individuals experiment.

### 3.1.2.3 Step and Hand Raising Detection

The step detection method used in this chapter is the same as the one exposed in Section 2.1.2.2. Recovery strategies are labelled in this chapter using the *Unified* recovery strategy classification proposed in Section 2.3.1.1. Only one modification has been made regarding classification of the *Unload Crossover Steps*. In Chapter 2, steps were considered *Crossover* if either the toe markers of the heel markers or participants feet crossed during the step, as defined in Section 2.1.2.2. In this study, steps were considered *Crossover* if both the toe markers and the heel markers of participants feet crossed during the step. Since no indication regarding foot placement was given during this dense groups experiment, some initial foot placement resulted in false positives' crossover detection. This new condition is however more restrictive and then does not allow the detection of smaller crossover for which the feet did not fully cross.

In this chapter we also study the moment when participants raised their hands in addition to stepping recovery strategies. The detection method for hand raising initiation is similar in many ways to the detection of step proposed in Section 2.1.2.2. This method relies on the analysis of the position and velocity of the reconstructed hand motion recorded during the experiments.

The following three-stage method was applied to each hand to detect hand raising.

1. The upward motion of the hand during a trial was checked to be higher than a distance threshold  $d_t = 20cm$  (i.e. greater than an average human hand [Aboul-Hagag et al., 2011; Guerra et al., 2014]),
2. The vertical speed of the hand was computed and positive peaks were assumed to correspond to motion induced by hand raising,
3. We then selected the first inflexion point before the peak for which the vertical speed value was under 10% of the global maximal speed (ensuring not to fall into local minimums).

This method returned the first inflexion point (before the first hand's vertical speed peak). This moment was considered to be the initial time of hand raising (see Fig. 3.6).

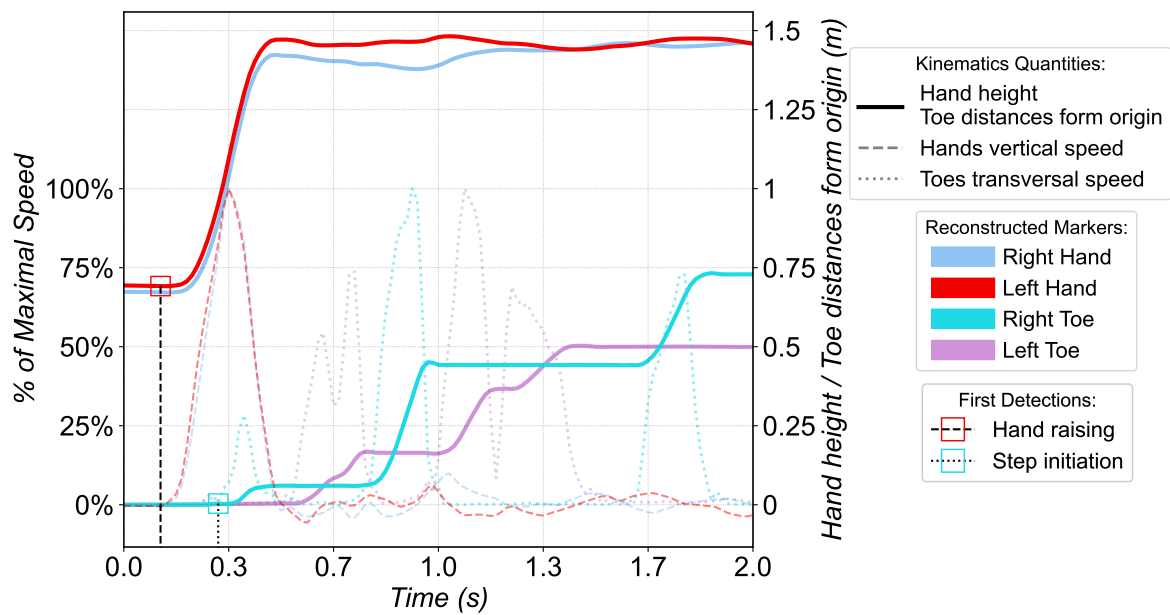


Figure 3.6 – Representation of the reconstructed hands’ height and toes’ transversal distance from origin, for a participant during the dense groups experiment. Vertical and transversal speed are represented in dashed or dotted lines for the reconstructed hands and toes respectively. The moments of hand raising and step initiation are considered to be the first inflexion points before speed peaks. The detection time of these moments is indicated by square markers.

### 3.1.2.4 Analysis

Statistical models such as logistic and linear regression models have been created based on this dataset using the same methods as presented in Sections 2.2.1 and 2.3.1.3.

To assess the effect of the experimental interpersonal distancing conditions, we built *Logistic Mixed Models* (LMMs) upon the dataset. This model is a general logistic model assessing the probability for participants of taking a step for a given minimal value of Ttb, considering the experimental interpersonal distancing conditions 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].

## 3.2 Results

### 3.2.1 Estimated Angles of Perturbation

Using estimated perturbation angles for trials with stepping recovery strategies one can see in Fig. 3.7 that perturbations were mainly coming from the back of the participant in the anteroposterior direction. Perturbation angles estimation seems to be less accurate when looking at the trials without stepping recovery strategies. There is also one perturbation coming from the front of the participant which lead to a LSS recovery strategy. This outlier was obtained following a contact of a participant with the up-front neighbour.

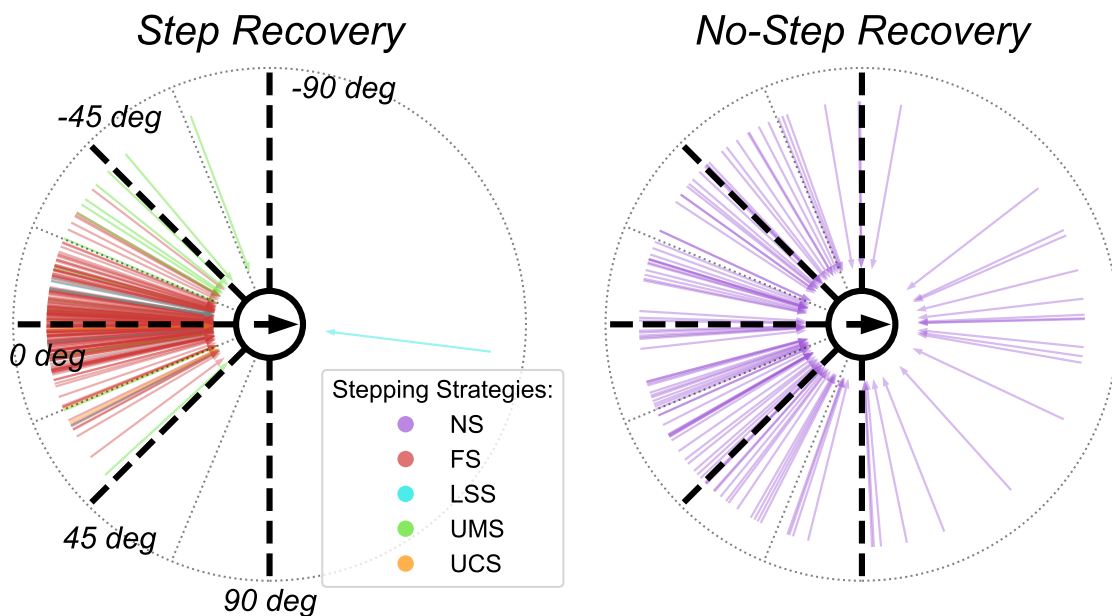


Figure 3.7 – Representation of the estimated perturbation angle based on the direction of the CoM velocity at the moment of minimal Ttb. The angles of perturbation are separated by recovery strategies, respectively *with* or *without* step. Trials are coloured by recovery Strategies (based on the *unified* classification).

### 3.2.2 Distancing Conditions and Density

The distribution of distance to first up-front neighbour and the density distribution compared to the distance to first up-front neighbour are shown in Fig. 3.8. The median distance to first up-front neighbour was  $29\text{cm}$  for the *No distance* condition and  $45\text{cm}$  for the *Elbow distance* condition. Standard deviation for each of the conditions were  $6\text{cm}$  and  $9\text{cm}$  respectively. Overlaps between the two experimental distancing conditions can be noticed. These are particularly visible when looking at the estimated local density around participants, especially between  $2\text{ ppl}/\text{m}^2$  and  $5\text{ ppl}/\text{m}^2$ .

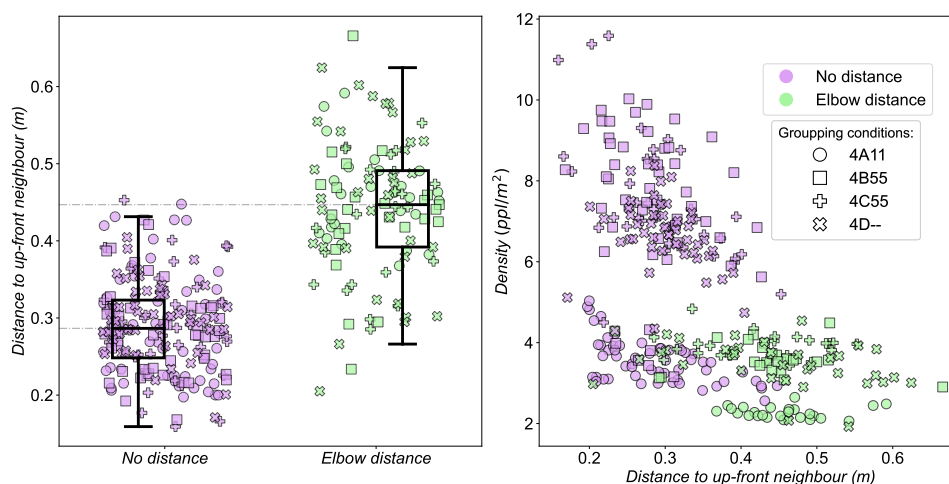


Figure 3.8 – Left-hand side: Distribution of the distance to first up-front neighbour for each experimental distancing condition. Right-hand side: Density distribution compared to the distance to first up-front neighbour. Data points are colored by experimental distancing condition. For all grouping conditions, density was computed using a *Voronoi density* method except for condition 4A11 (single line condition) where a 1D density definition was used.

### 3.2.3 Limit of Standing Balance in Dense Groups

Logistic models keep an overall accuracy above 90% (see Table 3.2) for both experimental distancing conditions. We can see in Fig. 3.9 that most recovery strategies achieved without stepping were done with a CoM momentum under  $20 \text{ kg.m/s}$  at the moment of minimal Ttb. The separation boundary for the *Elbow Distance* condition is  $0.52 \text{ s}$  based on the logistic model. This is more than 15 % higher than the separation boundary of the model based on the *No Distance* condition at  $0.43 \text{ s}$ . The effect of the experimental distancing conditions is also visible from a statistical point of view given the low p-value of the Fixed Effect Omnibus test of the LMM based on the present data (see Table 3.3). Eventually, in 211 trials out of the 221 trials for which a stepping strategy was used, i.e. 95%, the moment on minimal Ttb corresponds with the moment of step initiation regardless of the experimental condition distancing.

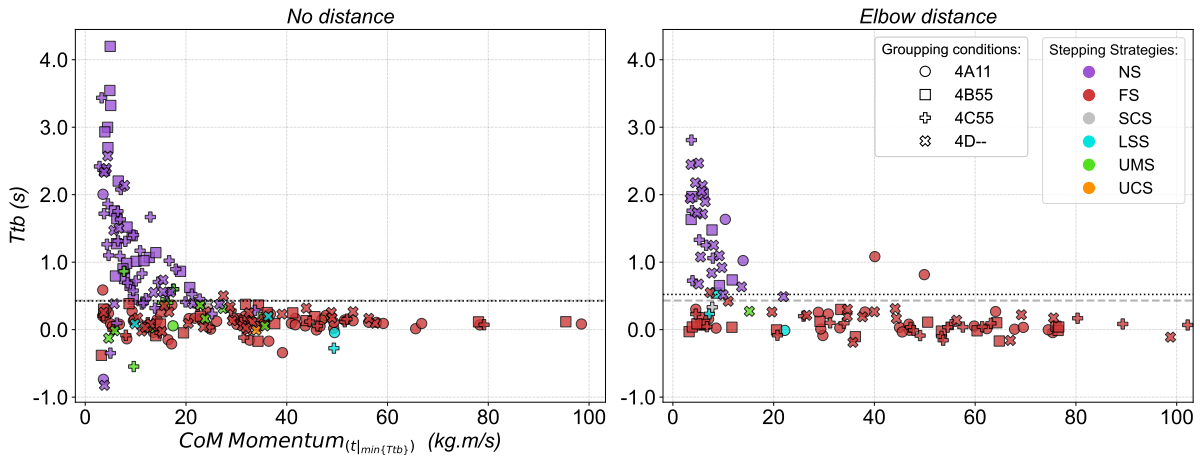


Figure 3.9 – Distribution of the Minimal *Time to Boundary* (Ttb) of the participants compared to their CoM momentum for each experimental distancing condition. Minimal value was computed before step initiation for trials involving a step and for the entire recorded motion for trials not involving step. Decision boundaries between trials with and without steps are represented for each experimental distancing condition by black dotted lines. The grey dashed lines represent the decision boundary of the logistic model obtained for the C-FS region created with data of the single individuals experiment Section 2.3.2.2. In this region *Forward Step* strategies were more likely to be used.

