Classification of First Recovery Steps After Quiet Standing Following External Perturbation from Different Directions

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Abstract

Recovery from external perturbations typically involves stepping, with the perturbation direction playing a key role in determining the recovery strategy. To date, classifications of these stepping strategies have relied on prior knowledge of perturbation direction, which is not always available when considering experimental paradigms close to real-world scenario. Here, we introduce a novel *Unified* classification method that enables the labelling of first recovery steps based solely on body kinematics. We have also developed and validated a logistic regression model that effectively differentiates between different recovery strategies.

Keywords: Balance recovery, Stepping strategies, Kinematics, Separation model

1. Introduction

Falls are leading causes of injury (World Health Organization, 2021). To mitigate this risk, researchers have extensively studied standing balance and factors affecting recovery following perturbations (Shumway-Cook and Woollacott, 1995; Melzer et al., 2001; Winser et al., 2019; Westerlind et al., 2019). Perturbation type, whether internal or external, significantly affects recovery behavior (Vinik et al., 2017; Tokur et al., 2020). Recovery strategies following external perturbations have been investigated using various experimental protocols (Carty et al., 2011; Inkol et al., 2018; Robert et al., 2018; Emmens et al., 2020). Studies showed that perturbation directions influence the stepping strategy used for recovery (Maki and McIlroy, 1997). However, studies labelling first recovery steps only investigated perturbation arising from a single direction, limiting the number of observed recovery strategies (McIlroy and Maki, 1996; Mille et al., 2005; Borrelli et al., 2021). Therefore, transitions between stepping recovery strategies remain unclear and require a precise identification protocol of recovery steps to be investigated. To address this limitation, we introduce a novel *Unified* classification method, enabling step labelling independent of perturbation information. We also propose a model to separate stepping recovery strategies from kinematic information.

2. Materials and Methods

2.1. Dataset

The data analyzed in this study are identical to those used in Chatagnon et al. (2023). This open-source dataset (Chatagnon, 2024) includes 1260 full-body motion capture recordings of 21 young adults (27.2 ± 4.2 *yo*) recovering from controlled external perturbations applied from five directions (see Fig. 1.a). Additional details are available in Chatagnon et al. (2023).

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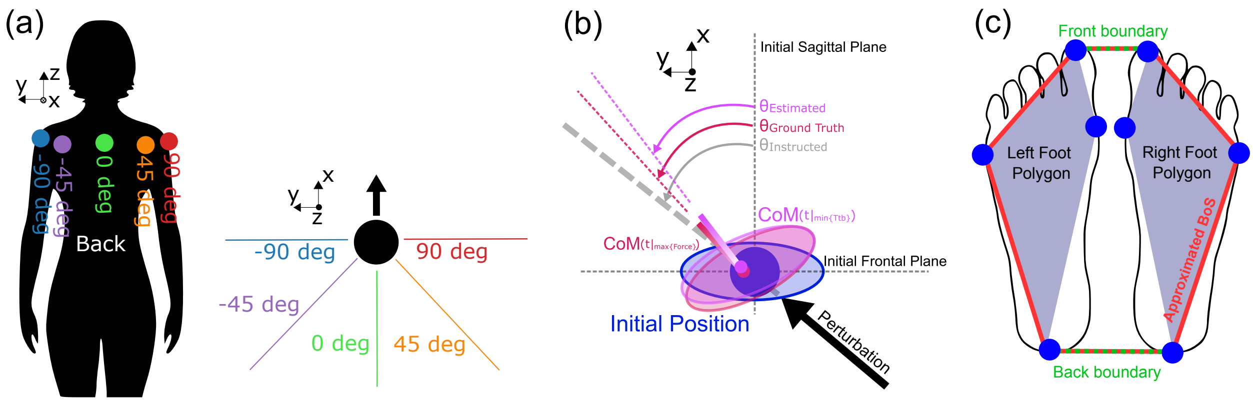

