Anticipatory adjustments of posture allow elderly fallers to achieve a balance recovery performance equivalent to elderly non-fallers

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Abstract
Background: In an important number of laboratory-based perturbation experiments, differences in the balance recovery performance of elderly fallers and non-fallers are moderate or absent. This performance may be affected by the subjects adjusting their initial posture in anticipation of the perturbation.
Research questions: Do elderly fallers and non-fallers adjust their posture in anticipation of externally-imposed perturbations in a laboratory setting, and how does this impact their balance recovery performance?
Methods: 21 elderly non-fallers, 18 age-matched elderly fallers and 11 young adults performed both a forward waist-pull perturbation task and a Choice Stepping Reaction Time (CSRT) task. Whole-body kinematics and ground reaction forces were recorded. For each group, we evaluated the balance recovery performance in the perturbation task, change in initial center of mass (CoM) position between the CSRT and the perturbation task, and the influence of initial CoM position on task performance.
Results: The balance recovery performance of elderly fallers was equivalent to elderly non-fallers ($p > 0.5$ Kolmogorov-Smirnov test). All subject groups anticipated forward perturbations by shifting their CoM backward compared to the CSRT task (young: 2.1% of lower limb length, elderly non-fallers: 2.7%, elderly fallers: 2.2%, Hodges-Lehmann estimator, $p < 0.001$ Mann-Whitney U). This backward shift increases the probability of resisting the traction without taking a step.
Significance: The ability to anticipate perturbations is preserved in elderly fallers and may explain their preserved balance recovery performance in laboratory-based perturbation tasks. Therefore, future studies aimed at predicting fall risk in elderly adults should carefully control for this postural strategy, by interleaving perturbations of different directions for example.

I. Introduction

With aging, there is an increasing incidence of falling (1), causing dramatic impact on health and quality of life (2). As falls may occur even in elderly adults who appear healthy (1), a research hypothesis is that elderly adults fall when they are unable to respond appropriately to an external perturbation (3,4). Therefore, a major focus of research has been to characterize the balance responses of elderly fallers and non-fallers to controlled external perturbations in a laboratory environment. Although certain studies show moderate differences between elderly fallers and non-fallers (3,5–7), there is a surprising number of prospective studies which fail to show any difference between future fallers and non-fallers (8–11). This is unlikely to be due to the study

design simply failing to pick up on existing differences, because these studies show clear differences between young and elderly adults (3).

Our hypothesis is that elderly fallers perform as well as elderly non-fallers in laboratory-based perturbation experiments because they are able to anticipate important characteristics of the upcoming perturbation (direction, timing, amplitude, etc.). This ability to anticipate provides several mechanisms for improving the response to perturbations which may otherwise lead to a loss of balance (12). Our specific hypothesis is that it allows subjects to adjust their initial posture. Indeed, a recent theory of postural control emphasizes that subjects can use their own weight to resist an external perturbation by shifting their center of mass (CoM) in the opposite direction to the perturbation force, prior to perturbation onset (13). This accounts for the experimental observation that young adults exposed to repeated backward translations of the support surface (equivalent to a forward push on the CoM) gradually shift their CoM backward and improve their ability to resist the perturbation without taking a step (14). It is however not known whether and to what extent the elderly adjust the position of their CoM in anticipation of external perturbations, and how this impacts their balance performance. Although elderly adults are able of adjusting their standing CoM position when explicitly instructed to do so, the range of standing postures which they can adopt is more limited than in the young (15). This suggests that the capacity for adjusting CoM position may be reduced in the elderly compared to the young. We nevertheless predict that this capacity for postural adjustment is preserved in elderly fallers compared to elderly non-fallers, thus attenuating the differences in balance recovery performance between elderly fallers and non-fallers.

Young adults, elderly non-fallers and elderly fallers participated in a forward waist-pull perturbation experiment. We first quantified the balance recovery performance of the different groups. We then determined the initial position of the CoM adopted by the different groups. Performance in this task would benefit from initially leaning backward, since this allows the person to use their own weight to resist the traction. For comparison, we assessed the initial posture of the same subjects when performing a Choice Stepping Reaction Time (CSRT) task (16). In this task, the subject must initiate a voluntary forward step, without an external perturbation, therefore leaning backward would be disadvantageous. We quantified the change in posture between the two tasks, and the effect of backward leaning on task performance in the perturbation task.

II. Methods

1. Protocol

a) Population

Fifty healthy subjects participated in both the stepping task and the perturbation task, spread in three groups: young, elderly non-fallers and elderly fallers. Fallers and non-fallers were separated based on their fall history in the previous year. Details of the inclusion and exclusion criteria are provided in the Supplementary Methods (V.1.a), and characteristics of the subjects are summarized in Table 1. Elderly subjects completed the Activities Specific Balance

Confidence questionnaire (17) to estimate fear of falling. All subjects provided written informed consent to the experiment as approved by the local and national ethics committees.

Table 1 Characteristics of the subjects

		Young	Elderly non-fallers	Elderly fallers
	Number of subjects Number of women	11 5	21 13	18 14
Age (years)	Mean Range	25 22 - 27	74 69 - 83	75 70 – 82
Mass (kg)	Mean Range	69 59 – 85	67 49 – 98	70 55 – 95
Height (m)	Mean Range	1.70 1.62 – 1.84	1.63 1.51 – 1.86	1.61 1.46 – 1.90

b) Experimental setup

The lower limb length of each subject was measured as the vertical distance between the great trochanter and the base of the foot. Subjects were equipped with reflective markers on the tip of the second toe of each foot, and on the fifth metatarsal joint of the foot, whose positions were recorded using eight cameras (Eagle 1.3 Mpx, Motion Analysis(R), Santa Rosa, CA, USA) sampled at 100 Hz. Four force platforms (60 cm × 40 cm, Bertec(R), OH, USA) were used to record ground reaction forces and torques sampled at 1000 Hz . All subjects performed the CSRT task first, and then the perturbation task. For each trial, subjects initially stood quietly with one foot on each of the two back platforms (Figure 1). The protocol and results of the CSRT are published elsewhere (16) and are summarized in the Supplementary Methods (V.1.b).

In the perturbation task, subjects wore a safety harness to prevent injury in case of a fall. Three cables were attached to the harness at waist level. Each cable could pull the person either straight forward or laterally at an angle of 30° (Figure 1.A). On any given trial, one of the cables was attached to a rotating motor which, after a random waiting period between 1 and 12 seconds, would apply a perturbation to the selected cable. This perturbation was proportional the person’s weight, and followed one of two signals: a short perturbation lasting 200 ms and with a peak amplitude of 27% of the subject’s weight (brown curve in Figure 1.B), and a long perturbation lasting 1000 ms and with a peak amplitude of 14% of the subject’s weight (orange curve in Figure 1.B).

To avoid a whipping effect when stretching the cable, an initial pretension was applied by the rotating motor. To prevent the perturbation direction from being sensed through this initial motor pretension, equivalent masses were attached to the two other cables. This resulted in a total forwards pretension force of around 3.5% of the subject's weight. Thus, on every trial, an experimenter would attach one of the three cables to the motor, and the other two cables to small masses. This was done behind a screen, such that the perturbation direction was not predictable for the subject. Additional details may be found in the Supplementary Results (VI.1).