	Decision Boundary (s)	Accuracy (%)	Sensitivity (%)	Specificity (%)
Single Individuals (C-FS, Table 2.4)	0.43	99	99	100
Dense Groups No Distance	0.43	92	97	83
Dense Groups Elbow Distance	0.52	94	95	93

Table 3.2 – Characteristics of the logistic models to separate trials with and without steps (NS) using minimal values of Ttb during trials. Models were created for each experimental distancing conditions.

	$R^2_{conditional}$	$R^2_{marginal}$	p-value : Fixed Effect Omnibus tests	
			Distancing Condition	Covariate (Min. Ttb)
NS/Step - Min. Ttb	0.884	0.884	0.029	< 0.001

Table 3.3 – Characteristics of the *Logistic Mixed Models* (LMMs) between trials with and without steps (NS). The covariate is the quantity on which the regression is based (here, the minimal Ttb during trials).

### 3.2.4 First Recovery Step Characteristics in Dense Groups

One can see in Fig. 3.12.a-b that there is no clear relationship between the first recovery step length or average speed, and the CoM momentum of participants at step initiation. Both step length and average speed during the considered dense groups experiment show mainly lower value for a given CoM momentum than the regression created using FS stepping strategies during the single individuals experiment (see Fig. 3.12.a-b). The relation between the first recovery step length and average velocity, in Fig. 3.12.c, is close to the one observed during the single individuals experiment when participants used an FS stepping strategy. However, the lower p-value of the Shapiro Test (see Section 3.2.4), indicates that the residuals are not normally distributed suggesting that data may not follow a strict linear model. Regarding the step deviation angle, we observed in Fig. 3.12.(d) a more dispersed data repartition than what was observed for the single individuals experiment. Unlike the observations made for the single individuals experiment (see Figs. 3.10 and 3.11), here the deviation angle does not seem to decrease as the CoM momentum of participants increased. This can also be seen through the high standard deviation in Section 3.2.4.

		Intercept	Coef.	$R^2$	RMSE	p-value Shapiro–Wilk test (residuals)
x: Step Length y: CoM Momentum (Fig. 3.12.a)	Single Individuals (FS)	$6.95e - 2$	$6.24e - 3$	0.624	$3.50e - 3$	$2.67e - 2$
	Dense Groups	$8.65e - 2$	$2.17e - 3$	0.202	$8.40e - 3$	$3.54e - 3$
x: Step Avg. Speed y: CoM Momentum (Fig. 3.12.b)	Single Individuals (FS)	0.537	$3.22e - 2$	0.726	$5.86e - 2$	0.478
	Dense Groups	0.517	$1.60e - 2$	0.38	0.190	0.98
x: Step Avg. Speed y: Step Length (Fig. 3.12.c)	Single Individuals (FS)	0.482	4.00	0.699	$6.44e - 2$	$8.23e - 2$
	Dense Groups	0.410	4.43	0.677	$9.87e - 2$	$4.46e - 3$

Table 3.4 – Characteristics of the linear regressions between the first recovery step length and average speed relative to the CoM momentum at step initiation. Regressions based on the observation from the dense groups experiment and on *Forward Steps* (FS) observed during the single individuals experiment (also presented in Section 2.3.2.3) are compared in this table.

	Median (deg)	Standard Deviation (deg)	Number of Values
Single Individuals (Fig. 3.10)	$8.50e - 2$	10.1	226
Dense Groups (Fig. 3.11)	-3.00	22.2	221

Table 3.5 – Summary of the step deviation angle median and standard deviation values. Observation from the dense groups experiment and on the single individuals experiment (also presented in Table A.4) are compared in this table.

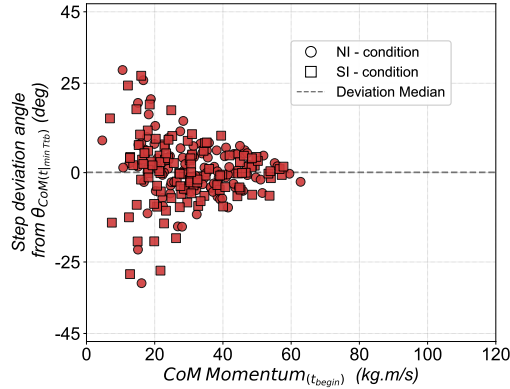


Figure 3.10 – Representation of the step deviation of a single individual after the *Forward Step* recovery strategy compared to the CoM momentum at the step. This figure is a zoomed-in representation of the results shown in Fig. 2.21.

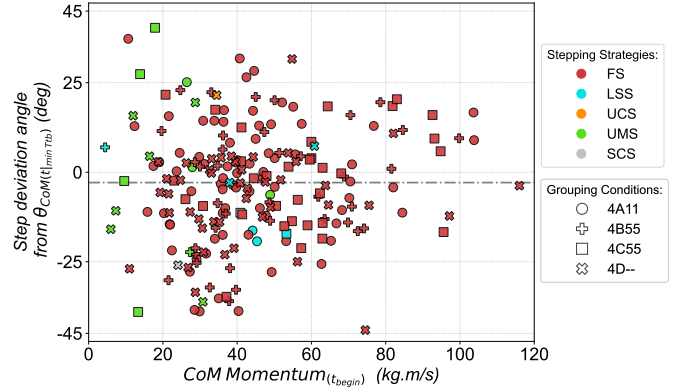


Figure 3.11 – Representation of the step deviation angle of participants during the dense groups experiment compared to the CoM momentum at step initiation. This figure is a zoomed-in representation of the results shown in Fig. 3.12.c with markers colored by stepping recovery strategy (labeled using the *Unified* classification).

### 3.2.5 Hands Raising and Step Initiation

Here we compare trials for which participants used a stepping recovery strategy and raised their hands in preparation to physical interactions with neighbours. We can see in Fig. 3.13 that for most of these trials we observe a positive delay between the moment of hand raising initiation and the moment of step initiation ( $t_{begin}$ ). This indicates that hand raising occurred in majority before step initiation. However, we can also observe that this delay can also be negative. For trials with negative delay, steps were initiated before hand raising. This happened especially when the CoM momentum of participants at the initiation of the hand raising was above  $10 \text{ kg.m/s}$  and seems to be more pronounced as the CoM momentum increases. Eventually, one should note that hand raising behaviour was only observed in a large minority of trials involving stepping recovery strategy, i.e. 100 trials out of 221. In the other trials where only a stepping recovery strategy was used, participants' hands seemed to remain in a lower position.

Median and standard deviation of the delay between hand raising and step initiation can be found as well as the number of considered trials in this study in Section 3.2.5.



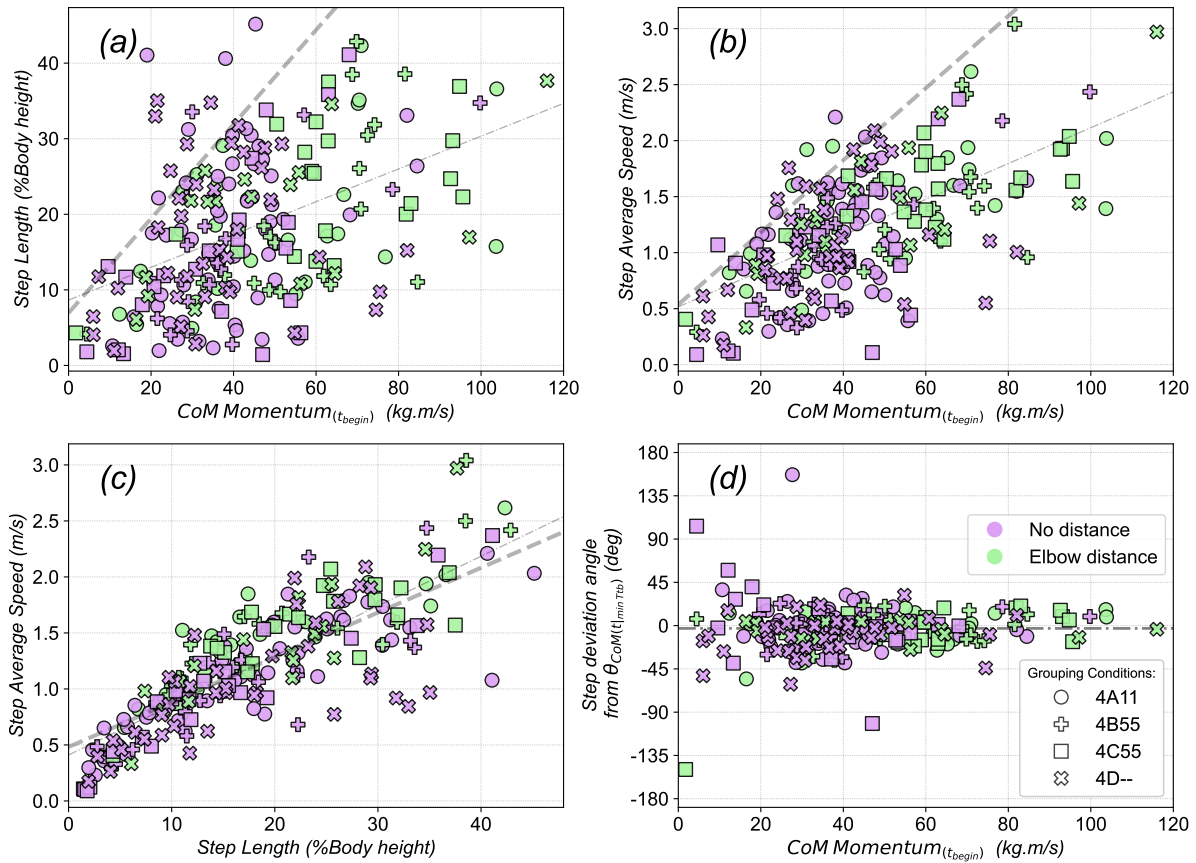


Figure 3.12 – (a) Representation of the first recovery step length compared to the CoM momentum at step initiation. (b) Representation of the average speed of the foot during first recovery step compared to the CoM momentum at step initiation. (c) Representation of the average speed of the foot during first recovery step compared to the step length. (d) Representation of the step deviation angle compared to the CoM momentum at step initiation. Markers are coloured by experimental interpersonal distancing (*No Distance* or *Elbow Distance*) and shaped according to the grouping condition of considered trials. The broad dashed lines represent the linear regressions on FS recovery strategies created using the single individuals experiment (see Section 2.3.2.3). The thin dash and dot lines in (a), (b) and (c) represent the linear regressions based on the dense groups experiment. The dash and dot line in (d) represents the median of the step deviation angle repartition at  $-2.90\text{ deg}$ .

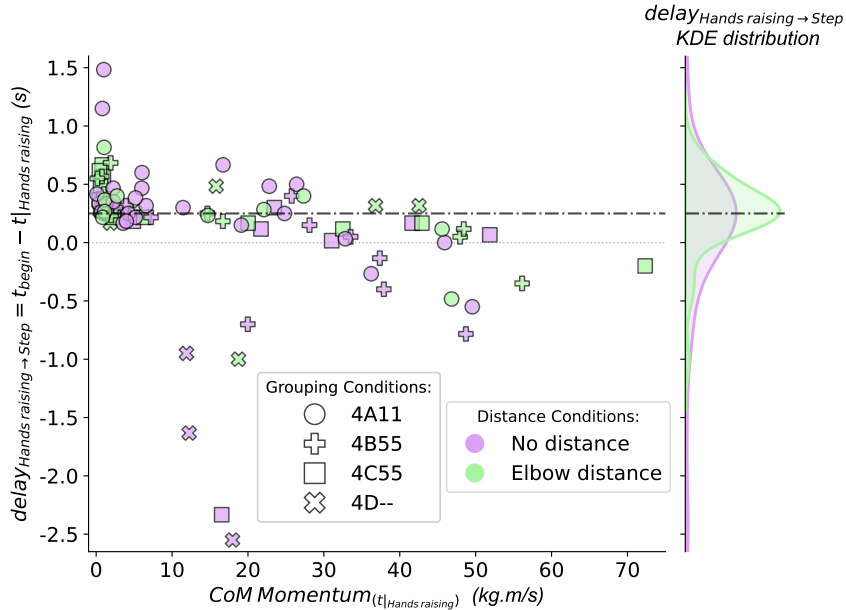


Figure 3.13 – Distribution of the delay between the moments of hand raising initiation and step initiation compared to the CoM momentum at the moment of hand raising initiation. Data are colored by experimental distancing condition. A positive delay reveals that hand raising occurred before step initiation. A *Kernel Density Estimation* (KDE) representation of the delay distribution is displayed in the right-hand margin. The black dash and dot line corresponds to the overall median of the delay distribution.

	Median (s)	Standard Deviation (s)	Number of Values
Elbow Distance	0.27	0.37	47
No Distance	0.22	0.73	53
Overall	0.25	0.59	100

Table 3.6 – Summary of the medians and standard deviations of the delay between hand raising and step initiation of the participants who used both strategies. Results are given for each experimental distancing condition as well as for the overall observations.

### 3.3 Discussions

#### Estimated Angles of Perturbation

We have seen in Fig. 3.7, that most perturbation direction for trials involving stepping recovery strategies were estimated to occur in the back of participants and close to the sagittal plane. This observation is in agreement with the experimental protocol. However, the accuracy of this estimation is highly uncertain for trials in which recov-

ery was achieved without stepping. For these trials a wide range of perturbation angles were estimated, with many of these angles being at the opposite to the experimental perturbation direction. This phenomenon was also observed during the single individuals experiment (see Fig. 2.15) and is due to a minimal Ttb different from the critical Ttb experienced following the perturbation. In the light of these findings, it can be suggested that different approaches should be used to estimate the direction of the external perturbation, depending on the recovery strategy used by participants to recover from the perturbations.

