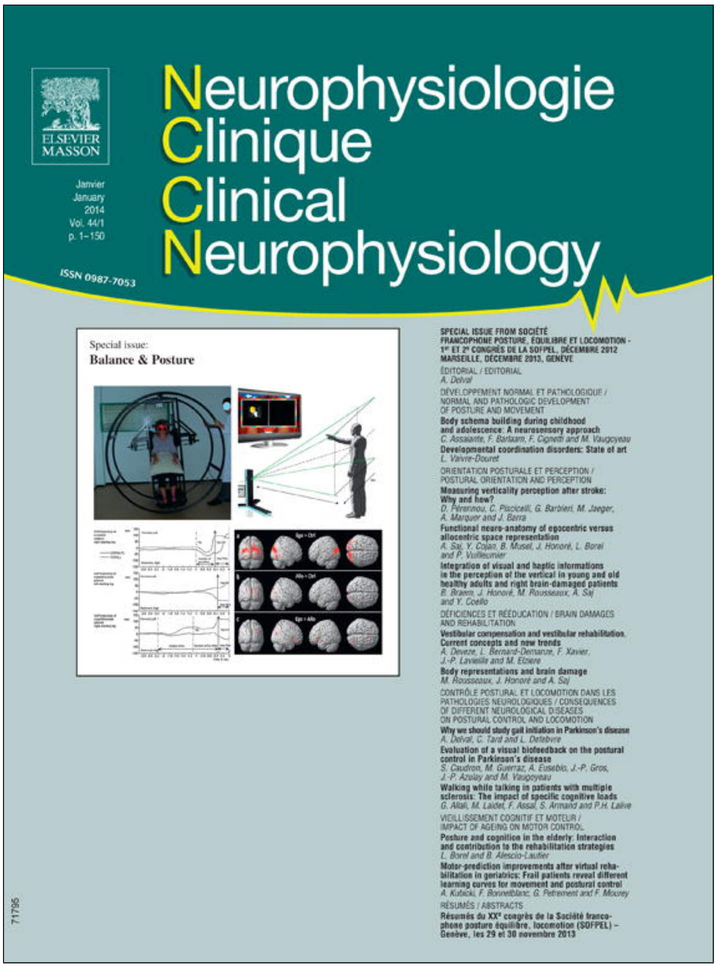

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ORIGINAL ARTICLE/ARTICLE ORIGINAL

Motor-prediction improvements after virtual rehabilitation in geriatrics: Frail patients reveal different learning curves for movement and postural control

Améliorations de la prédiction motrice après un entraînement en réalité virtuelle : les patients âgés fragiles présentent des courbes d'apprentissages différentes pour le contrôle du mouvement et de la posture

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KEYWORDS
Motor control;
Learning;
Frailty;
Virtual rehabilitation;
Anticipatory postural adjustments

Summary
Background. — Postural control associated with self-paced movement is critical for balance in frail older adults. The present work aimed to investigate the effects of a 2D virtual reality-based program on postural control associated with rapid arm movement in this population.
Methods. — Participants in an upright standing position performed rapid arm-raising movements towards a target. Practice-related changes were assessed by pre- and post-test comparisons of hand kinematics and centre-of-pressure (CoP) displacement parameters measured in a training group and a control group. During these pre- and post-test sessions, patients have to reach towards yellow balls appearing on the screen, form a standardized upright position (with 15 cm between the two malleoli). Training group patients took part in six sessions of virtual game. In this, patients were asked to reach their arm towards yellow balls appearing on the screen, from an upright position.

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Results. — After training, we observed improvements in arm movements and in the initial phase of CoP displacement, especially in the anticipatory postural adjustments. Learning curves for these two types of motor improvements showed different rates. These were continuous for the control of the arm movement, and discontinuous for the control of the CoP during the anticipatory postural adjustments.
Conclusion. — These results suggest that some level of motor (re)-learning is maintained in frail patients with low functional reserves. They also suggest that re-learning of anticipatory postural control (i.e. motor prediction) is less robust than explicit motor learning involved for the arm reaching. This last point should encourage clinicians to extend the training course duration, even if reaching movement improvements seems acquired, in order to automate these anticipatory postural activities. However, other studies should be done to measure the retention of these two types of learning on a longer-term period.