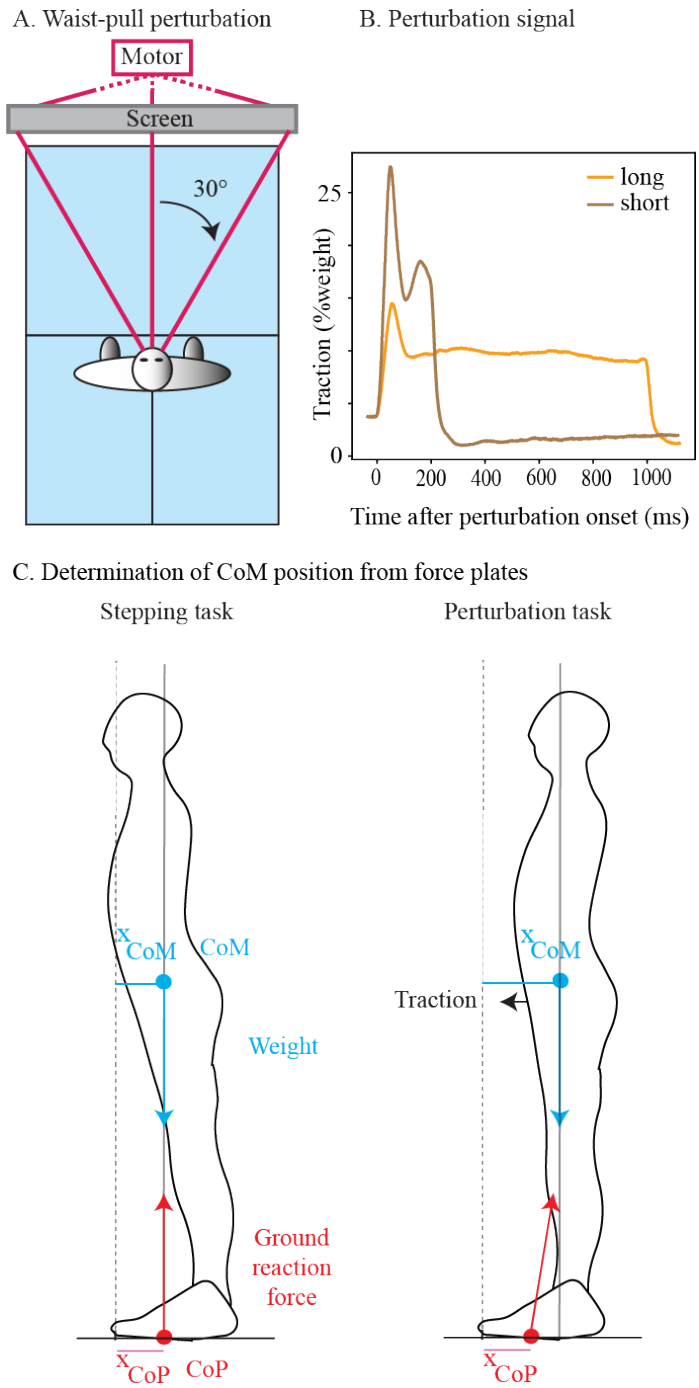

Figure 1 Methods A. Protocol: the subject initially stands with one foot on each of the two back force platforms out of four (blue); in the perturbation task three cables are attached to the subject's harness at waist level and, on any given trial, only one of these cables is attached to a motor hidden behind a screen. B. The perturbation is proportional to the subject's weight and is either short (brown) or long (yellow). C. The person is assumed to be in a quasi-static posture before trial onset. For the CSRT task (left), this entails that the CoM (blue dot) and CoP (red dot) are aligned. For the perturbation task (right), due to the initial pre-tension (black arrow), the CoM is backward of the CoP.

Subjects were instructed to recover balance as fast as possible and in the shortest possible distance. Each elderly subject performed at least 18 trials, with each of the six perturbations (three directions, two amplitudes) presented at least three times, in a random order. Each young subject performed at least 24 trials, with each perturbation presented at least four times, in a random order.

2. Analysis

a) Initial posture

In quasi-static standing posture, the torques acting upon the body cancel each other out. Therefore, the vertical distance between the CoM and the center of pressure (CoP) is determined by the torque of the external forces acting on the body other than weight and the ground reaction force (13). In free standing, such as during the CSRT task, the average positions of the CoM and CoP are therefore vertically aligned (Figure 1.C, left panel). The averages must be taken over a sufficient duration to validate the quasi-static hypothesis. We took averages over a 500 ms period. In the perturbation tasks, since there was an initial pretension exerted by the cables in the forward direction, the CoM is backward of the CoP (Figure 1.C, right panel). Nevertheless, the position of these points within the feet remained free, allowing subjects to adopt different initial postures. We therefore analysed the position of the CoM's projection on the ground relative to the midpoint between the toes of the left and right feet.

For perturbation trials, the traction was assumed to be horizontal and exerted at a height equal to the subject's lower limb length L. The mean forward traction exerted on the person was taken to be equal to the mean forward force exerted by the person on the ground F_x, as measured by the forceplates. The equilibrium of torques implies:

$$x_{CoM} = x_{CoP} + \frac{L.F_x}{M.g}$$

Where x_{CoP} and x_{CoM} are the antero-posterior location of the CoP and CoM relative to the mid-point between the toes of the left and right feet (Figure 1.C). x_{CoP} is measured by combining the force plate data and the kinematic positions of the markers on the toes of the left and right feet. $M.g$ is the person's weight, defined as the mean vertical ground reaction force during the waiting periods in the stepping task. The relative values of x_{CoP} and x_{CoM} in perturbation trials are shown in the Supplementary Results (VI.1).

All averages were taken over the 500 ms period preceding the onset of the trial. For comparison across subjects, results were normalized to the subject's lower limb length.

b) Performance in perturbation trials

Performance was assessed by the distance required to recover balance, measured between the initial foot position and the new foot position measured once a steady balance was recovered. The shorter the distance, the better the task success. For comparison across subjects, this distance was normalized to the subject's lower limb length. The distribution of distances was bimodal

(Figure 2.A-D), and in trials for which this distance was less than 8% of the person's lower limb length, it was considered that the subject did not step (non-step trial). Additional details are provided in the Supplementary Methods (V.2).

We then analyzed two variables: the frequency of non-step trials, and the recovery distance for perturbation trials in which the subject took at least one step (step trials).

3. Statistical analysis

The 2-proportion z-test is used to compare the proportion of non-step trials across subject groups and across perturbation amplitudes.

The Mann-Whitney U-test is used to compare differences in the median of distributions. It is first used to compare the median performance in the perturbation task across subject groups and across perturbation amplitudes. It is then used to compare the median initial CoM position between the CSRT task and the perturbation task, for each subject group. Finally, it is used to compare the median initial CoM position for perturbation trials with and without steps, for each subject group.

When a statistical difference in medians is found, then this difference is estimated using the Hodges-Lehmann estimator.

When no statistical difference in medians is found, as occurs for the performance in the perturbation task of elderly fallers and non-fallers for both perturbation amplitudes, then the Kolmogorov-Smirnof test is used to determine whether there is any difference in the distributions.