Figure 1: Overview of the different variables of the methods: (a) Instructed angles and the location of the perturbation application. For clarity, the referential of the instructed angles has been redefined in this study compared to Chatagnon et al. (2023). (b) Representation of the perturbation angles. The *Instructed* angle (grey) is defined as the angle between the initial sagittal plane and the perturbation direction given to the experimenter. The *Ground Truth* angle (red) is the angle between the sagittal plane and the direction of the participant's CoM velocity at peak perturbation intensity. The *Estimated* angle (purple) corresponds to the angle between the sagittal plane and the CoM velocity direction at the moment of minimal Ttb before step initiation. (c) Representation of the BoS, depicted as the polygon formed by linking all external foot markers (red). Blue dots indicate the positions of the motion-capture markers.

2.2. Variables and definitions

The methods for detecting step initiation and foot crossing, as well as variables like the *Center of Mass* (CoM), Base of Support (BoS), and *Time to Boundary* (Ttb), were implemented as detailed in Chatagnon et al. (2023).

In the previous work, the *Distance to Foot Boundary* (DtFb) was defined as the distance from the CoM ground projection to the boundary of the Non-Stepping Foot surface, using a reference linked to the foot position at foot movement onset. In this study, DtFb is redefined as the shortest distance from the CoM ground projection to the polygon boundary formed by Non-Stepping Foot markers at step initiation. This updated definition generalizes DtFb and enables its computation under all conditions.

We also refined the concept of the *perturbation angle*. In (Chatagnon et al., 2023), it was defined as the instructed angle given to the experimenter before each perturbation. However, this angle may not accurately represent the actual perturbation angle during a trial, as the compliant nature of the perturbations can cause it to change. To address this, we defined a *ground truth perturbation angle* based on the CoM velocity direction at the moment of maximal perturbation intensity.

For step recovery prediction, an *Estimated perturbation angle* was using only the CoM velocity direction at the moment of minimal Ttb. These angle definitions are illustrated in Fig. 1.b.

2.3. Unified Recovery Step Classification

We revisited recovery step classification with a *Unified* method allowing recovery strategies labelling after external perturbations from any direction, without prior knowledge of the perturbation. While our focus here is on the first recovery step, recovery strategies can include multiple steps (Borrelli et al., 2021).

The classification method relied on kinematic data, particularly the CoM trajectory and foot positions before recovery step initiation. The method assumed that the CoM projection on the ground within the BoS but outside the surfaces of both feet (i.e., positioned strictly between them) prior to the perturbation.

The main variables for this method were the CoM trajectory, the BoS front and back boundaries (defined by the toes and heels positions, see Fig. 1.c), and the initial feet surfaces, approximated by polygons formed by foot markers (see Fig. 1.c). The CoM trajectory was computed throughthe CusToM library, using inverse kinematics applied to an osteoarticular model fitted on the filtered motion-capture data (Butterworth, 5Hz) (Muller et al., 2019; Puchaud et al., 2020; Livet et al., 2023).

The proposed *Unified* recovery step classification algorithm is detailed in the flowchart shown in Fig. 2.