## **Distancing Conditions and Density**

Two experimental distancing conditions were studied during this dense group experiment, the *No Distance* condition and the *Elbow Distance* condition. We have seen in Fig. 3.8 that both distancing conditions corresponded to different ranges of interpersonal distances with the up-front neighbours. These ranges of interpersonal distances were associated with different density level during the experiments. Density levels were comparable to the one observed during events leading to deadly crowd accidents [Rahman et al., 2017; Sieben and Seyfried, 2023].

One can also see that density estimation also depends on the method used. For the line formation (4A11) a 1D method have been used to estimate density, this method results in lower density estimations than the Voronoi Density used for the other group formations regardless of the actual interpersonal distance with the direct neighbours.

## **Limit of Standing Balance in Dense Groups**

The limit of Standing balance was studied here using the minimal Ttb of participants during a considered trial. However, one may question this method as more complex *change-in-support* may be used by participants in this context, such as contacts with other individuals using their arms and upper body.

The Ttb corresponds to the time needed by the CoM to exit the BoS at given its current velocity. The moment when the minimal value of this metric is reached can be associated with the moment for which standing balance is in the most critical situation. During this experiment, we observed that 95% of the stepping recovery strategies were initiated at the moment of minimal Ttb. In other words, the majority of participants were initiating stepping strategies as their body was in the most unstable position. This means

that other *change-in-support* which could be used by participants had a limited effect on the Ttb. Thus, other possible *change-in-support*, such as upper body contacts, did not fully prevent critically unbalanced situations for which stepping strategies were initiated. In the light of this observation, we considered that the *Limit of Standing Balance* could then still be defined as the limit after which stepping recovery strategies were used by participants to regain balance.

Trials for which stepping recovery strategies were initiated after the minimal recorded Ttb correspond to situations where participants step several seconds after the perturbation. For these trials, step initiation seemed not to result from a necessary *change-in-support* to maintain balance but were rather used by participants to reposition themselves relative to the other participants after the perturbation. For some trials, the difference between the moment of minimal Ttb and moment of step initiation was only different by less than a few recorded frames. In this situation the step detection method may have detected the motion of the step slightly later than the actual step motion initiation leading to a minor increase of the distance between the CoM and the BoS and an augmentation of the Ttb before step detection.

Regarding the effect of the experimental distancing conditions, we observed that the separation between recovery with and without steps for the *No Distance* condition was the same as the limit obtained during the single individuals experiment. However, the accuracy of the separation model in this dense groups experiment is lower than the one created with single individuals experiments due to recovery strategies with lower and negative values of Ttb. We also observed that separation boundary of the logistic model was significantly higher when looking at the *Elbow* distancing condition (see Table 3.3). This suggests that participants reacted with stepping strategies for less critically unbalanced postures i.e. with higher values of minimal Ttb. One possible explanation of this phenomenon may be linked to the social dimension of the situation. Participants may indeed try to use more effective recovery strategy (i.e. stepping strategies), even at higher level of standing balance, in order to prevent or reduce physical interactions with other participants. This would explain why the *Limit of Standing Balance* is similar between groups with *No Distance* and single individuals, as in both case social rules did not apply (either due to already existing contacts or complete absence of possible contacts). Deeper investigation on that matter should however be conducted to draw any further conclusions.

Non-stepping recovery strategies with low and negative minimal Ttb are also an interesting feature of Fig. 3.9. Such balance recovery is not possible for single individuals since

a negative Ttb indicates that the CoM's ground projection is outside the BoS. Having a CoM's ground projection outside the BoS is a critical situation for which standing balance cannot be regained without using a *change-in-support*. In these situations, the main *change-in-support* is made through contacts with the neighbours and not by the use of steps, as we observed in the majority of trials with minimal Ttb beyond the model limit. This recovery strategy was only observed in a very limited number of trials, but such behaviour could lead to dangerous situations. Leaning on others can increase the static load on the front participants, causing physical discomfort and anxiety. In the worst possible scenario, this may lead to collective falls and asphyxiation if the loaded participants are unable to step out of the situation [Rahman et al., 2017; Wang et al., 2019; Sieben and Seyfried, 2023]. Further investigation of interpersonal contact is needed to better understand the role of physical interactions for balance recovery in this context.

## First Recovery Step Characteristics in Dense Groups

Regarding first recovery step characteristics no visible effect due to the distancing condition have been observed in Fig. 3.12. However, some major differences were observed in comparison with the single individuals experiment.

In particular, step length and average speed of participants in dense groups appeared to be lower than those observed in the individual experiments for a given CoM momentum at step initiation. This effect is likely to be associated with multiple factors relative to densely populated environments. The most significant differences between single individual situations and densely packed situations are the additional support provided by contacts (using hands or the upper body), the constrained available stepping area as well as limited visibility of the ground.

Smaller steps in dense crowds seem to prevail over the larger steps linearly correlated with the CoM momentum, as observed during the single individuals experiment. However, the average speed and the length of the first recovery steps seem to follow similar linear relationships in all experiments.

Another hint of the lack of available area to perform step recovery in dense groups is shown in Figs. 3.10 and 3.11. One can see that the distribution of the deviation angles during the dense groups experiment is more scattered than the one observed during the single individuals experiment. Moreover, this dispersion does not seem to decrease as the CoM increases, as it was observed during the single individuals experiment.

All of this seems to indicate that in the dense groups experiment, recovery steps were

not placed in the most convenient position for the participants, but rather on the close available area of the floor.

## **Hands raising and Step initiation**

When both hand raising and stepping recovery strategies were triggered during a trial, we observed that the hand raising seemed to be initiated before the stepping strategy (see Fig. 3.13). The median delay between hand raising and step initiation is of the same order of magnitude than the typical reaction time of young adults, i.e. from 0.18 s to 0.3 s for reactions to haptic or visual stimuli [Peon and Prattichizzo, 2013; Jain et al., 2015]. However, hand raising was only observed in 45% of the trials where participants used stepping recovery strategies. In the other trials hands seemed to be kept in a lower position. Therefore, hand raising behaviour was not systematic during balance recovery in this studied context. Nevertheless, this behaviour was observed in many recordings and thus may have a beneficial effect on participants' balance recovery in this densely populated environment.

This behaviour may be related to a more social aspect of balance recovery in this situation. Raising the hand is a limited intrusion into another participant's personal space (up to the point of physical contact), compared to stepping strategies that involve the motion of the whole body. In addition, raising the hands is also a way of ensuring that the potential physical contact with the up-front participants is done in a controlled manner using the arms to damp the perturbation. This creates a gradual loading on the up-front neighbours, allowing them to brace for the perturbation before it reaches its maximal intensity. In other words, having the hands up may allow individuals to touch their neighbours before reaching a maximal momentum and thus to propagate the information about the upcoming perturbation faster than the induced momentum propagation. All these discussions are only assumptions based upon observations and more investigations are required to draw any strong conclusions.

## **Limitations**

The proposed study also comes with limits that have to be acknowledged in order to fully grasp the context of validity of the previous results.

First, the motion recording technique used in this dense group experiment is different from the one used in the single individuals experiment. Here a commercial IMMU-based

solution was used. This enabled the recording of motion in dense group which could not have been done otherwise. However, this method only provides estimations of the limb positions and these estimations cannot be directly compared with ground truth motion. This reconstruction may induce a lower accuracy regarding the positions of the limbs, as raw sensor data have to be integrated for reconstruction purposes [Robert-Lachaine et al., 2017]. In such context, we observed a few unrealistic BoS for which both reconstructed heel positions were partly overlapping at rest. These observations indicate that the actual BoS limits may be different from the reconstructed recordings. The reconstruction error may however have a limited impact on the computation of the Ttb here. Most of the step detected here are labeled as *Forward Step*. Hence, the CoM crossed the front boundary of the BoS. The position of this boundary is governed by the feet length and direction. As feet lengths is a parameter of the reconstruction model and the directions of the feet showed no particular reconstruction artifacts, one can assume that the location of this boundary is close to the actual BoS of participants.

In addition, a biomechanical model was fitted on these reconstructed recordings in order to compute biomechanical quantities such as the CoM. The accumulation of models may result in a reduced accuracy due to the accumulation of estimations. However, further investigations are required to understand the effects of these errors on the presented results.

Eventually, regarding the hand raising behaviour, participants seemed to raise their hands in preparation for physical interactions. However, the method only provides information about the movement of the hands. We cannot know if a contact actually happened and when it happened following the hand were raised. Contact may also have already occurred at the moment the hand raising was initiated. New investigations regarding interpersonal contacts are required for further conclusions on this matter.

## 3.4 Chapter Conclusion

In this chapter, the reaction of young individuals in dense group formations was studied following force controlled perturbations. The participants' recovery in this context was compared with the observations and different models obtained in the study of the reaction of single individuals to external force-controlled perturbations (Chapter 2).

In particular, we saw that the *Limit of Standing Balance* obtained using the minimal value of the *Time to boundary* in the context of dense group formations remains close to

the one observed during the single individuals experiment when participants were asked to stand next to their neighbour without any interpersonal distance. When standing within an *Elbow* length of their neighbours, participants initiated stepping strategies for less critical situations i.e. higher values of minimal *Time to boundary*.

Most participants of the dense groups experiment reacted with Forward Steps to the anteroposterior perturbation. This was also observed during the single individuals experiment. Characteristics of the first recovery steps did not follow linear relationships with the *Center of Mass* momentum as this was observed for the single individuals experiment. However, the relationship between the length and the average speed of the first recovery step seems to remain similar between all experiments. In addition, for recovery in dense groups, the first recovery step direction seems to deviate more from the estimated perturbation direction. Step characteristics remained unchanged with respect to the experimental interpersonal distancing conditions studied here.

Eventually, external perturbations in dense groups involved physical interactions between participants. This was visible through the leaning strategies which involved lower and negative minimal values of *Time to boundaries* that were not followed by stepping recovery strategies. We also observed that some participants seemed to react by first raising their hands before initiating stepping strategies following external perturbations.

This experimental dataset can be used to further investigate balance recovery strategies in dense crowds. For example, by combining motion capture recordings and head trajectories. This method has been proposed by Feldmann and Adrian [2023] and may lead to further insights on recovery strategies in dense crowds situations. In particular, relative foot placement may be investigated using this method.

The observation and conclusions proposed in this study will be further discussed in the next chapter in the light of experimental results obtained following motion recordings of participants within punk rock music concert crowds.





# STUDYING RECOVERY STRATEGIES IN PUNK ROCK CONCERT CROWDS: A PROOF OF CONCEPT

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In Chapters 2 and 3 of this thesis we studied two laboratory experiments regarding standing balance following external perturbations. These experiments involved either single individuals or groups of individuals in different pre-defined formations. In this last chapter we focused on a field experiment we conducted to study the recovery strategies of individuals in real human crowds. This proof of concept resulted from a new experimental paradigm, deployed within punk rock concert crowds.

Following this experiment, we studied the direction of the perturbations associated to physical interactions in this context, together with the resulting stepping recovery strategies used. Models created using the single individuals experience about the *Limit of Standing Balance* and stepping strategies prediction, were then compared to the recordings obtained in concert crowds. The characteristics of participants' first recovery steps during this concert crowds experiment were also analysed. The observations made during these field experiments were compared to the results of the other experiments investigated in the frame of this thesis, namely the single individuals experience (see Chapter 2) and the dense groups experiment (see Chapter 3).

After a detailed overview of the context of this experiment, the nature of the data collected and the general methods used, the following scientific questions are addressed in their respective sections.

- What were the main recovery strategies used by participants to maintain their standing balance following physical interactions in this concert crowd context? (Sections 4.2.1 and 4.2.4)
- To what extent can the models developed with the study of single individuals can

be used to model the recovery behaviours of individuals in dense human crowds? (Sections 4.2.2 and 4.2.3)

- What are the similarities and differences between first recovery steps of participants in concert crowds and the recovery steps previously studied in the frame of this thesis? (Section 4.2.4)

Elements of discussion and conclusions regarding this study are proposed at the end of this chapter.

## 4.1 Material and Methods

### 4.1.1 Experimental Context

The experiment described in this chapter took place during the 2023 edition of the *Hellfest* festival. This Open-Air rock-metal music festival is held every year in Clisson (France) in a dedicated venue including 6 stages over 100,000  $m^2$  [Geoportail, 2023]. This edition was attended by 60,000 people per day over the 4 days of the festival with additional 5,000 volunteers each day (numbers from festival organisers' declarations).

Apart from the two main stages, the other stages of the festival are dedicated to different sub-genres of rock music. The experiments presented here were carried out in the crowds which formed in front of the “Warzone” stage of the festival (see Fig. 4.1). This stage mainly hosts artists and bands that fall under the punk rock or punk hardcore music style. Metal music together with punk music concerts are often associated with specific dances such as “moshing” (or “Slamming”) [Tsitsos, 1999]. This type of dance involves physical interactions in the form of disorganised pushing of neighbouring individuals with the arms or upper parts of the body. “Moshers” are dancing in an area called a “pit” in which physical interactions, often extremely strong, are socially accepted [Tsitsos, 1999] (see Fig. 4.3). We took advantage of this context in our experiments which relied on the diverse range of possible external perturbations one can experience in this type of crowd.