Additional details may be found in the Supplementary Methods (V.3).

III. Results

1. Performance in the perturbation task

The distribution of the distances required to stop for each group and the two perturbation durations are illustrated in Figure 2.A-D. When considering the distance required to stop in trials with at least one step, there was no significant difference between the performance of the elderly fallers (red) and elderly non-fallers (blue), regardless of the perturbation ($p > 0.5$ Kolmogorov-Smirnov test, for both short and long perturbations). For short perturbations, this distance was thus 33% of lower limb length for elderly non-fallers and 34% for elderly fallers. For long perturbations, this distance was thus 50% for both elderly non-fallers and fallers.

The elderly fallers and non-fallers were then grouped together (purple trace) for comparison with young subjects (green). For young subjects, the distance required to stop is 43% of lower limb length for both short and long perturbations. Thus, for long perturbations (Figure 2.D), elderly subjects recovered balance with more distance than young subjects ($p < 0.001$, Mann-Whitney U-test). This difference corresponds to an increase by 5.4% of lower limb length (Hodges-Lehmann estimator). However, for short perturbations (Figure 2.C), elderly subjects recovered

balance with less distance than young subjects ($p < 0.001$, Mann-Whitney U-test). This difference corresponds to a decrease of 9.3% of lower limb length (Hodges-Lehmann estimator).

The proportion of non-step trials was larger for short compared to long perturbations ($p < 0.001$, 2-proportion z-test, see Figure 2.E). Within each perturbation type, the proportion of non-step trial was slightly smaller for young compared to elderly but this difference was not significant. No difference was observed between elderly fallers and elderly non-fallers ($p > 0.1$, 2-proportion z-test), as for the distance to recover balance in step trials.

2. Change in posture across tasks

The distribution of initial CoM position for each group and both tasks is shown in Figure 3. For the perturbation task, the median initial distance between the CoM and the toes was 17.5% of the person's limb length, with no significant differences across groups ($p > 0.1$, Mann-Whitney U-test). For the stepping task, the median distance was 15.4% of the person's limb length. It was slightly smaller in non-fallers (15.2%), compared to fallers (15.9%, $p < 0.01$, Mann-Whitney U) and young adults (15.7%, $p < 0.05$, Mann-Whitney U). No significant difference was found between young adults and elderly fallers ($p > 0.5$, Mann-Whitney U).

All groups of subjects shift their CoM backward in the perturbation task compared to the stepping task (young: $p < 0.001$, non-fallers : $p < 0.001$, fallers : $p < 0.001$, Mann-Whitney U). This backward shift is of 2.1% of lower limb length for the young adults (Figure 3.A, Hodges-Lehmann estimator), 2.7% for the elderly non-fallers (Figure 3.B) and 2.2% for the elderly fallers (Figure 3.C).

At an individual level, in elderly adults, the change in posture across tasks (Hodges-Lehmann estimator) was not correlated with fear of falling as assessed with the Activities-specific Balance Confidence (17) (elderly fallers: $p > 0.3$, elderly non-fallers: $p > 0.7$, linear regression).

3. Influence of initial posture on balance performance in the perturbation task

To quantify the effect of the initial posture on performance, trials with and without steps were compared. Figure 4 shows the distribution of initial postures for trials without steps (pink) and trials with at least one step (purple) for each group. All groups of subjects had a more backward initial CoM position in non-step trials than in trials with at least one step (young adults : $p < 0.01$, Figure 4.A; elderly non-fallers : $p = 0.01$, Figure 4.B; elderly fallers : $p < 0.01$, Figure 4.C; Mann-Whitney U-test). This difference is of 2.8% of lower limb length for the young adults (Hodges-Lehmann estimator), 0.7% for the elderly non-fallers and 2.3% for the elderly fallers . In all non-step trials, all groups initially leaned backward by at least 15% of lower limb length.