MOTS CLÉS
Contrôle moteur ;
Apprentissage ;
Fragilité ;
Rééducation en réalité virtuelle ;
Ajustements posturaux anticipés

Résumé

Introduction. — Le contrôle postural associé à un déséquilibre auto-généré (intrinsèque) est essentiel dans la gestion de la fonction d'équilibration, notamment pour des patients âgés fragiles. Ce travail avait pour objectif d'étudier les effets d'un programme d'entraînement, basé sur un outil de réalité virtuelle en 2D, sur le contrôle postural associé à un mouvement rapide du membre supérieur au sein de cette population.
Méthodes. — Les participants effectuaient des mouvements rapides du membre supérieur à partir de la position debout. Les changements liés à l'entraînement ont été évalués par des comparaisons pré- et post-test sur les paramètres cinématiques des déplacements de la main et du centre de pression (CdP), mesurés au sein d'un groupe témoin et d'un groupe entraîné. Pendant ces séances pré- et post-tests, les patients devaient pointer en direction de ballons jaunes qui apparaissaient sur l'écran, à partir d'une position debout standardisée (pieds placés avec 15 cm d'écartement entre les deux malléoles). Les patients du groupe entraînement prenaient part à 6 séances d'entraînement par utilisation du jeu virtuel. Sur celui-ci, les patients devaient pointer en direction de ballons jaunes qui apparaissaient à l'écran, à partir de la position debout.
Résultats. — Après l'entraînement, nous avons observé des améliorations du mouvement du membre supérieur et de la phase initiale du contrôle postural, notamment pendant la phase correspondant aux ajustements posturaux anticipés. Les courbes d'apprentissage, pour ces deux types d'optimisation motrice, étaient différentes. Celle observée pour le contrôle du mouvement du membre supérieur était continue pendant l'ensemble de l'entraînement, alors que celle observée pour le contrôle du centre de pression pendant les ajustements posturaux anticipés, révélatrice de l'optimisation de la prédiction motrice, était discontinue.
Conclusion. — Ces résultats suggèrent qu'un certain niveau d'apprentissage (ou de réapprentissage) est maintenu chez des patients fragiles présentant de faibles ressources fonctionnelles. Ils suggèrent également que le réapprentissage du contrôle postural anticipé est moins robuste que l'apprentissage moteur explicite constaté pour le mouvement du membre supérieur. Ce dernier point devrait encourager les cliniciens à prolonger la durée de l'entraînement, même si des améliorations semblent acquises pour le mouvement du membre supérieur, afin d'automatiser les activités posturales anticipées. Néanmoins, d'autres études doivent être mises en place pour mesurer à plus long terme la rétention de ces différents apprentissages.

Introduction

Perturbations always challenge the control of equilibrium. For instance, when we interact with our environment, the central nervous system (CNS) has to detect and to counteract external perturbations (i.e., being pushed, etc.) rapidly. Even during a simple quiet stance, the CNS controls very low-amplitude oscillations, which can be considered as small perturbations [19]. In consequence, equilibrium is also challenged each time we move our limbs to perform a movement. These self-generated perturbations also have to be counteracted to allow individuals to perform movements efficiently and precisely, and to simultaneously avoid potential falls caused by the mechanical perturbation itself [1,18]. In cases of rapid arm movement, certain anticipatory postural adjustments (APAs) are triggered before the arm movement is initiated to compensate for the upcoming perturbation. These APAs are typical of some level of feedforward control, which is integrated into motor programming, and illustrate the brain's ability to predict and compensate for self-generated perturbations. These postural anticipations are essential for coordination between posture and movement, and very helpful to stabilize the body during every day activities, especially for elderly people [26]. However, age-related changes have been reported in the motor programming involved in optimizing the coordination between posture and movement [27]. Several studies have already highlighted some delayed APAs during self-generated rapid arm movements in aged adults [17], especially in a complex reaction time task, when the location of the target is not known before the go signal [11]. These studies suggest that normal aging could affect the brain's ability to coordinate posture and movement efficiently and to predict and compensate for self-generated perturbations.