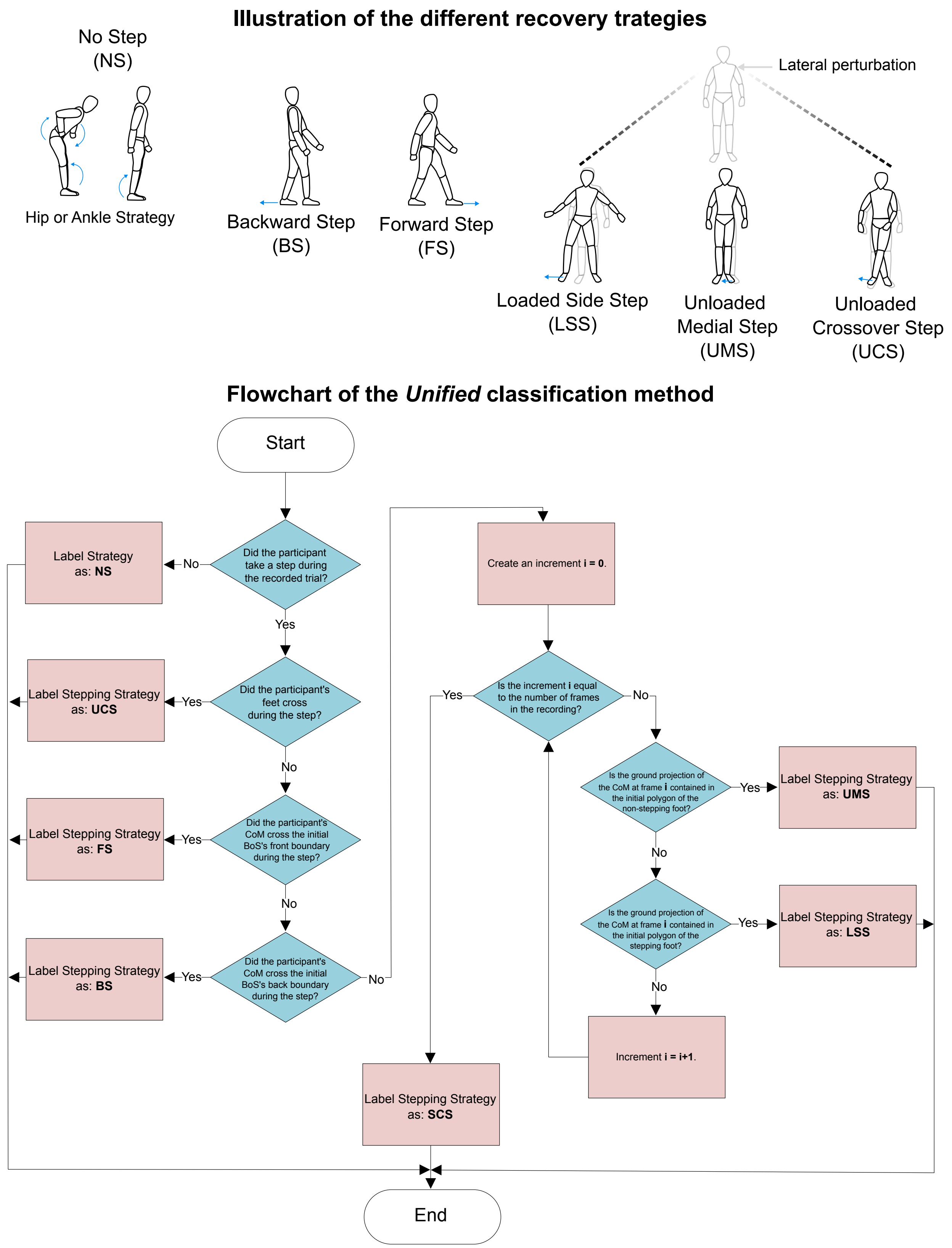

Figure 2: Flowchart of the *Unified* classification method for labelling stepping recovery strategies after external perturbations from any direction. Strategy names correspond to representations in the figure's top section. The *Sub-Critical Step* (SCS) is not depicted, as it can range from a minor foot slide to a small step in any direction.

The first step of the method assessed feet crossing during recovery. If a crossing was detected, the recovery step was labeled as an *Unloaded Crossover Step* (UCS). If no feet crossing occurred, the trajectory of the CoM projection on the ground and the initial BoS (prior to step initiation) were used to classify the stepping strategy. *Forward Step* (FS) and *Backward Step* (BS) strategies were labeled if the CoM crossed the front or back boundary of the initial BoS, respectively (Fig. 1.c). *Side Step* strategies without leg-crossover were labeled based on whether the stepping leg was *Loaded* or *Unloaded*. The loaded foot was identified as the polygon first crossed by the CoM trajectory (Fig. 1.c). Finally, steps where the CoM trajectory did not cross the BoS or any initial foot polygon were labeled as *Sub-Critical Step* (SCS). In these cases, the CoM projection remained within the original BoS, between both foot polygons.

