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Short communication

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 labeling 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.

1. Introduction

Falls are leading causes of injury (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 labeling 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 labeling 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).

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

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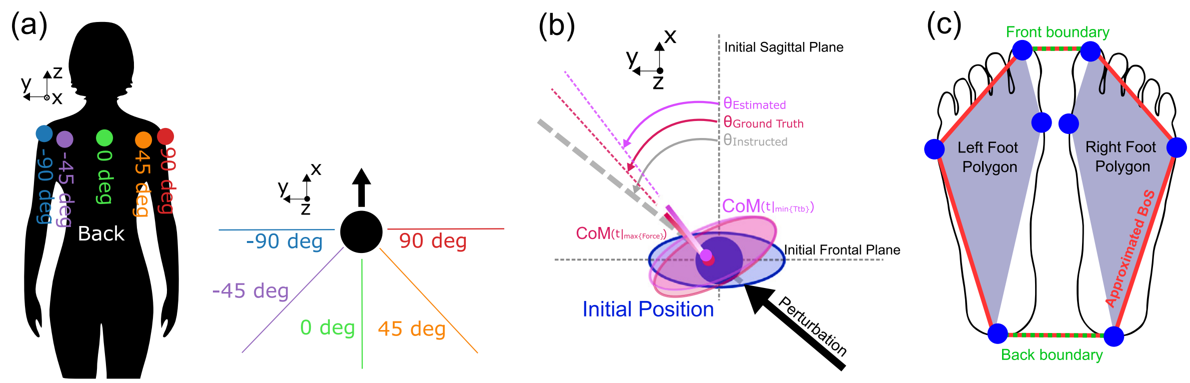

Fig. 1. Overview of the different variables of the methods: (a) Instructed angles and the location of the perturbation application. For clarity, the referential of the instructed angles has been redefined in this study compared to Chatagnon et al. (2023). (b) Representation of the perturbation angles. The *Instructed* angle (gray) 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. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 labeling 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, 5 Hz) (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.

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 ± 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.

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 labeling 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.