The “pits” in which the experiments were performed were located in the middle of the stage and between 1  $m$  and 10  $m$  from the barriers separating the audience from the stage. The participants together with the other attendees stood on a paved solid and dry ground. The floor was considered to be locally flat as no visible elevation was detected between the front and the rear of the area where the experiments occurred.

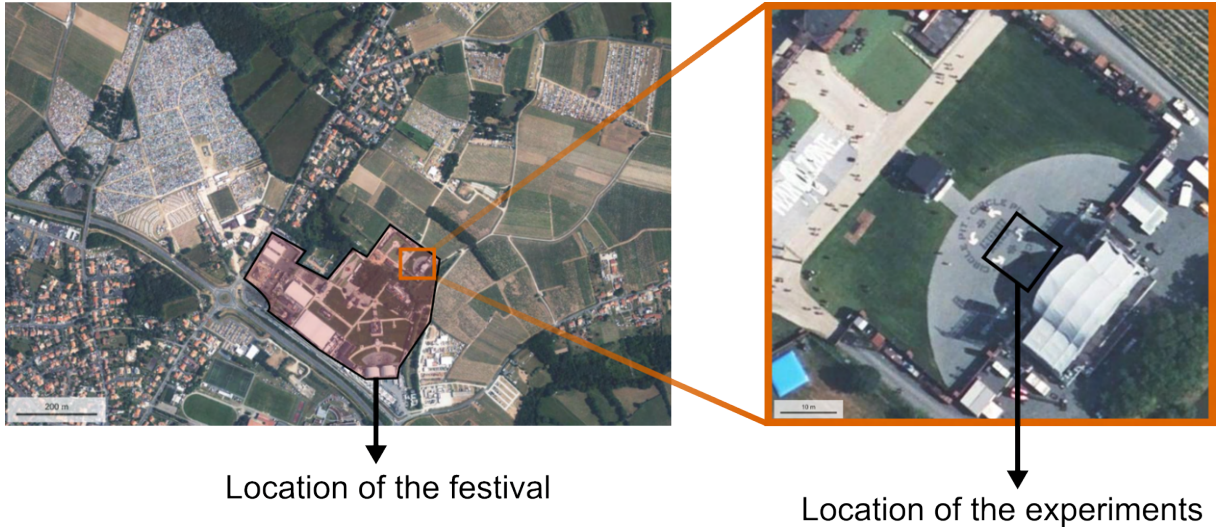


Figure 4.1 – Aerial view of the festival site taken on the 17.06.2022 during the 2022 edition of the festival. A zoomed-in view of the “Warzone” stage is shown on the right-hand side. Both images have been extracted from Geoportail [2023].

#### 4.1.2 Experimental Data Collection

This experiment received an ethical approval from the local INRIA “Comité Opérationnel d’Évaluation des Risques Légaux et Éthiques” on the 7<sup>th</sup> of June 2023 (approval number: 2023-22).

The body motion of three participants, later referred to as participants 1, 2 and 3, were recorded over two concerts happening during two consecutive days. Participants 1 and 2 took part in the crowd for the concert of *Cockney Rejects* starting at 16:40 on the 16<sup>th</sup> of June. Of the next day, participants 1 and 3 were immersed in the crowd during the concert of *Soul Glo* starting at 16:50. The recordings were performed during the entire set (45 to 50 minutes), with participants deciding when to enter the “pit” or to take a break. Each participant was followed by an additional experimenter who stayed within eyesight and could reach the participant for technical support or emergency. All three participants signed an informed consent form relative to the processing of their data.

Participants were asked to stand still and in balance in a location of their choosing until they lose balance due to external perturbations. The experimental protocol was self-initiated by the participants: a trial began when the participant is ready and in balance. This was indicated on the recording by a single clap of the participant’s hand. Participants were explicitly asked to use a foot stance no wider than their hips at the beginning of the trial. They were also asked not to move their feet after the beginning of the trial unless they

needed to step in order to recover from perturbations. This protocol consists of controlled and standardised initial postures followed by uncontrollable and disorganised physical interactions which caused perturbations in the participants' initial standing balance. This hybrid method enabled us to compare the recording of participants reactions in this real crowd context with the other experiments investigated in this thesis.

Full-body motion was recorded using the Xsens suits (MVN Links, 240 Hz). This IMMU-based motion capture technique is the same as the one used during dense groups experiment presented in Section 3.1.2.2. The calibrations protocols of the system were performed before and after the experiment in order to be able to accurately reconstruct body motion and minimise the effect of potential sensor displacement during the experiments. The data were then reconstructed using the Xsens MVN 2020.2 software and the quality was assessed using the software's calibration quality estimator and based on visual inspection. Parts of participant 1's recording during the first day of the experiment were discarded due to poor reconstruction quality. In particular, a twisted reconstructed spin was observed probably due to a large shift of the pelvic sensor over time.

Trials were manually retrieved from the recording by selecting sections after participants' hand clapping. The trial ended after the participants had used a recovery strategy to address the perturbation that led to the loss of standing balance. The analysis of the data was then based on virtual markers created by the Xsens MVN 2020.2 software. These markers are reconstructed anatomical landmarks determined by the relative position of IMMUs in the suit and the body measurements of each participant's limbs. The virtual reconstructed markers used here are comparable to the one used in Section 2.1.2.1.

In addition to the motion capture, bird's-eye view videos of the concert crowds were also captured (see Figs. 4.2 and 4.3). These videos were not analysed in the frame of this work but could serve several future research purposes such as density estimation or head trajectory tracking using a method similar to the one proposed by Sundararaman et al. [2021].

### 4.1.3 Post-Processing and Analysis

The methods presented in Chapters 2 and 3 were used to analyse the present experimental data.

- Biomechanical quantities such as the position of the participants' CoM was computed based on the method exposed in Section 2.1.2.1 and using anthropometric



Figure 4.2 – One of the participants joining the crowd before the beginning of a concert. The motion-capture suit was covered by large clothes. High visibility hats were worn by participants in order to easily detect on the recorded bird’s-eye view videos.

parameters provided in Table 4.1.

- Step detection was performed using the method proposed in Section 2.1.2.2. Recovery strategies are labelled in this chapter using the *Unified* recovery strategy classification created in Section 2.3.1.1. In particular, crossover steps were assessed based on the criterion formulated in Section 3.1.2.3.
- Separation models based on logistic regressions over the present dataset were created using methods presented in Sections 2.2.1 and 2.3.1.3.

A new region containing trials in which *Backward Steps* (BS) was delimited and added to the separation model proposed in Section 2.3.2.2. The separation was created between trials for which a BS strategy was used and all trials with other stepping recovery strategies. The boundaries of the region were defined using logistic regressions over the estimated



Figure 4.3 – Bird’s-eye view video recordings of a concert crowd in front of the “Warzone” stage of the Hellfest festival. A participant wearing a motion capture suit is visible in the orange rectangle in the right-hand image.

angles of perturbation.

The efficiency of the final separation model for stepping recovery strategies was assessed by the evaluation of the number of trials with expected stepping strategy (labelled using the *Unified* classification proposed in Section 2.3.1.1) in each region of the separation model and by the evaluation of the number of trials within the expected region for each stepping strategy (labelled using the *Unified* classification). These evaluations were performed using an *Expectation Rates* defined as the number of expected values over the total number of observations.

Gender	Mass (kg)	Height (m)	age (yo)
Male	77	1.74	22
Male	72	1.84	23
Female	62	1.74	37

Table 4.1 – Demographic and anthropometric details of the three participants who performed the experiments.

## 4.2 Results

A total of 147 trials were analysed during these experiments. Twenty-five of the trials recorded for participant 1 during the first concert, and all 48 trials captured during the second concert were kept for this study. Participants 2 and 3 performed 42 and 32 trials



respectively during the concerts they attended. The numbers of recovery strategies labelled using the *Unified* recovery strategy classification created in Section 2.3.1.1 are presented in Table 4.2.

Strategy	Number of Trials with Corresponding Strategy		
	Participant 1	Participant 2	Participant 3
<i>No Step</i> (NS)	1	-	1
<i>Sub-Critical Step</i> (SCS)	1	2	3
<i>Forward Step</i> (FS)	28	20	18
<i>Backward Step</i> (BS)	13	10	3
Positive - <i>Loaded Side Step</i> (LSS)	6	2	3
Positive - <i>Unloaded Medial Step</i> (UMS)	6	1	-
Positive - <i>Unloaded Crossover Step</i> (UCS)	4	3	1
Negative - <i>Loaded Side Step</i> (LSS)	2	1	1
Negative - <i>Unloaded Medial Step</i> (UMS)	4	2	1
Negative - <i>Unloaded Crossover Step</i> (UCS)	8	1	1
Total	73	42	32

Table 4.2 – Number of each recovery strategy observed during the concert experiments for each participant. Recovery strategies are labelled using the *Unified* classification method proposed in Section 2.3.1.1. *Side Step* recovery strategies, i.e. LSS, UMS, UCS, are separated between the reaction following external perturbation with *Positive* estimated angles and reaction following external perturbation with *Negative* estimated angles.

### 4.2.1 Estimated Perturbation Angles

One can see in Fig. 4.4 that perturbations were estimated as arising from every potential direction during the experiments. We observed that 55 or the 147 recorded trial, i.e. 37%, occurred within a limited range of perturbation angles between  $-30\text{ deg}$  and  $30\text{ deg}$  (close to the posterior direction). However, the rest of the perturbations are spread over the whole spectrum of possible angles.

### 4.2.2 Stepping Recovery Strategy Separation

In Fig. 4.5 stepping strategies observed during the concert crowds experiment are compared to the separation model for stepping strategies based on the estimated angle of perturbation and the *Distance to Foot Boundary* (DtFb) using the data acquired during the single individuals experiment (see Section 2.3.2.2). Due to the large variety of



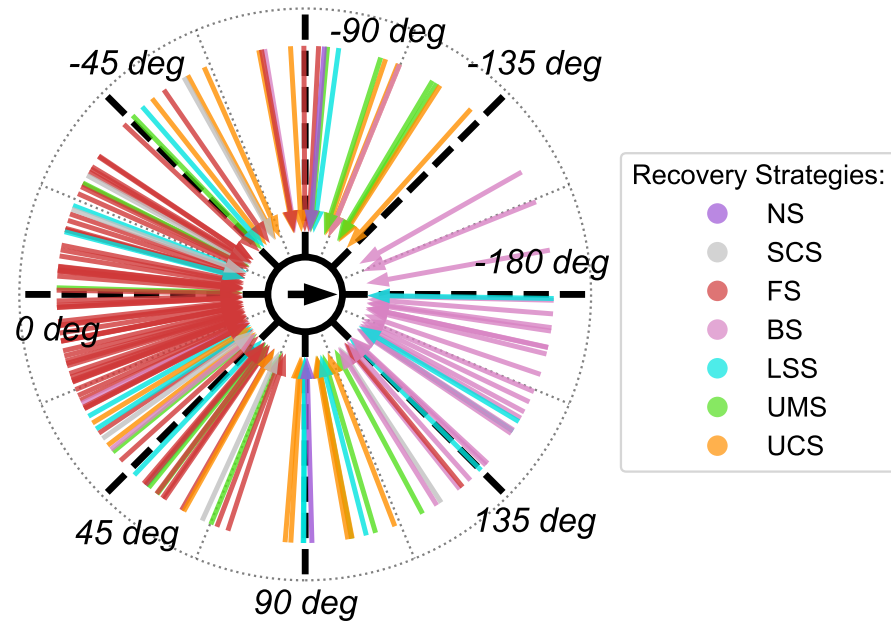


Figure 4.4 – Representation of the estimated angle of perturbation, i.e. angle between the sagittal plane and the direction of the CoM velocity at the moment of minimal Ttb (method in Section 2.3.1.2). Arrows representing the perturbation directions are coloured by recovery strategies, labelled following the *Unified* classification method proposed in Section 2.3.1.1.

perturbation directions, a stepping strategy classified as *Backward Step* was used in 26 of the 147 recorded trials. Based on these data, we created logistic separation models to create an additional cluster containing this recovery strategy. The *Centered - Backward Step* (C-BS) region was defined to contain trials involving a stepping recovery strategy following perturbation with an angle greater than  $122.8 \text{ deg}$  or lower than  $-131.8 \text{ deg}$ . Characteristics of the logistic separations between BS trials and the other trials are given in Table 4.3

One can see in Table 4.4 that, except for the N-LS and the P-LS, all the regions are populated by more than 77% of the expected stepping strategies. Regarding stepping recovery strategies, over 68% of every category of stepping strategies are located in the expected region, except for the LSS strategies (see Table 4.5).

Estimated Perturbation Angles	Logistic Separation for C-BS			
	DB (deg)	Accuracy (%)	Sensitivity (%)	Specificity (%)
Positive Angles	122.8	88	92	85
Negative Angles	-131.8	96	92	100

Table 4.3 – Characteristics of the logistic regressions used to create the separation of the C-BS region visible in Fig. 4.5.