2.4. Analysis

Labeled data was used to develop a logistic regression-based model for separating recovery steps, relying on estimates of the perturbation angle and DtFb prior to step initiation. This model included multiple logistic separations between recovery strategies, as in Chatagnon et al. (2023) [1]. Accuracy, sensitivity, and specificity were calculated to evaluate the separation quality among recovery strategy sets. The performance of the predictive model was further evaluated using *Expectation Rates*, defined as the ratio of expected values to the total number of observations, calculated relative to the model's prediction region or a specific recovery strategy.

3. Results

3.1. Estimation of Perturbation Angles

The estimated perturbation angle is illustrated in Fig. 3. Estimation accuracy was higher for perturbations triggering a stepping strategy, showing a mean difference of $7 \pm 8\,deg$ from the ground truth. For non-stepping perturbations, the mean difference increased to $12\,deg$, with a standard deviation of $34\,deg$, as some estimates were nearly opposite to the ground truth.

[1] Information regarding the regressions and parameters of the models can be found in the supplementary materials

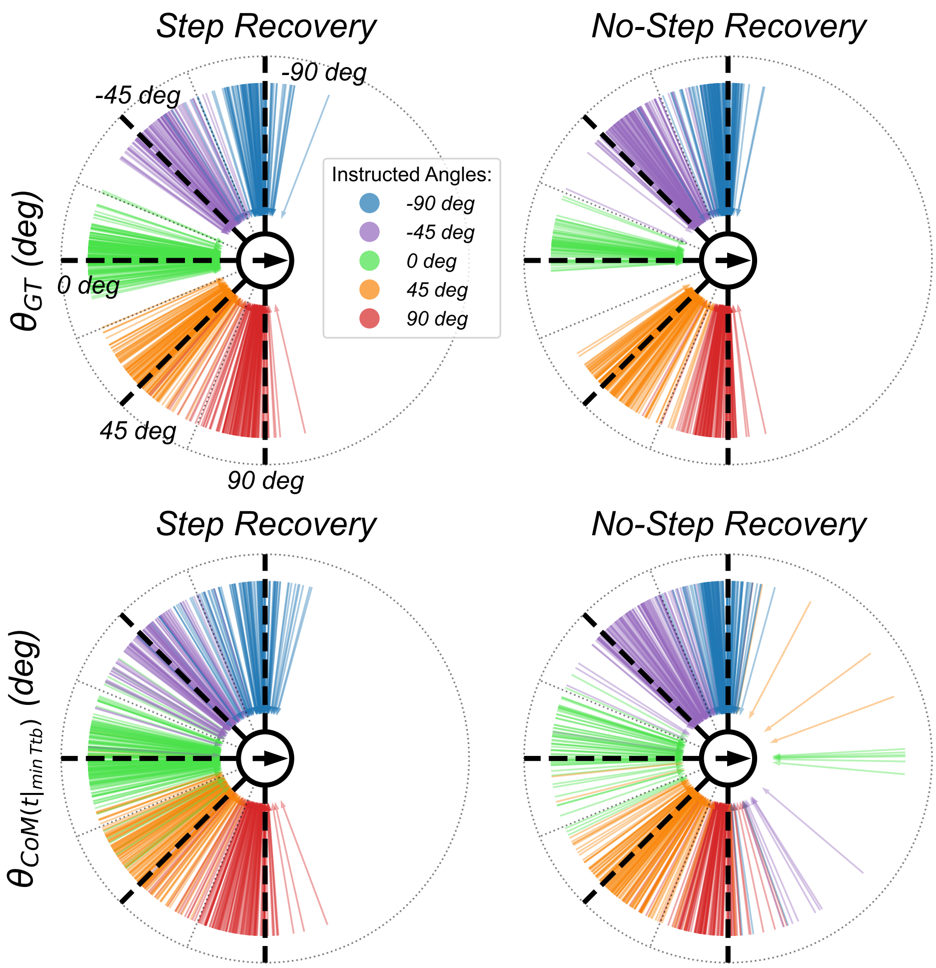

Figure 3: Representation of the estimated perturbation angle ($\theta_{CoM(t_{min\ Ttb})}$), derived from the CoM velocity direction at the moment of minimal Ttb, compared to the *Ground Truth* perturbation angle (θ_{GT}), determined by the CoM velocity direction at the peak perturbation intensity. The angles are displayed for recovery strategies *with* or *without* step. Observations are color-coded based on the *instructed angles* which were provided to the experimenter applying perturbations.

3.2. Recovery Strategy Separation