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

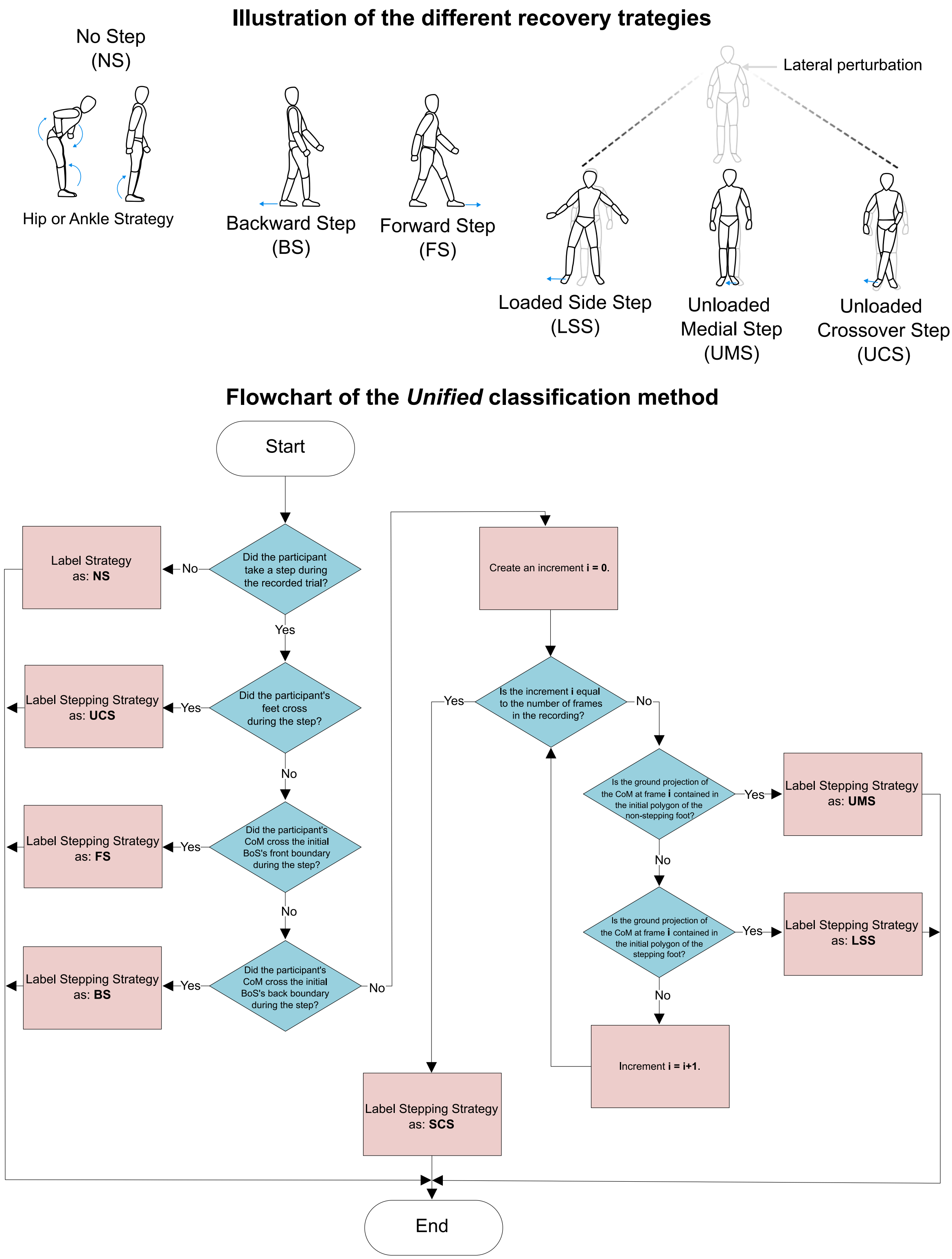

Fig. 2. Flowchart of the *Unified* classification method for labeling stepping recovery strategies after external perturbations from any direction. Strategy names correspond to representations in the figure's top section. The *Sub-Critical Step* (SCS) is not depicted, as it can range from a minor foot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

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,

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).

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

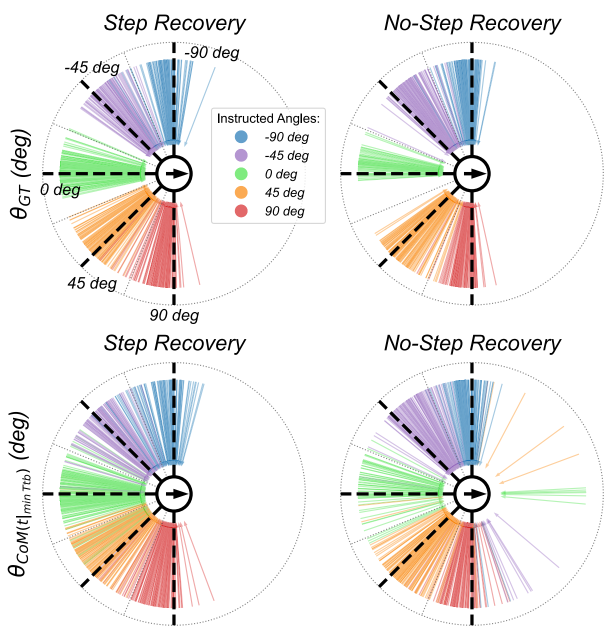

Fig. 3. Representation of the estimated perturbation angle ($\theta_{CoM(t_{min\,Ttb})}$), derived from the CoM velocity direction at the moment of minimal Ttb, compared to the *Ground Truth* perturbation angle (θ_{GT}), determined by the CoM velocity direction at the peak perturbation intensity. The 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.

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.

Logistic separations between these regions are detailed in Table 1.

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 labeling 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, labeling 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 labeling.

Finally, it is important to note that the proposed classification method is limited to labeling 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.

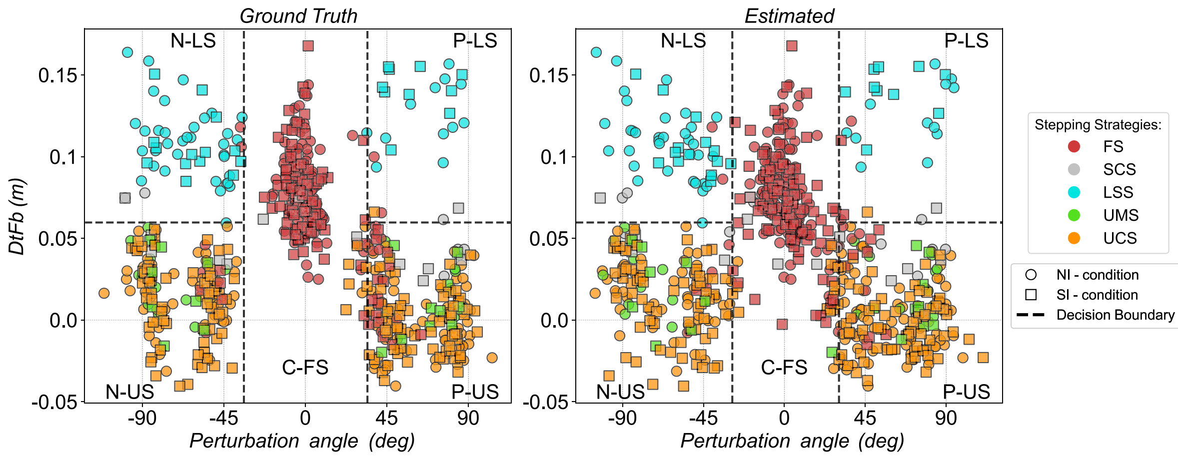

Fig. 4. Distance to Foot Boundary (DtFb) plotted against the perturbation angle, with the left panel showing the *Ground Truth* angles and the right panel showing the *Estimated* angles for all recordings involving stepping recovery strategies. Data points are colored by labels of the *Unified* classification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

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 labeling 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)

CRediT authorship contribution statement

Thomas Chatagnon: Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Anne-Hélène Olivier:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Ludovic Hoyet:** Writing – review & editing, Supervision. **Julien Pettré:** Supervision, Funding acquisition. **Charles Pontonnier:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jbiomech.2025.112639.

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