In cases of non-optimal aging, as in frail older adults, this anticipatory capacity seems to be even more challenged [15]. Interestingly, in this study, the patients' functional capacities correlated with the delays in postural adjustments that followed a self-generated perturbation, namely with the lack of anticipatory capacity. A sedentary lifestyle could lead to deficiencies in the updating of internal models of action. These internal models are essential to predict the sensory consequences and mechanical perturbations associated with a rapid arm movement [19]. In normal aging, a recent study has shown that specific training could improve these feedforward mechanisms in a few sessions [14]. In this work, a virtual rehabilitation system (with video-game-based biofeedback) was used to give trial-by-trial feedback (knowledge of result) and to improve the motivation of aged individuals. At the end of this experimental protocol, trained subjects developed greater APAs than did control subjects, and showed improvements in feedforward postural adjustments. These results demonstrated that learning could improve performances in aged individuals by involving central changes.

The potential benefits of this kind of training in pathological aged patients like frail older adults remain largely unexplored. Frailty is a general concept used by gerontologists who need a global approach to aging. Frailty describes a ''multidimensional syndrome of loss of reserves (energy, physical ability, cognition, health) that gives rise to vulnerability'' [20].

With a similar virtual geriatric rehabilitation program, we aimed to determine whether some level of motor improvement was possible for these patients, who present substantial functional impairments. More specifically, we also tried to investigate whether some improvements could be explained by central changes and especially better predictive or anticipatory capacities about perturbations linked to their own movement.

Material and methods

Patients

A total of 46 patients participated in the present study after giving their written consent. The French Committee for the Protection of Persons (CPP) approved the experimental protocol, which was carried out in agreement with legal and international requirements (Declaration of Helsinki, 1964). The participants were patients in the short-term rehabilitation service of the Benigne Joly Clinic, Burgundy, France. One inclusion criterion was to present a balance disorder, but also to be able to remain standing without any mechanical or human help. The patients all presented multiple causes of hospitalization, but all patients with pyramidal or extra-pyramidal syndrome or peripheral neuropathy were excluded. Nevertheless, inclusion required a conscientious examination, and the diagnosis of frailty was made by a geriatrician according to the clinical features of the syndrome. Frailty was defined as a clinical syndrome in which three or more of the following criteria were present: unintentional weight loss, self-reported exhaustion, weakness, slow walking speed, and low physical activity [10]. Moreover, patients were excluded if there was a suspicion of dementia (Mini Mental State Examination was performed, and dementia was considered for MMSE < 24). All of the patients were right-handed. They were randomly divided into two groups: (1) the control group (CG) composed of 23 patients, including 6 males and 17 females, and (2) the training group (TG) composed of 23 patients, including 5 males and 18 females. To perform this randomization, each participant had to pick a paper with a number comprised between 1 and 46 (the total number of participants). Even and odd numbers were assigned to the training and control group respectively. Patients' characteristics are summarized in Table 1 and flow charts of patients are given on Fig. 1.

Experimental device

The set-up used was an active motion-capture system based on vision technology manufactured by Fovea Interactive®. This system was able to track the marker held by the patient in his right hand. The camera was positioned in front of the participant at a standard distance depending on the patient's height. The experimental device was placed underneath a large screen (200 cm × 205,130 cm, screen diagonal: 238 cm), onto which a marker position was projected. In this way, the right-hand movements were represented on the screen, with a delay of 33 ms. The right index finger was represented on the screen by a white hand. In the lower part of the virtual scene, there was a half circle with many needles. Patients were asked to put their hand on this circle to pick up a needle (automatic pick-up). In this way, this half circle placed in the lower part of the screen was the starting point of the reaching movement. When the patient put his right hand on this half-circle, a yellow ball appeared somewhere on the screen (the radius of the yellow ball was 10 cm), after a short variable delay (0.2—2 seconds) and in a random position (eight standard positions: four in the right half of the screen and four in the left half). This was repeated over 10 trials per sequence. For each target, the reaction time and the peak velocity were recorded. At the end of the 10 trials, the means of these parameters were calculated and communicated to the patients. This immediate feedback was given to the patients to help them maintain their motivation (see Fig. 2 for experimental device).