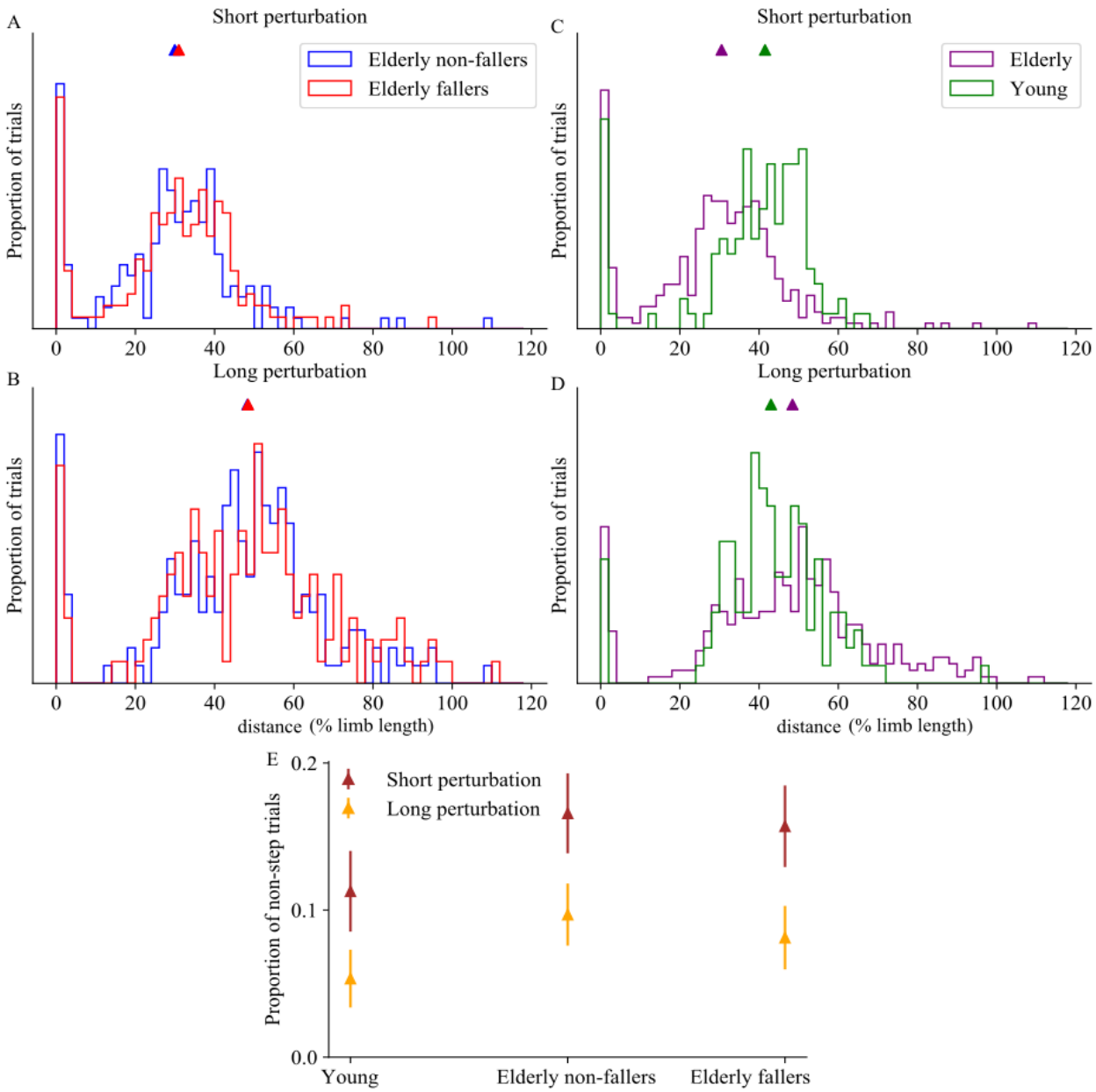

Figure 2 Performance in the perturbation task. Graphs show the normalized distribution of distance required to stop the motion triggered by the perturbation, normalized to the subject's lower limb length, for short (A, C) and long (B, D) perturbations. In panels A. and B., elderly non-fallers are shown in blue and elderly fallers in red. In panels C. and D., elderly fallers and non-fallers are pooled (purple), for comparison with the young subjects (green). The median distance for each group and perturbation duration is indicated as a triangle on the top of the graph. E. Proportion of non-step trials for short (brown) and long (orange) perturbations; error bars indicate the standard error on the estimation of this proportion (additional details are provided in the Supplementary Methods V.3).

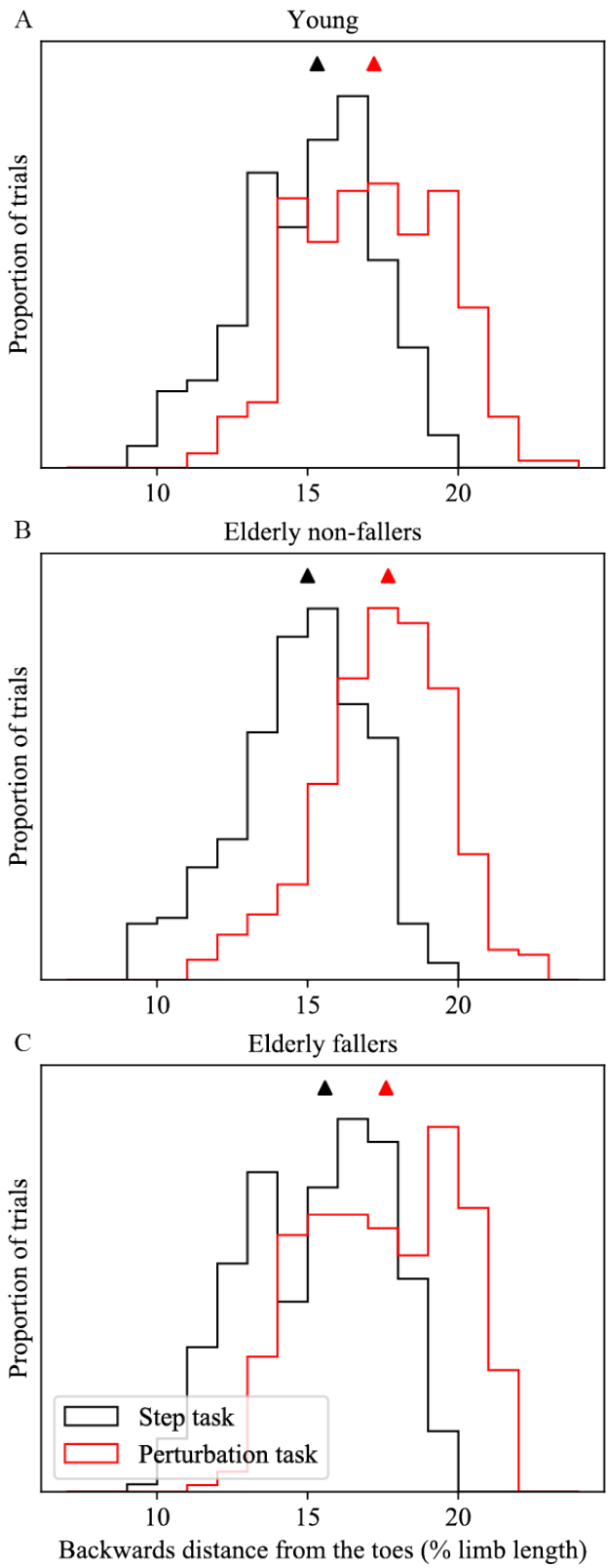

Figure 3 Change in posture across tasks. Graphs show the normalized distribution of the initial position of the CoM backward of the toes in the perturbation task (red) and in the CSRT task (black), for young subjects (A), elderly non-fallers (B) and elderly fallers (C).

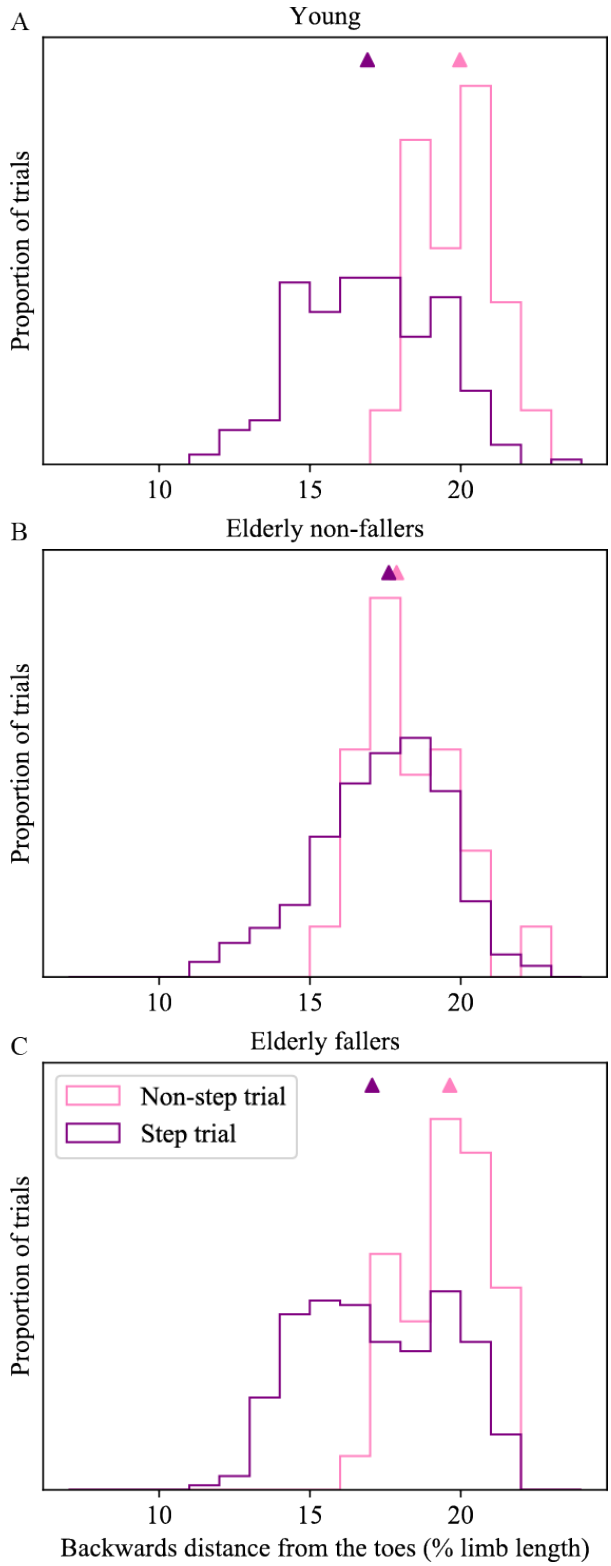

Figure 4 Influence of posture on balance performance. Graphs show the normalized distribution of the initial CoM position in the perturbation task for trials where the subjects took a step (purple) and for trials where the subjects did not step (pink), for young subjects (A), elderly non-fallers (B) and elderly fallers (C).