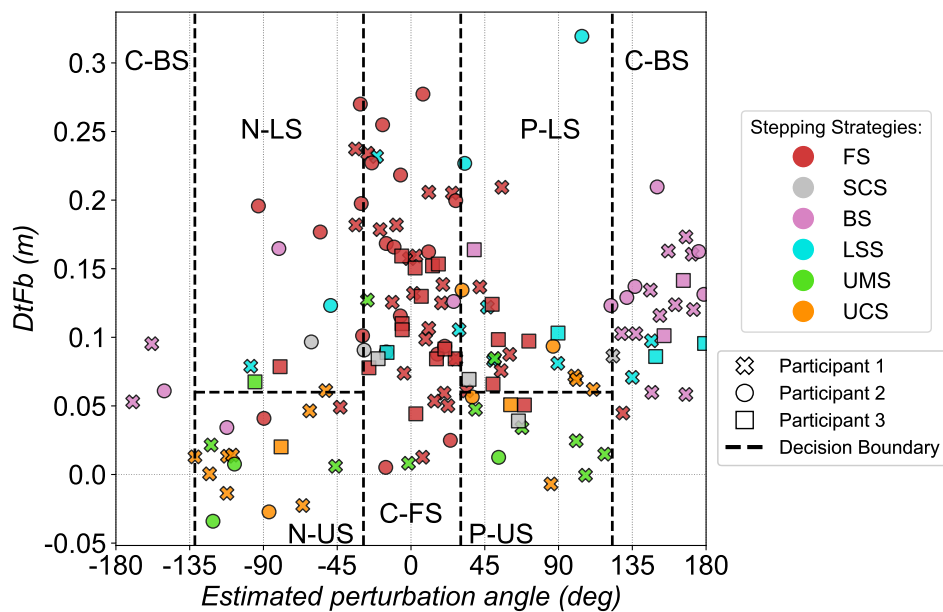


Figure 4.5 – Representation of the separation model of stepping recovery strategies using the estimated angle of perturbation and the *Distance to Foot boundary* (DtFb).

Rate of Trials of Expected Stepping Strategy in Each Region					
Region	Expected Strategy	Total in Region	Expected	Incorrect	Expectation Rate (%)
N-US	UMS/UCS	16	13	3	81
N-LS	LSS	14	2	12	14
C-FS	FS	53	45	8	85
P-LS	LSS	24	6	18	25
P-US	UMS/UCS	11	9	2	82
C-BS	BS	27	21	6	78

Table 4.4 – Count and rate of the expected stepping strategies for each stepping strategy regions. The Expectation Rate here corresponds to the number of trials with the expected stepping strategy divided by the total number of trials in the region.

Rate of Trials in Expected Regions for Each Stepping Strategy					
Strategy	Expected Region	Total Trials per Strategy	Expected	Incorrect	Expectation Rate (%)
UMS/UCS	N-US/P-US	32	22	10	69
LSS	N-LS/P-LS	15	8	7	53
FS	C-FS	66	45	21	68
BS	C-BS	26	21	5	81

Table 4.5 – Count and rate of the trials expected in the expected regions for each stepping recovery strategy. The Expectation Rate here corresponds to the number of trials in the expected cluster divided by the total number of trials for which the stepping strategy was used.

### 4.2.3 Step Initiation and Limit of Standing Balance

In this section, the limit of standing balance is assessed using the minimal Ttb during trials (observed before step initiation for trials in which recovery steps were taken). Unlike in the previous studies, no separation model between trials with and without steps were created as only two trials with recovery strategy not involving steps were retrieved from the experimental data. Trials from the present experiment were, however, compared in Fig. 4.6 with separation models created using the single individuals experiment (Chapter 2). One should also note that the moment of step initiation was detected less than 25 frames (i.e., less than 0.1 s) after the moment of minimal Ttb for 90%, i.e., 130 out of the 145 recorded trials involving stepping recovery strategies. In 123 trials, i.e., 85% of the trials involving stepping recovery strategies the moment of minimal Ttb corresponded with the moment of step initiation detection. Step initiation was detected more than a second after the moment of minimal Ttb in only 4 of the trials involving stepping recovery trajectories.

The models selected for this comparison are the one presented in Section 2.3.2.2 which are associated with:

- The N-LS and N-US regions, i.e. the regions of the separation model containing LSS or UMS and UCS strategies following perturbations with negative angles.
- The C-FS regions, i.e. the region of the separation model containing the FS strategy.
- The P-LS and P-US regions, i.e. the regions of the separation model containing LSS or UMS and UCS strategies following perturbations with negative angles.

In particular, out of the 66 trials for which a stepping strategy labelled as FS was used, 60 (i.e. 91%) are under the decision boundary of the separation model between stepping a non-stepping recovery strategy for the C-FS region (see Section 2.3.2.2). One can see that

the larger decision boundary of the separation model created based on the observations of the dense group experiment with *Elbow Distance* between participants include slightly more trial, with 94% of the FS trials below the boundary.

Similarly, 94% of all the minimal values of Ttb observed before step initiation fall under the highest separation boundary of the separation models created based on single individuals reactions (see Section 2.3.2.2).

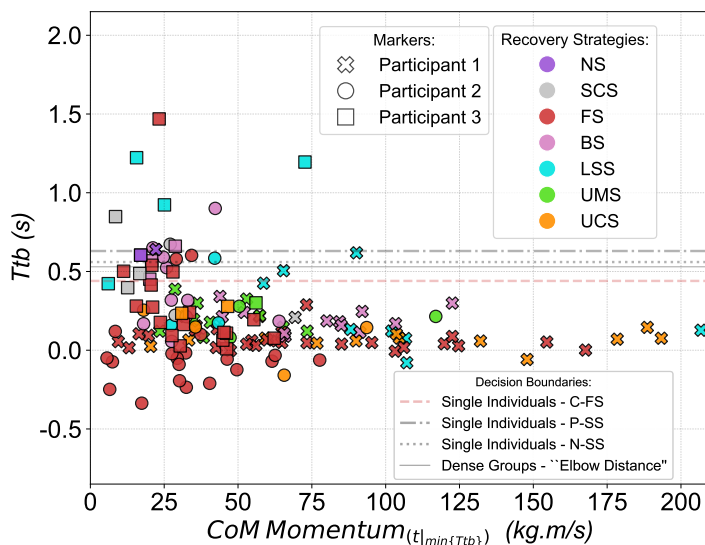


Figure 4.6 – Distribution of participants’ minimal *Time to Boundary* (Ttb) compared to their CoM momentum. The thick and red dashed line represents the decision boundary of the separation models between trials with and without steps created on the central region of recovery strategies (C-FS) observed during the single individuals experiment (Section 2.3.2.2). In this region, *Forward Step* strategies were more likely to be used. The black dashed and dotted line and the dotted lines represent the decision boundaries of the separation models between trials with and without steps respectively created on the positive (P-SS) and negative (N-SS) lateral regions of recovery strategies observed during the single individuals experiment Section 2.3.2.2. In these regions *Side Step* strategies (i.e. LSS, UMS or UCS) were more likely to be used. The thin solid line represents the decision boundary of the separation model based on observations during the dens groups experiments with the *Elbow Distance* condition. Markers are coloured by recovery strategy based on the *Unified* classification method.

#### 4.2.4 First Recovery Step Characteristics

The characteristics of the first recovery steps taken by the participants during the concert crowds experiment are represented in Figs. 4.7 to 4.9. As for the dense groups

experiment presented in Chapter 3, the first step characteristics are compared with the regression model created after the single individuals experiment dataset (see Section 2.3.2.3).

We can see in Figs. 4.7 to 4.9 -(a) that smaller first recovery steps were used for a given CoM momentum compared to what was observed during the single individuals experiment. The relationships between the CoM momentum and the average speed of the first recovery step seems to be close to the one observed during the single individuals experiment, especially for FS and US (i.e. UCS, UMS) strategies (see Figs. 4.7 to 4.9 -(b)). Eventually, we can see in Figs. 4.7 to 4.9 -(c) that the first recovery steps were taken faster than during the single individuals experiment. This is particularly visible for participant 1 who appeared to use faster recovery steps than the other participants.

Regarding the step deviation angles, a trend similar to the one observed during the dense groups experiment (Chapter 3) is visible in Fig. 4.10. We observe here a diminution of the deviation angle as the CoM momentum increases until  $40 \text{ kg.m/s}$ . Beyond this limit, the deviation angles of the first recovery steps are bounded between  $-45 \text{ deg}$  and  $45 \text{ deg}$ . The observed median here is  $0.91 \text{ deg}$ , with a standard deviation of  $39.3 \text{ deg}$ .

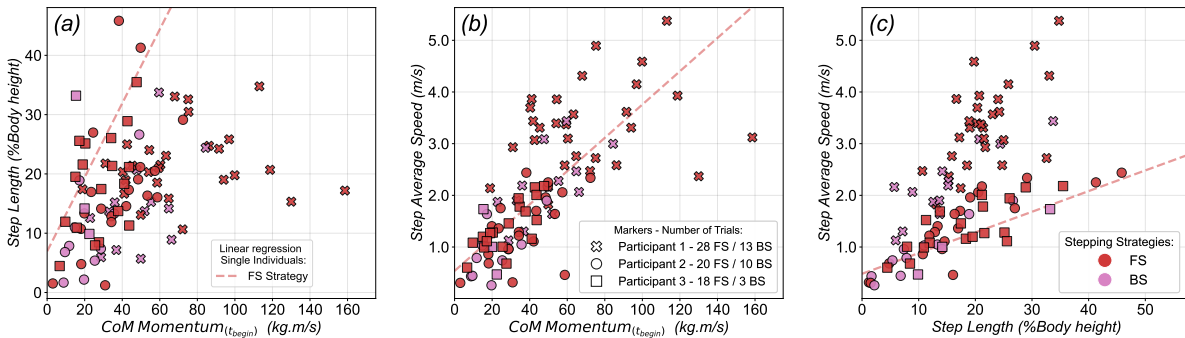


Figure 4.7 – Representation of the first recovery step length and average speed for stepping strategies labelled as FS and BS. (a) First recovery step length compared to the CoM momentum at step initiation. (b) Average speed of the foot during the first recovery step compared to the CoM momentum at step initiation. (c) Average speed of the foot during the first recovery step compared to the step length. The dashed lines represent the linear regressions based on FS stepping recovery strategies observed during the single individuals experiment (Section 2.3.2.3).

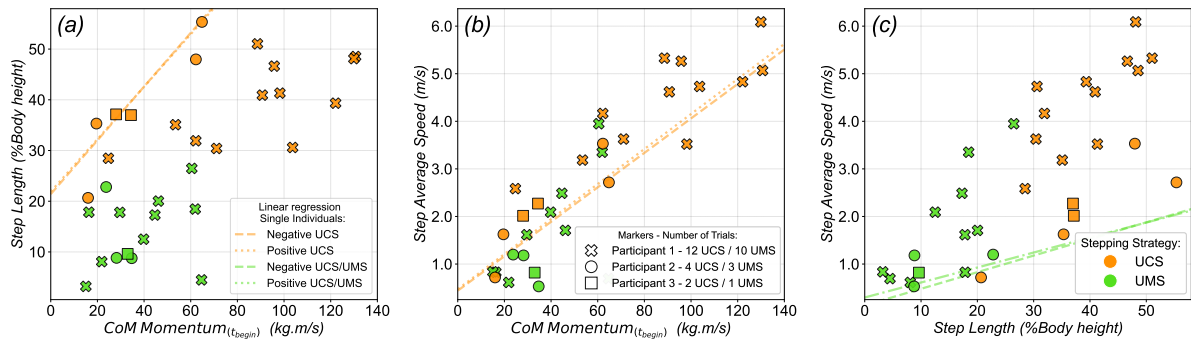


Figure 4.8 – Representation of the first recovery step length and average speed for stepping strategies labelled as UCS and UMS. (a) First recovery step length compared to the CoM momentum at step initiation. (b) Average speed of the foot during the first recovery step compared to the CoM momentum at step initiation. (c) Average speed of the foot during the first recovery step compared to the step length. The dashed lines represent the linear regressions based on UCS or *Unloaded Steps* (i.e. UCS and UMS) observed during the single individuals experiment (Section 2.3.2.3).

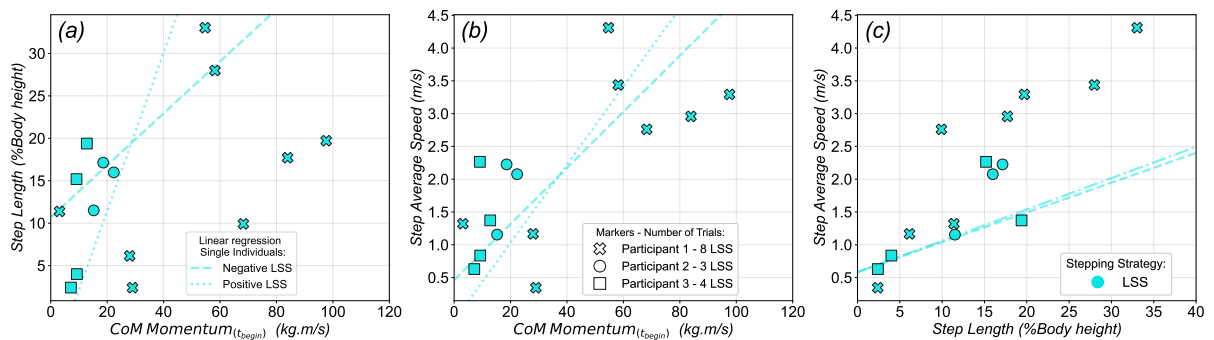


Figure 4.9 – Representation of the first recovery step length and average speed for stepping strategies labelled as LSS. (a) First recovery step length compared to the CoM momentum at step initiation. (b) Average speed of the foot during the first recovery step compared to the CoM momentum at step initiation. (c) Average speed of the foot during the first recovery step compared to the step length. The dashed lines represent the linear regressions based on LSS stepping recovery strategies observed during the single individuals experiment (Section 2.3.2.3).