Experimental procedure

Patients of both groups participated in a first evaluation session (pre-test session: first Monday) and a final evaluation session (post-test session: third Friday), with an interval of three weeks between these two test sessions. Only the TG patients participated in the six training sessions between the pre-test and the post-test, with at least 48 hours between each one (please see Fig. 5 for the calendar). All of the patients participated in the classical rehabilitation sessions (3 sessions per week). The experimental session (evaluation

Table 1 Patients characteristics (part A) and functional capacities (part B) in the two groups.

Part A

Hospital causes		Medical histories	
Orthopaedic	8	High blood pressure	26
Traumatic (falls)	13	Dyslipidemia	10
Cardiac decompensation	9	Hypothyroidism	5
Cancer	6	Hyperthyroidism	2
Others	12	Arrhythmia	6
		Cardiac insufficiency	9
		Renal insufficiency	4
		Vision deficiency	7
		Cancer	6

Part B

	TG	CG	*t*	*P*
Age (years)	82.21 ± 6.85 [71; 94]	81.52 ± 4.95 [74; 89]	0.381	0.704
Weight (kg)	66.67 ± 16.45	66.87 ± 12.76	0.081	0.935
Height (m)	1.62 ± 0.07	1.61 ± 0.09	0.429	0.669
BMI	23.9 ± 4.42	25.79 ± 4.83	0.324	0.621
TUG (s)	22.84 ± 7.09	20.28 ± 11.03	0.935	0.354
Walk speed (m/s)	0.61 ± 0.17	0.69 ± 0.29	1.146	0.257
Walk speed in dual task (m/s)	0.52 ± 0.14	0.58 ± 0.23	1.178	0.245

TG: training group; CG: control group.

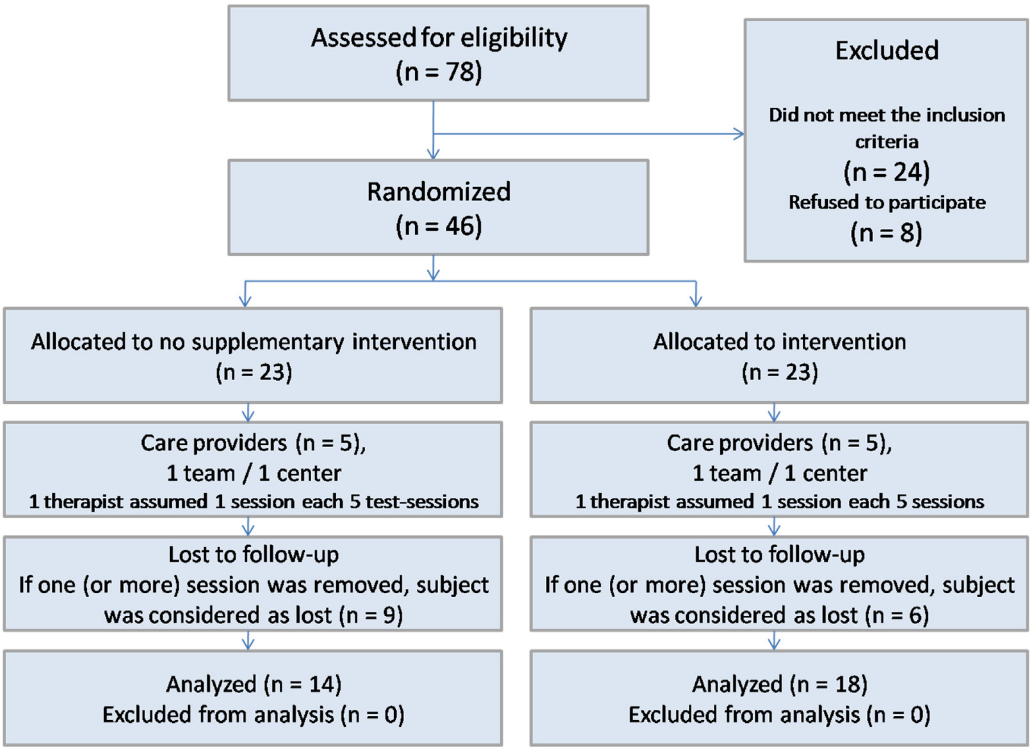

Figure 1 Enrolment flow chart.