IV. Discussion

When exposed to repeated waist-pull perturbations with a dominant forward component, elderly fallers performed as well as elderly non-fallers in terms of distance required to recover balance, even though the perturbation timing, amplitude, duration and lateral direction were all unpredictable. This study completes the list of studies which have failed to reveal differences in the balance responses of elderly fallers and non-fallers to externally-triggered perturbations in a laboratory setting (8–11).

In the protocol used in this study, subjects must produce a backward torque to compensate for the forward torque induced by the traction. This aspect probably appeared very clearly to each subject as soon as the three cables were attached to the harness. The biomechanical action required is a shift of the CoP in front of the CoM. However, the CoP cannot be brought further forward than the toes. Therefore, if the person's feet remain in place, the maximal backward torque which they can exert is proportional to the distance between their initial CoM position and the toes. Shifting the CoM backward in anticipation of the perturbation would thus increase this distance, thereby increasing the backward torque for resisting the traction. This biomechanical requirement predicts the more backward position of the CoM adopted by all groups of subjects in the perturbation task, relative to the CSRT task (Figure 3).

With aging, there is a reduction of the functional base of support (15,18), suggesting that elderly subjects may be less able to bring their CoP close to the toes to compensate for a forward destabilization. A more relevant functional variable may therefore be the backward distance between the CoM position and the forward edge of the functional base of support. In the Supplementary Results (VI.2), we show that the results still hold when considering the initial position of the CoM relative to the fifth metatarsal joint, which may be considered closer to where the forward edge of the functional base of support is in elderly adults.

Shifting the CoM backward in preparation for the perturbation appears crucial for resisting the traction without taking a step. In this experiment, subjects were instructed to recover balance in the shortest possible distance. Therefore, recovering balance without taking a step is the best response, according to the task instructions. Our results show that initially positioning the CoM further backward increases the chance of avoiding stepping. Trials without steps only occurred when the initial CoM position relative to the toes was larger than 15% of the lower limb length. Thus, the possibility of resisting the traction without taking a step seems to rely critically on the subject's backward initial posture.

Our results thus show that, with advance knowledge of the upcoming perturbation direction, subjects shift their CoM prior to the perturbation onset in the opposite direction of the perturbation direction. This ability is preserved in elderly adults, regardless of their experience of a fall. Thus, this preserved ability may contribute to the capacity of elderly fallers to perform as well as elderly non-fallers in laboratory experiments, notably when the perturbation direction can be anticipated. Additionally, such advance knowledge of the perturbation may allow subjects to prepare an appropriate response, thus potentially explaining the faster initiation of stepping after a perturbation in elderly fallers compared to non-fallers (4). Anticipation of upcoming balance

perturbations has thus been suggested to improve action selection, processing, conduction delay compensation and error identification (12).

In daily life, we suggest that if elderly subjects fall it is mostly when they encounter a perturbation which they had not anticipated. They then cannot adjust their CoM position accordingly. Thus, in order to better distinguish between elderly fallers and non-fallers, future studies must be designed to probe the response of the subject to perturbations of unexpected direction. Forward and backward (or leftward and rightward) perturbations should therefore be interleaved in a random manner, to prevent subjects from anticipating on perturbation direction. If all perturbations have a dominant forward direction, the subjects can efficiently resist the perturbation simply by leaning backward. However, leaning backward is a counter-productive strategy in the case of backward perturbations. Therefore, interleaving forward and backward perturbation should prevent the subjects from using an anticipatory leaning strategy, and would therefore specifically probe the response of the subject to a perturbation of unexpected direction. This may be more relevant to ecological situations in which an elderly person encounters an unexpected perturbation, and may therefore provide a better assessment of fall risk.

V. Supplementary methods

1. Protocol

a) Population

Young subjects aged less than 30 years were recruited, and were excluded if they had a medical history of musculo-skeletal or neurological problems, or if they were taking medication that could affect motor performance.

Elderly subjects aged at least 70 years were recruited, and were excluded following a medical visit if they met the following criteria:

- Taking more than 3 different psychotropic medications per day
- Regularly using walking aids, such as a crutch or a walking stick
- Severe dyspnea for light efforts
- Congestive cardiac failure at level 3 or more, according to the New York Heart Association standards
- Taking medication for Parkinson or Alzheimer’s disease
- A Mini Mental State Examination score of less than 23
- Having experienced a stroke, either in the previous six months, or that left lasting damage
- Having undergone lower limb surgery in the previous six months
- Having visual acuity of less than 2 on the Monoyer scale
- Having a frailty score of 4 or more, according to Fried and colleagues (19)

Elderly subjects were retrospectively classified as fallers if they had experienced a fall in the previous year, defined as ‘an event, following an imbalance, which results in a person coming to rest inadvertently to a lower level, involving an impact, consecutive to the balance recovery actions failure and not a result of a major intrinsic event or overwhelming hazard’(20).

All subjects provided written informed consent to the experiment as approved by the Comité de Protection des Personnes Lyon Sud Est III.

b) Choice Stepping Reaction Time task

The protocol of the CSRT is illustrated in Figure 5. There were four stepping targets placed in front of the subject at a distance of 40% of the subject's lower limb length. Two of these targets were located centrally (yellow and orange), and the two others were located laterally, at an angle of 30° (red and green). Four light-emitting diodes (LED), corresponding to the four targets, were placed in front of the subject to indicate on which target the subject should step. The subject was instructed to step onto leftwards targets (red and orange) with the left foot, and onto rightwards targets (yellow and green) with the right foot. The task instruction was the following: "As soon as a LED lights up, place your foot as fast as possible onto the target indicated by the LED." Each subject performed a series of at least 16 trials, with each target presented at least four times, in random order. Trials in which the subject appeared to hesitate for a long while, or in which the subject stepped with the wrong foot, were repeated at the end of the initial sequence of 16 trials.