## 4.3 Discussions

### Estimated Angles of Perturbation

A majority of perturbations have been estimated to occur in the anteroposterior direction during the considered concert crowds experiment. However, perturbations from

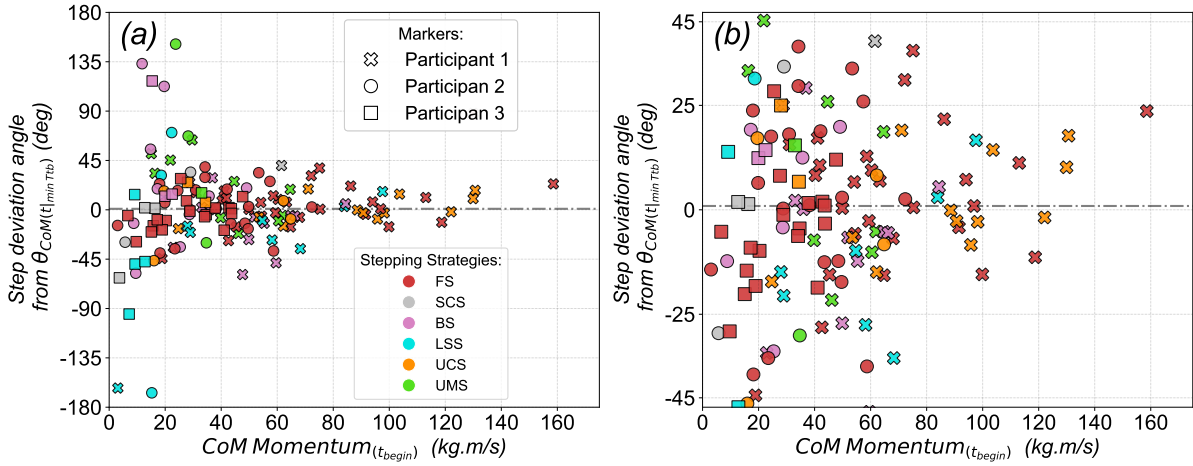


Figure 4.10 – (a) Representation of the step deviation angle compared to the CoM momentum at step initiation. (a) Zoomed-in representation of the step deviation angles compared to the CoM momentum at step initiation. Markers coloured by recovery strategies, labelled following the *Unified* classification method proposed in Section 2.3.1.1. The dashed and dotted line represents the median of the step deviation angles repartition at  $0.91 \text{ deg}$ .

nearly the whole spectrum of possible perturbation angles were observed. In particular, several perturbations were detected with an angle beyond the limits previously studied. These observations allowed us to study recovery strategies involving *Backward Steps* (BS) which have not been detected during the previous experiments conducted in the frame of this thesis.

## Stepping Recovery Strategy Separation

Using the BS recovery strategies observed during the concert crowds experiment we proposed to add another region to the separation model for stepping recovery strategy based on the single individuals experiment (see Section 2.3.2.2). The relevance of this separation model was then assessed by testing its prediction capabilities over the recorded trials during the concert crowds experiment.

The model demonstrates good prediction potential except for the *Loaded Side Step* (LSS) strategy and the associated regions, i.e. N-LS and P-LS. Even though, all LSS trials featured a *Distance to Foot boundary* (DtFb) above the limit to separate *Loaded* from *Unload* steps, we observed a large range of estimated perturbation angles for these trials. In particular, LSS were observed for angle of perturbations for which other stepping

strategies were expected. This observation can be extended to other stepping strategies observed during the concert crowds experiment (e.g. FS and BS), but is particularly striking for LSS as a large amount of the observed trials are incorrectly predicted.

In addition to the limited number of total trials analysed, several factors may explain this observation. In particular, due to the unpredictable nature of the environment, we found that participants could be exposed to perturbations even after initiating a stepping strategy. This may have led to changes in the nature of the stepping strategy after the initial perturbation from which the perturbation angle was estimated. We can also consider the complexity of the *change-in-supports* adopted by the participant who may have used the help of their environment contacts involving their hands or upper body. Finally, one should keep in mind that only the first recovery step was used to label the stepping strategies, but more complex recovery strategies involving multiple steps may have been used to cope with the challenging environment investigated.

## Step Initiation and Limit of Standing Balance

The minimal value of the Ttb for each trial recorded during the concert crowds experiment was compared with the *Limit of Standing Balance* (LoSB) observed during the single individuals experiment.

It is important to note that similarly to what was observed during the dense groups experiments, the moment of Ttb corresponded with the moment of step detection for a large majority of trials involving stepping strategies during the concert crowds experiment. We also observed that the difference between the moment of minimal Ttb and step detection represented only a limited number of recorded frames for several trials. This phenomenon was also observed during the other experiments presented in this thesis. This was likely due to the presence of multiple inflection points before the first peak of the transversal foot velocity considered in the step detection method. Hence, the detection of the step initiation may be different by a limited number of frames to the initial motion of the feet. Here, this phenomenon is increased due to the presence of noise associated to the considered frequency of reconstructed motion capture data, i.e. 240 Hz in the concert crowds experiment and 60 Hz in the dense group experiment. Eventually, step initiation was detected more than a second after the moment of minimal Ttb in 4 of the trials involving stepping recovery trajectories. For these trials we observed that participants undergone multiple perturbations with different intensities before initiating steps. In this situation the minimal value of Ttb was likely obtained following the perturbations with



the maximal intensity, however this perturbation was then mitigated by other physical interactions which induced other perturbations which later resulted in step initiation of the participants.

Considering all these observations, we can see that, similar to what we observed in the dense groups experiments, stepping strategies were initiated in this real crowd situation when standing balance of participants was in its most critical state. In this situation we found relevant to define the LoSB as a critical state of balance after which recovery could not be maintained without the use of stepping strategies.

Regarding the LoSB in the current context, no model could be created based on the presented data as only two trials not involving a stepping strategy were retrieved from the recording. In both of these trials a lateral perturbation was observed, with estimated perturbation angles of  $90$  and  $-90$  *deg* respectively (see Fig. 4.4). We can see in Fig. 4.6 that these trials are on the edge of the decision boundary of the separation models of recovery strategies following lateral perturbations for single individuals.

We also observed here that almost all the trials involving a stepping recovery strategy showed a minimal Ttb below the limit of the separation model between trials with and without stepping recovery strategy created after the other dataset studied in this thesis. The number of recorded trial under the limit of the models are comparable with the *Sensitivity* of the models. As a remainder, the *Sensitivity* of a these separation models represent the number of step trials correctly detected divided by the total number of trials with steps. However, we could also expect the LoSB in this context to be located for slightly higher values of Ttb than in the previous experiments. This is suggested by the several trials involving stepping strategies with minimal values of Ttb above the boundary of the previous models. For these trials the participants were in a state of balance which was considered as acceptable by participants during the single individuals experiments. This observation is likely link to a higher stress level regarding standing balance in this kind of environment, especially in regard to the experimental protocol, in with participants were asked to stand still and wait for physical interactions. This may have led participants to the use of more conservative recovery strategies, i.e. stepping strategies initiated after a more restrictive LoSB [Maki and McIlroy, 1997].

Due to the limited number of trials without steps, it was not possible to build a model similar to the other analyses. Therefore, only qualitative conclusions could be drawn from this study about the LoSB in this concert crowds experiment.

## First Recovery Step Characteristics

Smaller first recovery steps for comparable CoM momentum at step initiation were observed during the concert crowds experiment in comparison to what was recorded during the single individuals experiment. This observation matches the behaviour seen during the dense groups experiment described in Section 3.2.4. However, here step average speed seemed to follow relationships with the CoM momentum more similar to the one observed during the single individuals experiment.

Hence, for a given CoM momentum (linked to a given perturbation intensity) participants of the concert crowds experiment reacted with smaller, but faster recovery steps than the ones observed during the other experiments studied in the frame of this thesis. This trend, however, varied depending on the considered participant and is most visible for trials realised by participant 1.

These faster and smaller first recovery steps seem to indicate that participants may have mainly used recovery strategies involving multiple smaller steps to regain balance. In addition, the relationships between the stepping speed and the CoM momentum may imply that the use of contacts with other individuals, was limited during the first phase of the recovery. As a comparison, one could have a look at the speed of the first recovery step during the dense groups experiment (see Fig. 3.12). In this experiment, participants could use upper body contacts with other individuals as a support, enabling them to use slower steps to regain balance. Further investigation of follow-up steps is and effort linked to physical interactions are required to support these assumptions.

The deviation angles of the first recovery steps recorded in the concert crowds experiment show a similar trend to that found in the dense groups experiment, with a significant standard deviation of observations. This behaviour may again be related to the complex environment in which the participants were immersed, with multiple perturbations arising even after step initiation requiring participants to adapt their recovery strategies.

## Limitations

The presented concert crowds experiment was carried out in a real crowded environment which enabled us to observe standing balance recovery behaviours in a complex environment. However, such a context also involves a lower level of control over experimental parameters. In this section we review the different limitations at stake for this experimental dataset, and the implication these limitations may have on our conclusions.

The limited number of participants together with the uncontrollable aspect of the perturbation resulted in a limited set of standing recovery observations. In particular, the number of recovery strategies following a lateral perturbation may not be sufficient to draw strong conclusions about these behaviours.

One of the main technical challenges during this experiment was the motion recording process. By definition the environment of the experiment was very unpredictable and could lead to unwanted position shifting of the IMMUs of the suit on the body. Such position shift could result in lower quality of the reconstructed limbs motion. In addition, as the experiments could not be stopped, this position change may then vary along the experiments. This means that a proper reconstruction could not be performed even based on calibrations of the system before and after the experiments. Such issue seemed to have happened with the motion recordings of participant 1 during the first concert. As a result, only a fraction of the recording could be used for which the original calibration provide an appropriate reconstruction. However, assessing the reconstruction quality of the recording in this situation is a real challenge. Here, only a qualitative assessment of the representativeness of the reconstructed body movement was used.

Eventually, no information regarding the nature on the perturbation, i.e. intensity and temporal profile, could be retrieved during these experiments. Here we observed qualitatively “short” perturbations with intensities resulting in high CoM momentum. This kind of perturbation is in some extent comparable to the one realised during the other experiments investigated in the frame of the thesis. However, one should keep in mind that physical interactions happening in mosh “pits” are likely different to the one happening in very dense crowds. Contact in dense crowds have also been shown to result in longer physical interactions and increasing load [Bokhary, 1993; Sieben and Seyfried, 2023].

## 4.4 Chapter Conclusion

In this chapter, we studied the recovery strategies of three young participants following external perturbations resulting from physical interactions with dancers in punk rock concert crowds. The characteristics of the recovery strategies used in this real crowd experiment were then compared with the previous studies regarding standing balance and recovery strategies proposed in Chapters 2 and 3.

In particular, we observed a spectrum of angles of perturbations substantially larger

than the ones observed during the other experiments analysed in this thesis. This wider range of perturbation angles resulted in a large variety of recovery strategies used by participants. We especially observed stepping recovery strategies involving *Backward Steps* which have not been recorded in the single individuals experiment or during the dense groups experiment.

Almost only recovery strategies involving steps were observed during this experiment in concert crowds. The vast majority of the minimal *Time to boundary* were observed as expected with values below the boundaries of the models created to estimate the *Limit of Standing Balance* in Chapters 2 and 3. However, trials involving stepping strategies with minimal Ttb above the boundaries of the previous models suggest that steps were initiated before the LoSB observed during the previous experiments. In addition, apart from the recovery strategies involving *Loaded Side Step*, all stepping strategies recorded during the concert crowd experiment could be accurately predicted based on kinematic information prior to step initiating using the separation model for stepping recovery strategies proposed in Section 2.3.2.2. This model was also augmented in this chapter with new boundaries for prediction of recovery strategies involving *Backward Steps*.

The characteristics of the first recovery step of participants were compared to what was observed during the other experiments analysed in this thesis. Small first recovery steps, comparable to what was observed during the dense groups experiment were recorded in concert crowds. However, the average speed of the first recovery steps during the concert crowds followed the same relationships with the CoM moment as what was observed during the single individuals experiment. All of these observations seem to indicate that participants' recovery strategies in concert crowds involved multiple small recovery steps with limited help from other "change-of-support" such as contact with other individuals.

The proposed investigation of the standing balance in these punk rock concert crowds could be taken a step further by using the bird's-eye view recordings of the crowds which were also captured during the festival. This footage could be used to assess the local density around the participants as well as their displacement in relation to the position of their neighbours.

Finally, the present study proposed a new approach which open up new research opportunities. Novel knowledge regarding human recovery strategies in complex crowded environment were retrieved from the proposed experiment. This study also includes an original experimental paradigm which enable a transition from laboratory to field experiments. Such a paradigm can be used to gain general knowledge about human motion

in dense crowds, but also to validate and compare models based on previous laboratory experiments.

# CONCLUSION

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In this thesis, standing balance and recovery strategies following external perturbation was studied in different situations with the aim of offering new perspectives to model human balance in dense crowds.