Before presenting our separation model, we note that classical step recovery classification (which relies on perturbation direction information) can be compared directly to the proposed *Unified* classification for perturbations from antero-posterior and medio-lateral directions. A total of seven labelling discrepancies were observed between the methods. In these cases, recovery steps were labeled as *Forward Steps* or *Side Steps* by the classical method, while the *Unified* method identified them as *Sub-Critical Steps* (SCS). This indicates that the CoM projection neither exited the initial BoS nor entered the support surfaces of the participants' feet.

Stepping recovery strategies labeled using the proposed *Unified* classification are shown in Fig. 4, visualizing strategy regions based on perturbation angle and DtFb. The *Forward Step* strategy was predominantly observed for perturbations with ground truth angles between $-34\ deg$ and $34.3\ deg$, or $-29\ deg$ to $30.4\ deg$ using estimated angles. This region is referred to as the *Centered - Forward Step* (C-FS) region.

Loaded and *Unloaded* side steps were distinguished solely by DtFb, resulting in four distinct regions.

Steps outside the C-FS region with positive perturbation angles were assigned to the *Positive - Side Step* (P-SS) regions, which included the *Positive - Loaded Step* (P-LS) region for DtFb exceeding $6\ cm$, and the

Positive - Unloaded Step (P-US) region for DtFb below 6 cm. Similarly, steps with negative perturbation angles were classified into *Negative - Side Step* (N-SS) regions, divided into the *Negative - Loaded Step* (N-LS) or *Negative - Unloaded Step* (N-US) regions based on DtFb.

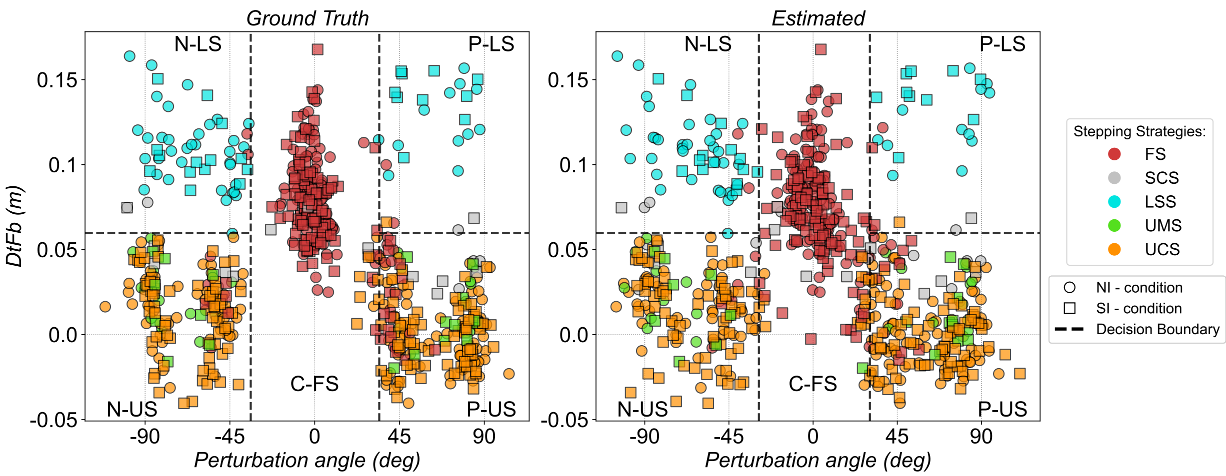

Figure 4: Distance to Foot Boundary (DtFb) plotted against the perturbation angle, with the left panel showing the *Ground Truth* angles and the right panel showing the *Estimated* angles for all recordings involving stepping recovery strategies. Data points are colored by labels of the *Unified* classification method. Dashed lines indicate the decision boundaries of the separation model for recovery strategy.