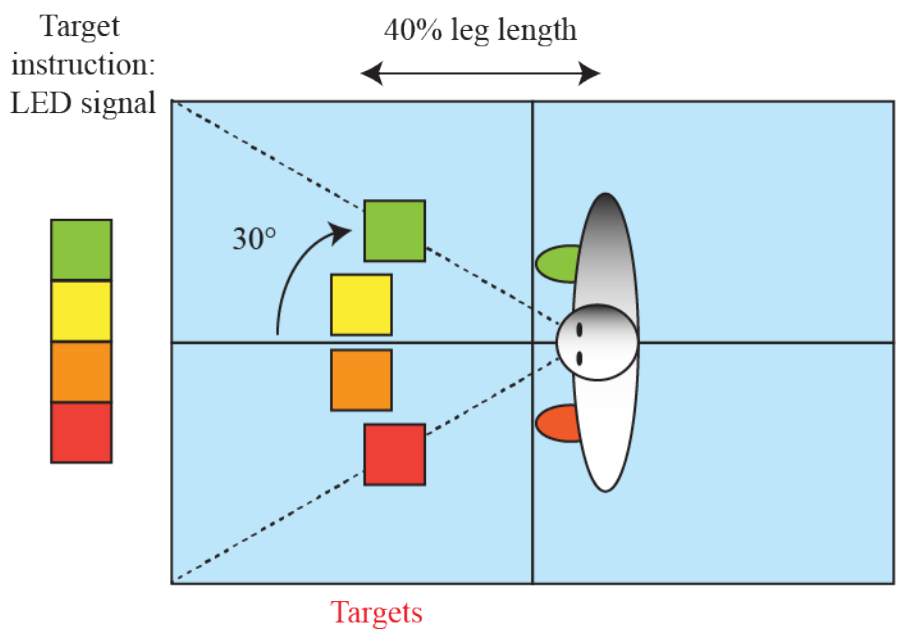

Figure 5 CSRT protocol. As in the perturbation task, there are four force platforms (blue) and the subject stands initially with one foot on each of the back platforms. Additionally, there are four LEDs which indicate which of the four targets the subject should step on.

2.Performance in the perturbation task

Subjects were instructed to recover balance as fast as possible and in the shortest possible distance. In the perturbation task, there were a certain number of trials for which the person did not take a step. Given the task instruction, which was to recover balance as fast as possible and in the shortest possible distance, trials without steps should be considered a success. In such trials however, the time at which balance was recovered is ambiguous. Therefore, performance was not

determined according to the time required to initiate or perform a protective step, which are commonly used measures of performance in perturbation tasks (4).

Instead, performance was determined as the distance required to recover balance, based on the trajectory of the person's feet. Thus, if the subject's feet did not move, this distance was considered null. If the person took a step, then this distance was the length of the step. In the example presented in Figure 6, the person took two steps forward (one with each foot), then took a step backward with the left foot (blue). The distance required to stop is then considered to be the distance required to stop for the foot which stepped the furthest away from its initial position (here the left foot).

The position of each foot is determined by a kinematic marker placed on the fifth metatarsal joint of the foot. For each foot, the average initial position during the 500 ms preceding the perturbation onset is determined (Figure 6, blue and red dots for the left and right feet). The trajectory of the foot in the 2.5 seconds following the perturbation onset is projected onto the horizontal plane (Figure 6, blue and red curves). The point on this trajectory which is furthest from the initial position is determined (Figure 6, black dots and lines), and this is considered the distance required by that foot to stop. The distance required by the person to stop is then the maximum of the distance required by each foot. Finally, this distance is normalized to the subject's lower limb length for comparison across subjects.

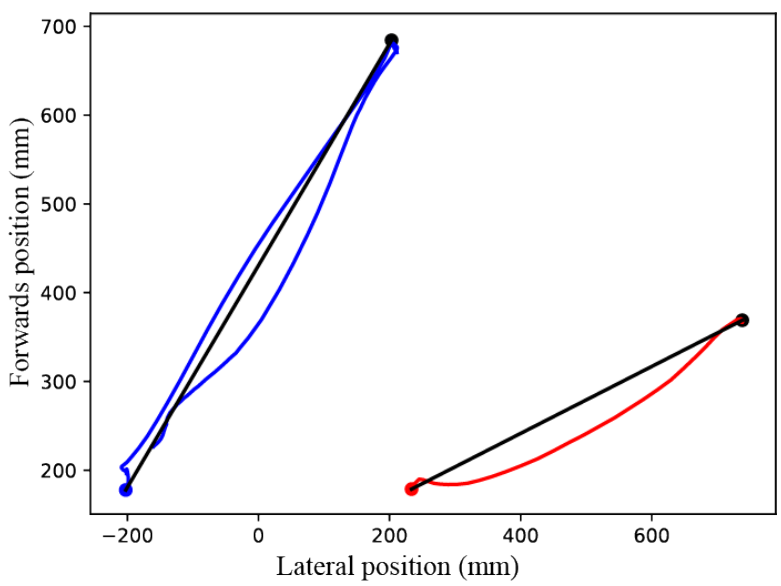

Figure 6 Calculation of the distance required to stop. The initial position of the left and right feet are shown as a blue and a red dot. The trajectory of the foot after the onset of the perturbation is projected onto the horizontal plane (blue and red curves). The point of the trajectory furthest from the initial position is shown as a black dot.

3. Statistics

a) Proportion of trials without steps

The 2-proportion z-test is used to compare the proportion of non-step trials across subject groups and across perturbation amplitudes. The null hypothesis is that the observations in the two subsets come from two binary distributions with the same mean. With the first subset containing $N_{trials,1}$ trials and $N_{non\text{-}step,1}$ non-step trials, and the second subset containing $N_{trials,2}$ trials and $N_{non\text{-}step,2}$ non-step trials, the pooled sample mean is given by:

$$M = \frac{N_{nonstep,1} + N_{nonstep,2}}{N_{trials,1} + N_{trials,2}}$$

The standard error of the sample mean, when sampling N_{trials} trials from a binary distribution of mean M is given by:

$$SE = \sqrt{\frac{M(1-M)}{N_{trials}}}$$

Thus, the standard error of observing the two sample means is:

$$SE = \sqrt{\frac{M(1-M)}{N_{trials,1}} + \frac{M(1-M)}{N_{trials,2}}}$$

The test statistic is a z-score, which quantifies how likely the observed difference in proportions across the two subsets is, given this standard error:

$$z = \frac{\frac{N_{nonstep,1}}{N_{trials,1}} - \frac{N_{nonstep,2}}{N_{trials,2}}}{SE}$$

When the each subset of trials contains at least 10 successes and 10 failures (a condition which is indeed verified in our data), then this z-score is normally distributed, and the probability of observing a z-score at least as extreme is evaluated as a p-value.

For graphical representation (Figure 2.E), we estimate the proportion of trials in a given subset as:

$$P = \frac{N_{nonstep,i}}{N_{trials,i}}$$

And the standard error on this estimate as:

$$SE = \sqrt{\frac{P(1-P)}{N_{trials,i}}}$$

b) Differences in medians of distributions

We use the Mann-Whitney U-test to evaluate whether there are differences in the medians of the distributions of:

- performance in perturbation trials with steps, between subject groups and between perturbation amplitudes
- initial CoM position between the CSRT task and the perturbation task, for each subject group
- initial CoM position between perturbation trials with and without steps, for each subject group.

The null hypothesis is that the observations come from distributions with the same median. To evaluate this, the observations are pooled and ranked, and R_1 the sum of ranks of the first group is calculated . The U-statistic is given by:

$$U = R_1 - \frac{N_{trials,1}\left(N_{trials,1}+1\right)}{2}$$

Note that if the samples from the first group are all smaller than those from the second group, then $R_1 = \frac{N_{trials,1}\left(N_{trials,1}+1\right)}{2}$, and $U = 0$.

The ranking of observations is illustrated in Figure 7.A for the comparison of performance in perturbation trials with steps, between elderly (white) and young (black) subjects, for short (left panel) and long (right panel) perturbations.