In the first place, the characteristics of single individuals' reaction to an external perturbation from different directions were studied in Chapter 2. Along this chapter we have seen that, the *Limit of Standing Balance*, defined in this context as the state of balance after which balance cannot be recovered without stepping, could be evaluated using the *Margin of Stability* as well as the *Time to Boundary*. This *Limit of Standing Balance* was found to remain unchanged in regard to the proposed experimental variation of the *Level of Awareness* to upcoming perturbations. However, different *Limit of Standing Balance* were found depending on the angles of the external perturbations. Similarly, different stepping recovery strategies have been observed depending on the perturbation angles. We proposed in this chapter a new classification method which enabled us to label stepping strategies based on the trajectory of participant *Center of Mass* and the initial position of their feet during a trial. Separations between the different stepping strategies were proposed based on intrinsic kinematic characteristics associated with each stepping strategy observed during the considered experiment. These separations resulted in the creation of a model which can be used to predict the type of stepping recovery used based on participants' kinematic prior to the step initiation. Eventually, the characteristics of the first recovery step was studied for each stepping strategy observed in the experiment. Relationships between the step characteristics and the estimated momentum associated to the *Center of Mass* were exposed in the final part of the chapter. In addition to all these results, the dataset created in the frame of this study proposes a novel experimental paradigm featuring human reactions to perturbations arising from different directions which had never been explored, to the best of our knowledge. Therefore, one may use this dataset for purposes out of the scope of the work proposed here.

All the result exposed in Chapter 2 build the foundation of the entire work proposed in this thesis. These results have then been compared with experimental data associated with more complex situation involving multiple individuals.

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In Chapter 3, we studied the standing balance and recovery strategy of individuals within dense group formations following external anteroposterior perturbations. Physical interactions were part of the recovery strategies observed in this context as the imposed experimental distancing only allowed participants a very limited range of motion without making contact with their neighbours. In particular, we observed an effect of the experimental interpersonal distancing on the *Limit of Standing Balance*, with participant initiating step earlier in groups with lower density. Following, the *Unified* classification for stepping recovery strategies, we found that most participants used *Forward Step* to recover from the perturbations. Major differences regarding first recovery steps were found in comparison with the previous experiment involving single individuals. These differences unveil the use of recovery strategy involving smaller and slower recovery step with a significant deviation compared to the estimated perturbation angle. Such slower steps were likely made possible by the use of other *change-in-supports*, namely contact using upper body, to prevent participants from falling in this context. Preparation to physical interaction in this context was studied using the initiation moment of hand raising motion. Although hand raising was observed in less than half of the trials for which stepping strategies were used, we found for these trials that hand raising motion seemed to be triggered significantly before step initiation. We also showed that even though physical interaction occurred in this situation, recovery steps were initiated at the most critical stage of standing balance.

All of these findings suggest that, event though physical interactions were inevitable in this context, participants attempted to minimise the amount of effort being passed on to their neighbours by making early hand contact with their neighbours. When possible, this behaviour was coupled with initiation of stepping strategies for early stages of balance loss.

In the light of these findings, we would like to suggest further investigations into the hand contact before and during physical interactions as this was observed during this experiment. Scientific investigations remain regarding both the mechanical damping capacity and the ability to propagate information of such behaviour.

We would like to acknowledge the members of the Institute for Advanced Simulation, IAS-7: Civil Safety Research of the Forschungszentrum Jülich for the direction of these dense groups experiments. The large dataset collected during this experimental campaign constitute a groundbreaking approach for research regarding standing balance and physical interaction in dense crowds. The results presented in this thesis are based on a very

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limited amount of the data acquired during these experiments. Further research, based on this material, concerning the different stages of reaction exhibited by participants under external perturbation in this context is currently under publication process.

Finally, in Chapter 4, the results of the laboratory experiments presented in Chapters 2 and 3 were compared with observations of individuals' recovery of standing balance following physical interactions in a real punk rock concert crowd. In this context participants were exposed to perturbation arising from almost all possible directions. This especially lead to the use of stepping recovery strategies involving *Backward Steps* which haven't been observed in the other experiments analysed in the frame of this thesis. The predictive capacity of the separation model for stepping recovery strategies developed in Chapter 2 was evaluated on the data collected during this field experiment and showed encouraging results. In particular, trials in regions were well associated with the expected recovery strategies except for the few observed trials involving stepping strategies with *Loaded Side Steps*. The model was also extended with the creation of new boundaries around the region containing the observed trials involving *Backward Steps*. The *Limit of Standing Balance* was also studied and separation models based on the previous experiment were compared to the observations of the concert crowds experiment. Most of the trials observed in this final experiments fell under the decision boundary of the models based on the two previous experiments. However, the minimal *Time to Boundary* observed for several trials involving stepping recovery strategies remained higher than the limit fixed by the previous models. This observation suggests that the limit of standing balance of participants in this concert crowds experiment was actually stricter than during the previous experiments with step initiated at lower level of balance disturbance. Eventually, the characteristics of the first recovery steps was analysed and compared for each stepping strategy to the linear regression based on the observations made during the single individuals experiment. This analysis especially revealed the use of smaller recovery steps for equivalent estimated momentum (associated with the perturbation intensity). These first recovery steps were also executed faster suggesting that participants used recovery strategies involving multiple steps with little or no help from other "change-of-support" as this were observed during the dense groups experiment.

In the light of these final experimental results, we have seen that this concert crowds experiment has not only provided us with validation support for part of the proposed models, but has also allowed us to observe new recovery behaviours that had not been captured in the other experiments studied in the framework of this thesis. In particu-



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lar, thanks to these experiments, we found that frontal perturbations play an important role in the disturbance of standing balance in this context. Finally, recovery strategies involving multiple steps seemed to prevail in this context and would benefit from further investigation, for instance based on more controlled laboratory experiments.

## Limitations and Perspectives

All the studies presented in this thesis also had several limitations. In this final section, we have tried to highlight the main limitation of this work and suggest research perspectives that could be considered to fill the remaining gap in knowledge regarding standing balance and balance recovery in dense crowds.

Above all, methodological limitations remain in our approach. Here, we almost exclusively worked using kinematic information deriving from full-body motion capture recordings. Additional kinetic information may however be monitored to study external perturbations and recovery strategies. For instance, the use of wearable pressure pads could provide a clearer perspective on interpersonal contact. Another relevant measurement could be related to the reaction force between the participants' feet and the ground. This information would not only allow an estimation of the participants' *Centre of Pressure*, but could also allow a more accurate detection of step initiation and leg loading. For experiments involving single participants, these measurements are usually performed using ground mounted force plates. However, this solution cannot be used in situations with multiple participants, as this technology averages the resulting load on its surface. One solution could be the use of recently developed shoe soles equipped with wireless pressure sensors. Large pressure pads that could be diploid on the floor of a laboratory environment are also under development and could also be considered for this technical challenge.

Another methodological limitation of the work proposed here comes from the population studied. In the introduction to this thesis, we presented the problems associated with age in terms of standing balance and balance recovery. We also pointed out that the average age of the world's population is increasing, which may lead to a greater representation of older people among dense crowds in the years to come. However, only younger adults participated in the experiments studied in this thesis. This limitation is related to safety requirements. Because of the novelty and the non-negligible risk of falling in the experiments considered, we decided to recruit only healthy participants for whom the risk

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of injury from falling was very low. In previous studies related to balance recovery of elder populations, the classic approach to preventing falls has been to use a safety harness to avoid hard collisions with the ground. In order to test balance recovery of multiple participants at risk in the same environment, one could imagine the development of a multiple harness system allowing to carry out completely fall-free laboratory experiments.

The final limitation discussed here concerns the field experiments conducted to study standing balance and balance recovery. This type of experiments allows the observation of reactions in unique social and environmental crowd contexts. Therefore, the difference of contexts of the studied crowds have to be taken into account when analysing the behaviours observed for each situation. Standing balance and recovery strategies are likely to differ between sports fans at a stadium opening and pilgrims during a religious ceremony. In this thesis we study the recovery of participants during punk rock concerts. This situation remains very specific and may not be representative of events where density reaches very high levels. However, static crowd events, in which physical interactions are socially accepted and induce standing balance loss, are particularly rare. We believe that metal and punk rock concerts are interesting environments to study balance recovery in static, dense crowds. These crowds provide a safe environment where participants can be exposed to physical interactions, in addition to being part of a complex environment in which balance recovery could be challenging. In the light of the results obtained in the present work, we could imagine replicating the experimental protocol proposed in Chapter 4 in other contexts. For example, participants could be monitored while attending cultural events with very dense static crowds, where physical interaction may arise from non-voluntary contacts associated with the proximity between individuals.

In line with all the results obtained in this thesis, new simulations of human crowds could be proposed. These simulations could integrate representation of balance recovery strategies based on the models presented in this thesis. Such tool may then be used for crowd safety as well as reconstituting past crowd accidents to better understand and try to prevent such disasters. Physical simulations of three-dimensional articulated humans recovering from external perturbations have already been created based on the present work [Jensen et al., 2023]. These simulations are the first steps towards crowd simulations featuring advanced experimentally based models of standing balance and balance recovery.

Beyond perspective for crowd simulations, this thesis provides new insights into standing balance in dense crowds, which may be useful for early detection of potential falls in such contexts. By coupling the proposed models be coupled with computed vision systems

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one could for instance detect step triggering and use this information to assess the level of balance of people in a given crowd.

Finally, the work proposed in this thesis also requires to be extended to better understand balance recovery within moving dense crowds. We know that recovery strategies following external perturbations are different when standing than when walking or running. Based on the present findings, we can expect that recovery strategies during navigation in a moving dense crowd will have different characteristics from those observed for single individuals. However, this research would need to address various issues associated with moving crowds, such as the higher risk of injury following potential falls in this context.

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# ADDITIONAL RESULTS RELATED TO CHAPTER 2

## A.1 Difference Between Estimated and the Ground Truth Angles of Perturbation

Here is displayed the differences between the *Estimated* and the *Ground Truth* angles of perturbation for trials for which a stepping recovery strategies was used and trial with recovery strategies not involving steps.

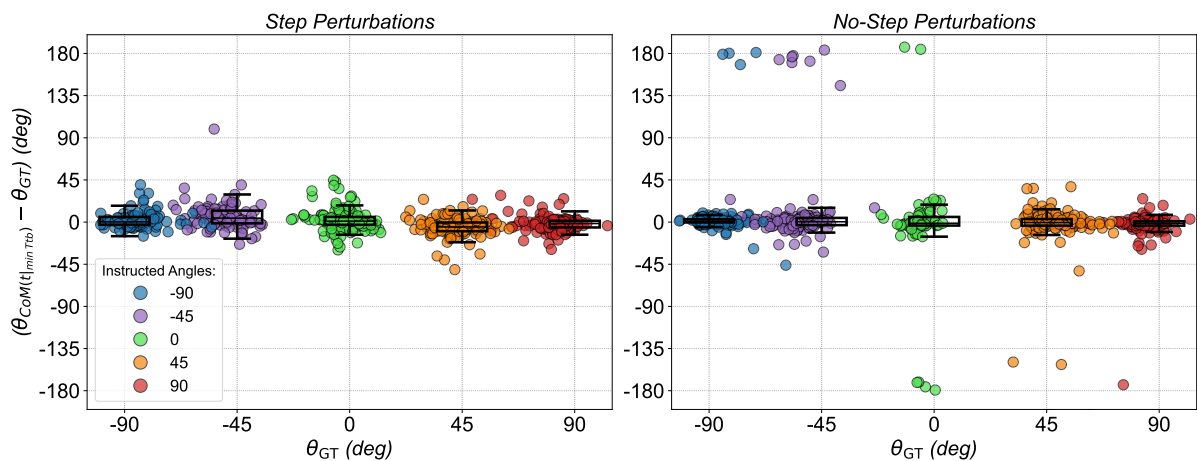


Figure A.1 – Difference between the estimated perturbation angle based on the direction of the CoM velocity at the moment of minimal Ttb compared to the *Ground Truth* (GT) perturbation angle given by the direction of the CoM velocity at the moment of maximal perturbation intensity. Trials are coloured by *instructed angles* given to the experimenter who applied the perturbation.

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## A.2 Accuracy Evaluation of the Separation Model for Stepping Recovery Strategies

In this section we proposed an evaluation of the separation model for stepping strategy proposed in Section 2.3.2.2. This evaluation was performed using a method also used in Section 4.2.2. We computed the number of expected stepping strategy (labelled using the *Unified* classification proposed in Section 2.3.1.1) in each region of the separation model. We also monitored the of the number of trials within the expected region for each stepping strategy (labelled using the *Unified* classification). These observations can be summarised using an *Expectation Rates* defined as the number of expected values over the total number of observations.

We can see in Table A.1 that the regions delimited by the separations of the models contain more than 76% and up to 91% of trials with the expected stepping recovery strategies. Similarly, over the entire dataset, trials with stepping recovery strategies are distributed in the expected regions of the separation models for more than 88% of the observations.

Rate of Trials of Expected Stepping Strategy in Each Region					
Region	Expected Strategy	Total in Region	Expected	Incorrect	Expectation Rate (%)
N-US	UMS/UCS	53	137	13	91
N-LS	LSS	150	48	5	91
C-FS	FS	222	199	23	90
P-LS	LSS	29	22	7	76
P-US	UMS/UCS	188	164	24	87

Table A.1 – Count and rate of the expected stepping strategies for each stepping strategy regions. The Expectation Rate here corresponds to the number of trials with the expected stepping strategy divided by the total number of trials in the region.