Logistic separations between these regions are detailed in Table 1.

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	$6.00 * 10^{-2}$ m	99	99	99

Table 1: Characteristics of the logistic regressions used to create the separation between all regions visible in Fig. 4. Separations were created between the *Centered - Forward Step* (C-FS) region and *Side Steps* (SS) regions, i.e. either N-SS regions 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) regions was created using the *Distance to Foot Boundary* (DtFb).

The performance of the separation model, based on the estimated perturbation angle, was also evaluated using *Expectation rates* (see supplementary materials). This shown that, model's regions contained between 76% and 91% of the expected recovery strategies. Additionally, across the entire dataset, more than 88% of observed stepping recovery strategies were located in the expected regions of the model.

4. Discussion and Limitations

4.1. Classification method

The *Unified* classification method proposed in this work relied solely on kinematic data, enabling recovery step labelling without prior knowledge of the perturbation angle. This is essential for studying recovery strategies in ecological settings, where perturbations are not directly applied by an experimenter, such as in Feldmann et al. (2024).

Although we selected direct kinematic variables to minimize the number of hypotheses required, the proposed method still relies on assumptions that must be carefully considered. For example, the classification assumes that the CoM trajectory is relevant for assessing the loaded leg. While this is true in our study, where participants use perturbation load to initiate recovery strategies, it may not apply to other experiments, such as when participants stand on a loaded leg before perturbation. Such an assumption could be problematic to extend this classification method to other contexts such as perturbed locomotion. Additionally, the effectiveness of the method depends on accurate CoM estimation, which is influenced by both the biomechanical model and motion data accuracy. An alternative classification based on the *Center of Pressure* could be inspired from this work but would require an appropriate dataset.

We observed 7 different classifications when comparing the classical approach with our method for perturbations in the antero-posterior and medio-lateral directions. However, our method provided additional information, labelling these recovery steps as *Sub-Critical Steps*, meaning the CoM did not exit the initial BoS or enter the support surfaces under the feet. For recovery steps following perturbations from intermediate directions ($-45 : deg$ and $45 : deg$, see Fig. 1.a), our method is, to the best of our knowledge, the only one capable of providing such labelling.

Finally, it is important to note that the proposed classification method is limited to labelling only the first recovery step. However, subsequent steps can also be classified, particularly following *Side Step* strategies (Borrelli et al., 2021).

4.2. Estimation of Perturbation Angles

As shown in Fig. 3, the perturbation angle can be estimated using the direction of the CoM velocity at the moment of minimal Ttb. The difference between the ground truth and estimated angles was generally small, except for some perturbations that did not lead to stepping recovery strategies. In these cases, the estimated angle was nearly diametrically opposite to the actual perturbation angle, suggesting that the minimal Ttb occurred during recovery, as the CoM was moving back from the perturbation.

Additionally, the proposed estimation method may not be appropriate if an individual is undergoing several perturbations from different directions.

4.3. Separation Model

We proposed a separation model that could cluster stepping strategies based on kinematic information prior to step initiation. Five regions were defined, with three groups (N-SS, C-FS, P-SS) emerging from separation based on perturbation angles. The boundaries between these groups varied depending on whether the separation used ground truth or estimated angles. However, the difference between decision boundaries remained smaller than the average difference between the ground truth and estimated angles. The DtFb was then used to separate *Loaded* and *Unloaded* steps within the *Side Steps* regions (N-SS and P-SS). This separation achieved near-perfect accuracy, similar to results obtained using instructed perturbation angles in Chatagnon et al. (2023).