When a statistical difference in medians is found, then the amplitude of this difference is estimated using the Hodges-Lehmann estimator. All possible pairs are formed with a sample from the first and a sample from the second distribution. For each pair, the difference between the first and second sample is calculated, and the median of these differences is used as an estimate of the difference between the two distributions. The distribution of differences is illustrated in Figure 7.B for the comparison of performance in perturbation trials with steps, between elderly and young subjects, for short (left panel) and long (right panel) perturbations.

When no statistical difference in medians is found, then the Kolmogorov-Smirnov test is used to determine whether there is any difference in the distributions. The null hypothesis is that the two sets of observations come from an identical distribution. The test statistic is the maximal difference between the cumulative distribution functions of the two observations, shown as a black bar in Figure 7.C for the comparison of performance in perturbation trials with steps, between elderly non-fallers (blue) and elderly fallers (red), for short (left panel) and long (right panel) perturbations.

VI. Supplementary results

1. Compensation for the initial pretension in perturbation trials

In perturbation trials, there is an initial pretension in the cables which exerts forward torque on the subject, which must be compensated by a forward position of the CoP relative to the CoM (Figure 1.C right panel). The distribution of CoP (blue) and CoM (red) in perturbation trials is shown in Figure 8 relative to the CoM position in CSRT trials (black). Relative to the CSRT trials, subjects compensate for the pretension through a slight forward shift in CoP (Y: 0.4% limb length, $p = 0.05$, O : 0.7%, $p < 0.01$, F : 0.9%, $p < 0.01$), and a larger backward shift in CoM (Y: 2.1% limb length, $p < 0.01$, O : 2.7%, $p < 0.01$, F : 2.2%, $p < 0.01$).

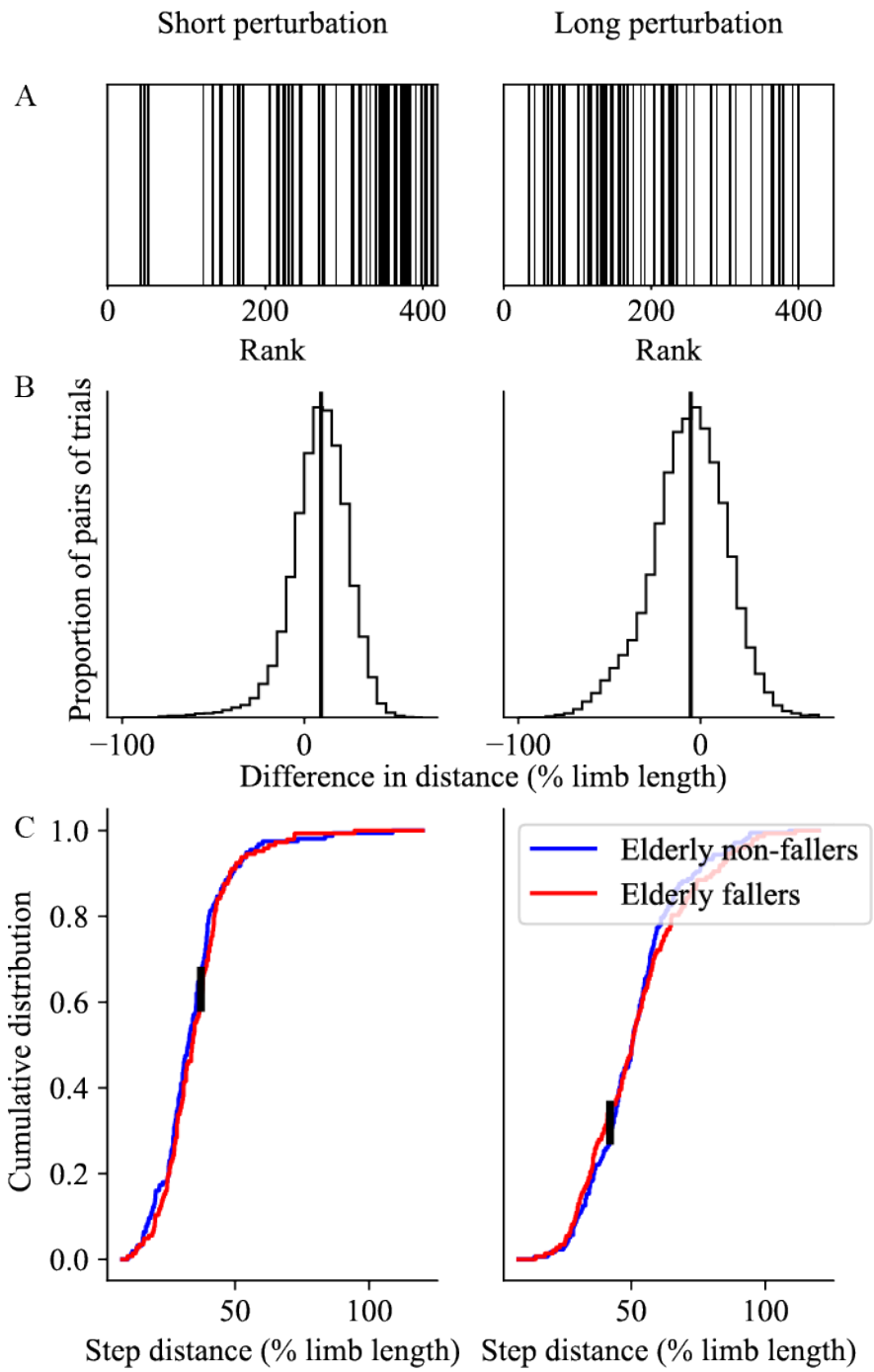

Figure 7 Illustration of statistical methods. Differences in the distribution of distances required to stop in perturbation trials with steps (normalised to limb length), between young and elderly subjects (A,B), and between elderly fallers (red) and elderly non-fallers (blue) (C), for short perturbations (left panels) and long perturbations (right panels). A. Trials sorted by rank, with the elderly shown in white and the young shown in black. B. Distribution of the difference in distance between elderly and young subjects, for all pairs of trials. C. Cumulative distribution of distances for elderly non-fallers (blue) and elderly fallers (red). The maximal difference between the two cumulative distributions is indicated as a black bar.