## A.3 Limit of Standing Balance Compared to CoM Momentum

Minimal values of Ttb were also compared to the CoM momentum for the three considered perturbation angle sections created following the separation of stepping strategies using the *Estimated* angle of perturbations (see Fig. A.2). One can see here that non-stepping recovery strategies are mainly made before 20 *kg.m/s*. Hence, overlap between

Rate of Trials in Expected Regions for Each Stepping Strategy					
Strategy	Expected Region	Total Trials per Strategy	Expected	Incorrect	Expectation Rate (%)
UMS/UCS	N-US/P-US	317	301	16	95
LSS	N-LS/P-LS	71	70	1	99
FS	C-FS	226	199	27	88

Table A.2 – Count and rate of the trials expected in the expected regions for each stepping recovery strategy. The Expectation Rate here corresponds to the number of trials in the expected cluster divided by the total number of trials for which the stepping strategy was used.

NS and step recovery strategies only appear for a limited range of CoM momentum. However, a separation only using the CoM momentum cannot be achieved as both non-stepping and stepping strategies are largely used between  $10 \text{ kg.m/s}$  and  $20 \text{ kg.m/s}$ .

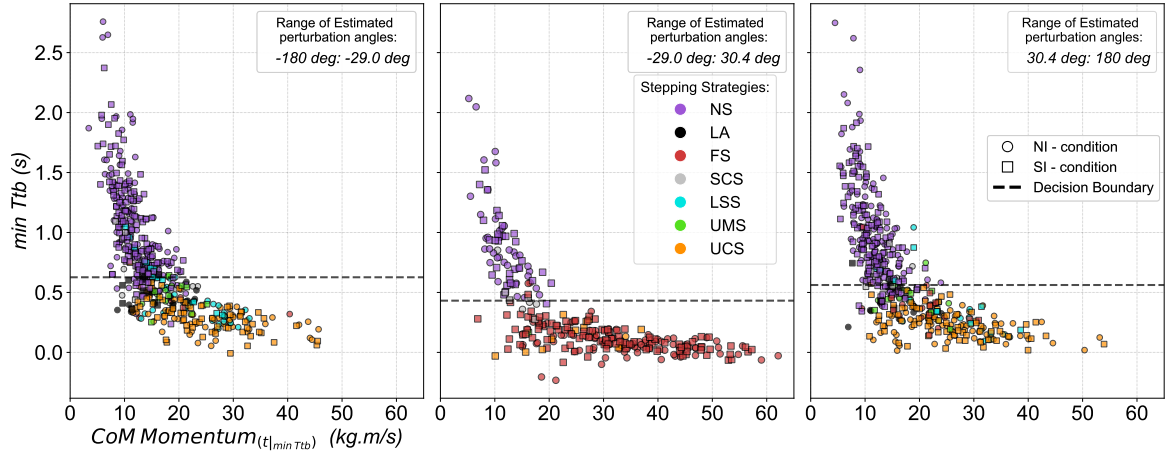


Figure A.2 – Minimal *Time to boundary* (Ttb) for every trial in relation to CoM momentum at the moment of minimal Ttb. Minimal value was computed before step initiation for trials involving a step. Data are coloured using the *Unified* classification method. Horizontal dashed lined represent the decision boundaries of the proposed separation models between trial with and without steps. This figure is divided into three axes, each representing a range of perturbation angles associated with the stepping strategy regions visible in Fig. 2.16.

## A.4 Step Characteristics Tables

	Stepping Strategies	Intercept	Coef.	$R^2$	RMSE	p-value Shapiro–Wilk test (residuals)
x: Step Length y: CoM Momentum (Fig. 2.18)	UCS Negative angles	0.214	$5.30e-3$	0.289	$4.89e-3$	0.230
	LSS Negative angles	0.107	$3.06e-3$	0.103	$3.39e-3$	0.125
	FS	$6.95e-2$	$6.24e-3$	0.624	$3.50e-3$	$2.67e-2$
	LSS Positive angles	$-7.19e-2$	$9.32e-3$	0.531	$4.66e-3$	$5.35e-2$
	UCS Positive angles	0.219	$5.17e-3$	0.229	$6.99e-3$	$2.62e-2$
x: Step Avg. Speed y: CoM Momentum (Fig. 2.19)	UCS Negative angles	0.440	$3.62e-2$	0.586	$6.54e-2$	$5.80e-2$
	LSS Negative angles	0.460	$4.28e-2$	0.514	$7.22e-2$	$1.83e-5$
	FS	0.537	$3.22e-2$	0.726	$5.86e-2$	0.478
	LSS Positive angles	-0.161	$5.96e-2$	0.696	$9.41e-2$	0.781
	UCS Positive angles	0.473	$3.68e-2$	0.542	$8.96e-2$	$3.14e-2$
x: Step Avg. Speed y: Step Length (Fig. 2.20)	UCS \ UMS Negative angles	0.297	3.15	0.573	0.112	$4.71e-2$
	LSS Negative angles	0.585	4.54	0.524	$7.06e-2$	0.152
	FS	0.482	4.00	0.699	$6.44e-2$	$8.23e-2$
	LSS Positive angles	0.582	4.78	0.733	$8.27e-2$	0.735
	UCS \ UMS Positive angles	0.131	3.49	0.683	$7.33e-2$	0.581

Table A.3 – Characteristics of all the linear regression proposed in Section 2.3.2.3.

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	Median (deg)	Standard Deviation (deg)	Number of Values
UCS Negative angles	-8.6	21.7	122
LSS Negative angles	-18.0	19.4	49
FS	$8.5e - 2$	10.1	226
LSS Positive angles	11.1	39.0	22
UCS Positive angles	7.8	18.6	155

Table A.4 – Recapitulate table of the median values and standard deviations for the first recovery step deviation angles exposed in Fig. 2.21.

# ADDITIONAL RESULTS RELATED TO CHAPTER 3

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## B.1 Separation Model for Stepping Recovery Strategies over the Dense Group Experiment Dataset

We tried to evaluate if the recovery strategies recorded during the dense groups experience would fit to prediction of the separation model for stepping recovery strategies of single individuals proposed in Section 2.3.1.1. This evaluation was performed using method used in Section 4.2.2 with the use of *Expectation Rates*.

Most recovery stepping strategies observed during the dense group experiment and visible in Figure B.1 have been estimated with perturbation angles matching the central region of recovery strategies (C-FS) of the separation model proposed in Section 2.3.2.2. We can see in B.1 that the C-FS and the Left USS clusters are mainly composed with the expected stepping strategies. However, we can also see in Table B.2 that unlike the FS strategy, most of the labeled *Side Steps* Strategies (LSS, UMS, UCS) are not found in the expected regions of the separation model based on single individuals experiment. However, as only a limited fraction of the observed stepping strategies were labelled as side step strategies (LSS, UMS, UCS) we cannot provide any strong conclusion on the relevance of the proposed separation model regarding side steps in the context of these dense groups experiment. Further experimental investigation with the addition of different perturbation directions to the dense group paradigm could be considered to explore all possible recovery strategies in more detail.

Rate of Trials of Expected Stepping Strategy in Each Region					
Region	Expected Strategy	Total in Region	Expected	Incorrect	Expectation Rate (%)
N-US	UMS/UCS	9	7	2	78
N-LS	LSS	2	0	2	0
C-FS	FS	207	189	18	91
P-LS	LSS	-	-	-	-
P-US	UMS/UCS	3	1	2	33

Table B.1 – Count and rate of the expected stepping strategies observed during the dense groups experiment for each stepping strategy regions of the separation model for stepping strategies based on results of the single individuals experiment. The Expectation Rate here corresponds to the number of trials with the expected stepping strategy divided by the total number of trials in the region.

Rate of Trials in Expected Regions for Each Stepping Strategy					
Strategy	Expected Region	Total Trials per Strategy	Expected	Incorrect	Expectation Rate (%)
UMS/UCS	N-US/P-US	18	8	10	44
LSS	N-LS/P-LS	7	0	7	0
FS	C-FS	194	189	5	97

Table B.2 – Count and rate of the trials expected in the expected regions of the separation model for stepping strategies based on results of the single individuals experiment for each stepping recovery strategy observed during the dense groups experiment. The Expectation Rate here corresponds to the number of trials in the expected cluster divided by the total number of trials for which the stepping strategy was used.



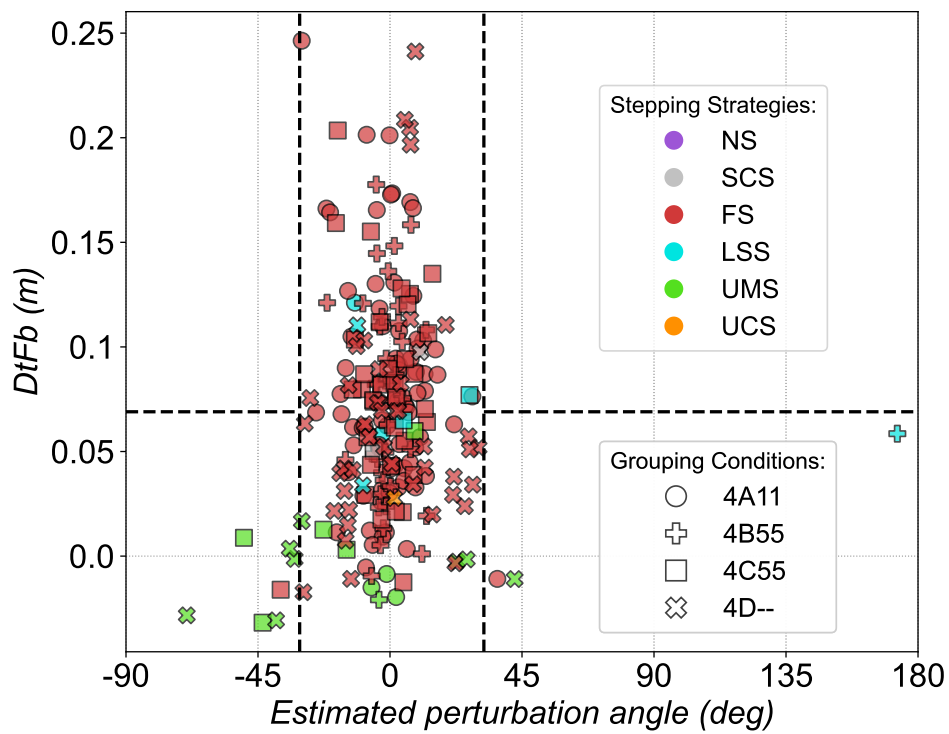


Figure B.1 – *Distance to Foot boundary* (DtFb) in relation with the estimated perturbation angle for every trial involving stepping recovery strategies. Data are coloured using the *Unified* classification method. Dashed lines represent the decision boundaries of the separation model for stepping recovery strategies based on single individuals experiment.



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**Titre :** Stratégies de récupération de l'équilibre posturale suite à des perturbations externes : Une approche multi-échelle avec applications pour les foules denses.

**Mot clés :** Biomécanique, Contrôle postural, Perturbation externe, Stratégie de rétablissement de l'équilibre, Foules denses

**Résumé :** Chaque année dans le monde on rapport plusieurs accidents liés aux foules denses. Ces accidents peuvent entraîner des blessures et même des décès dans les cas les plus extrêmes. Les chutes dans les foules denses ont été observé comme l'un des éléments déclencheurs possibles de ces accidents. De telles chutes résultent des difficultés de recouvrement de l'équilibre postural dans ce contexte particulier. Cependant, les connaissances concernant l'équilibre postural dans ce contexte sont très limitées en raison de la nature complexe des environnements liés aux foules denses. Dans cette thèse, nous proposons une approche expérimentale pour étudier le rétablissement d'équilibre postural suite à des perturbations externes dans des environnements de foules humaines avec différents niveaux de densité. En particulier, comme les perturbations peuvent survenir de n'importe quelle direction dans les foules, nous étudions dans un premier temps

la réaction d'individus isolés à des perturbations externes provenant de plusieurs directions. Nous proposons ensuite une méthode permettant de prédire les stratégies de recouvrement d'équilibre des participants sur la base d'informations cinématiques uniquement. Des expériences impliquant plusieurs individus sont par la suite étudiées. En particulier, nous avons étudié l'effet de la densité de la foule sur l'initiation et les caractéristiques des pas de récupération d'équilibre. Finalement, un nouveau paradigme expérimental a été proposé pour étudier l'équilibre postural en conditions réelles lors d'événements impliquant des foules denses. Cette approche a ensuite été utilisé au sein de foules durant des concerts de musique punk rock. Les résultats fournissent de nouvelles informations concernant la nature des interactions physique et les stratégies de récupération d'équilibre utilisées dans ce contexte.

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**Title:** Standing Balance Recovery Strategies Following External Perturbations: A Multiscale Approach With Applications to Dense Crowds

**Keywords:** Biomechanics, Postural Control, External Perturbation, Balance Recovery Strategy, Dense Crowds

**Abstract:** Every year, several crowd accidents are reported around the world. These accidents can result in injuries and even fatalities. One of the triggering element of these accidents has been reported to result from

falls associated with loss of standing balance in this dense crowd context. However, knowledge regarding human standing balance in dense crowd is very limited due the complex nature of this environment. In this thesis we

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proposed an experimental approach to study standing balance recovery of individuals following external perturbations in environments with different crowd density. In particular, as perturbation may occur from any direction in dense crowds we first study the reaction to single individuals to external perturbations arising from different directions. Based on the data collected during of this experiment we were able to propose a method to predict participants' recovery strategies following external perturbations based on kinematic information.

Experiment involving multiple individuals were then considered. In particular, we study the effect of the crowd density on the initiation and the characteristics of recovery steps. Eventually, a novel experimental paradigm was proposed to study standing balance during real crowded events. This approach was then used within punk rock concert crowds. Results provided new insights regarding the physical interactions and recovery strategies observed in this context.