Eventually, a separation model for stepping and non-stepping recovery strategies could be developed using a similar approach to Chatagnon et al. (2023). Combining both models would create a comprehensive model to predict recovery strategies following external perturbations from any direction. The model's quality would primarily depend on the motion-capture data quality and the accuracy of kinematic variables like the CoM.

5. Conclusion

In this work, we presented a novel classification method for recovery strategies following external perturbations. This method does not require prior knowledge of perturbation angles and enables continuous labelling of recovery strategies, independent of perturbation direction. It could be applied in field studies within ecological environments where limited information on external perturbations is available, offering insights into how balance recovery varies across environments and social contexts.

Additionally, we proposed a separation model to differentiate stepping recovery strategies using kinematic data before step initiation. This model effectively separate various stepping strategies with high accuracy. Further developments could integrate non-stepping strategies, creating a comprehensive tool for predicting recovery strategies after external perturbations based solely on pre-step kinematics with the use of a biomechanical model. Such findings could improve our understanding of recovery strategies and could be used to simulate humanoid agents capable of recovering from similar perturbations, as suggested by Jensen et al. (2023)

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Classification of First Recovery Steps After Quiet Standing Following External Perturbation from Different Directions

Supplementary Material

1. Logistic Separation Models

We expose here the parameters of the logistic regression which have been computed to separates the different recovery strategies observed during the experiments. As a reminder, the formulation of a logistic function is:

$$p(x) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x)}}. \quad (1)$$

The parameters β_0 and β_1 are selected using the maximum likelihood estimation method. The value of these parameters is given for the regression between each region of the model in Table 1. We also provide the decision boundaries, i.e., the value $x_{db} = -\beta_0/\beta_1$, so that $p(x_{db}) = 1/2$. The model predicts the transition from one region to another when the variable of separation reaches the value of the decision boundary.

Regions separated by the regression	Variable of separation	Decision Boundary ($-\beta_0/\beta_1$)	β_0	β_1
C-FS/P-SS (Ground Truth)	Ground Truth Perturbation angle (deg)	34.3 deg	4.69	$-1.37 * 10^{-1}$
C-FS/P-SS (Estimated)	Estimated Perturbation angle (deg)	30.4 deg	4.32	$-1.42 * 10^{-1}$
C-FS/N-SS (Ground Truth)	Ground Truth Perturbation angle (deg)	-34.0 deg	5.47	$1.61 * 10^{-1}$
C-FS/N-SS (Estimated)	Estimated Perturbation angle (deg)	-29.0 deg	5.95	$2.05 * 10^{-1}$
LS/US	DtFb (m)	$6.00 * 10^{-2}$ m	-20.9	349

Table 1: Parameters of the logistic regressions used to create the separation between all regions of the models. Separations were created between the *Centered - Forward Step* (C-FS) region and *Side Steps* (SS) regions, i.e. either N-SS regions 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) regions was created using the *Distance to Foot Boundary* (DtFb).

2. Expectation rates

We provide here two tables containing rates of expectation of the proposed model is the view of our experimental data. *Expectation Rates* are defined as the ratio of expected values to the total number of observations. Here we first present expectation rates with respect to the regions of the model, i.e., the numbers of expected recovery strategies in each region of the model (see Table 2). The second table present expectation rates with respect to the different possible recovery strategies, i.e., the numbers of observation in the expected region of the model for each possible recovery strategy (see Table 3).

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 2: Count and rate of the expected stepping strategies observations for each region of the model. The Expectation Rate here corresponds to the number of times the expected recovery strategy has been observed in a given region of the model divided by the overall number of observations in the region.

Observations Expected in 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 3: Count and rate of observations in the expected regions of the model for each stepping recovery strategy. The Expectation Rate here corresponds to the number of times a given recovery strategy has been observed in the expected region divided by the overall number of times the recovery strategy was used in the dataset.