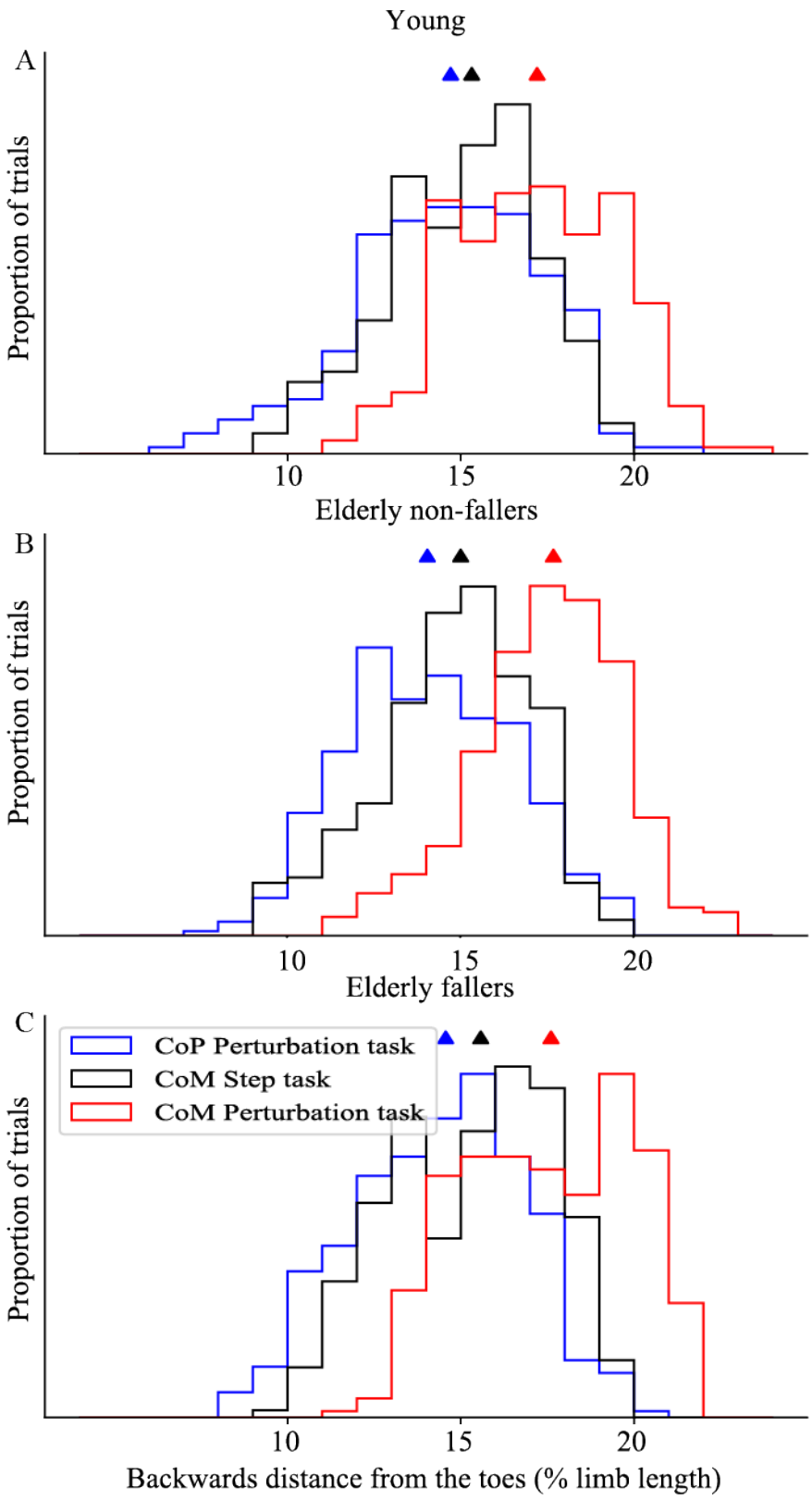

Figure 8 Initial backward position relative to the toes (normalised by limb length) of the CoM in CSRT trials (black) and in perturbation trials (red), and of the CoP in perturbation trials (blue), for Y (A), NF (B) and F (C).

The actual value of the pretension was not tightly controlled due to the limitations of the motor applying the traction (which was a step motor), and the distribution of pretensions is shown in Figure 9 (estimated using the average value of the forward component of the ground reaction force in the 500 ms before trial onset). There is no difference in the median pretension between NF and F ($p > 0.4$, Mann-Whitney U). The median pretension is slightly smaller for Y compared to the elderly ($p = 0.03$, Mann-Whitney U, difference of 0.3% subject weight, Hodges-Lehmann estimator).

At a trial by trial level, variations in pretension were not correlated with initial CoM position ($p = 0.06$, $r^2 = 0.004$, linear regression) but were correlated with initial CoP position ($p < 0.01$, $r^2 = 0.18$, linear regression). This suggests that subjects adapt to the perturbation task by shifting their CoM backward by a given amount, then compensate for the variable pretension through a forward shift in CoP relative to the CoM of variable amplitude.

2. Reduced functional base of support with aging

The range of initial CoM position relative to the foot which subjects can adopt is reduced in elderly compared to young subjects (15,18). Therefore, the backward position of the CoM relative to the toes might not be functionally relevant in elderly subjects. It may thus be more relevant to consider the backward distance relative to the fifth metatarsal joint, as a rough estimate of the forward limit of the functional base of support. The change in CoM position in the perturbation task relative to the CSRT task is comparable when considering either the distance to the fifth metatarsal joint, or the distance to the toes (Table 2). The difference in CoM position in perturbation trials with steps relative to non-step trials is comparable for the young when considering either the distance to the fifth metatarsal joint, or the distance to the toes (Table 3). For elderly non-fallers and fallers, this difference is stronger when considering the distance to the fifth metatarsal joint, compared to the distance to the toes, suggesting that the reduced functional base of support in the elderly is indeed functionally relevant.

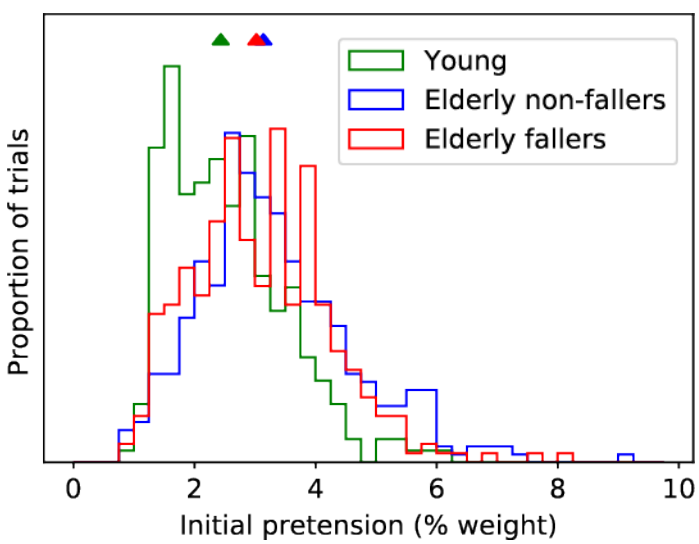

Figure 9 Initial pretension in perturbation trials (normalized by subject weight) for Y (green), NF (blue) and F (red). Medians of the distributions are shown as triangles.

Table 2 Change in CoM position in the perturbation task relative to the CSRT task

	Distance to toes (% limb length)	Distance to fifth metatarsal joint (% limb length)
young	2.1 ($p < 0.01$)	2.2 ($p < 0.01$)
non-fallers	2.7 ($p < 0.01$)	2.7 ($p < 0.01$)
fallers	2.2 ($p < 0.01$)	2.3 ($p < 0.01$)

Table 3 Difference in CoM position in perturbation trials with steps relative to trials without steps

	Distance to toes (% limb length)	Distance to fifth metatarsal joint (% limb length)
young	2.8 ($p < 0.01$)	2.8 ($p < 0.01$)
non-fallers	0.7 ($p = 0.01$)	1.8 ($p < 0.01$)
fallers	2.3 ($p < 0.01$)	3.0 ($p < 0.01$)

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