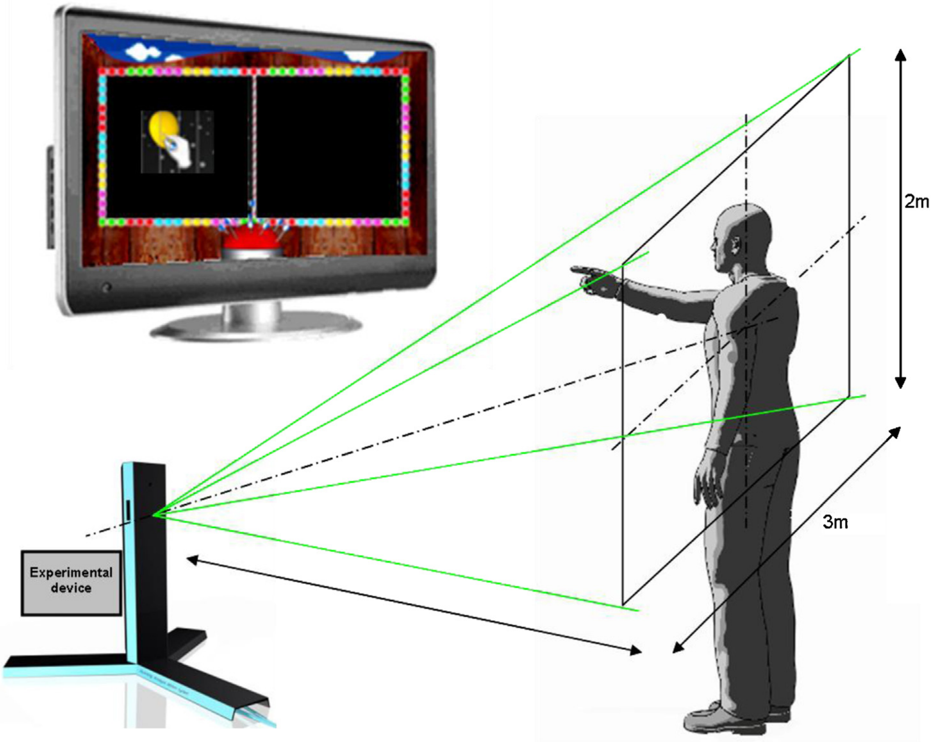

Figure 2 Schematic representation of the experimental device and of the virtual scene of the game.

or training) was always done before any classical rehabilitation session.

Evaluation sessions: pre-test and post-test

Initially, patients performed the following functional tests: Timed Up and Go test (TUG), Walking Speed, and Walking Speed in a dual task. Then the therapist explained the task to the patient, and showed a short demonstration of the game. The patient used the device first in a familiarisation sequence: the instruction was to burst the yellow ball with the right hand. Patients were asked to react as soon as possible and to reach the ball as fast as possible. After this first familiarization sequence (10 balls), patients were asked to perform 3 sequences with the same instruction. The experimental device, coupled with a force plate (see *data recording and statistical analysis*), recorded the centre of pressure and hand positions during these 3 sequences. Throughout these sessions, the patients' feet were placed in the standard position, on the force plate prints (without shoes, 15 cm between the two malleoli, corresponding to feet placed shoulder width apart).

Training session

One training session was composed of 10 sequences. The 3 first sequences were performed with the feet in a standard position. The instruction was to burst the yellow ball with the right hand. Patients were asked to react as soon as possible and to reach their arm to the ball as fast as possible. The experimental device recorded the centre of pressure and hand positions during these first 3 sequences. During the 7 following sequences, the patients' feet were placed in a position chosen by the therapist, with respect to the patients' abilities (feet together, tandem stance, foam under the feet, unstable plate use).

Data recording and statistical analysis

During the first 3 sequences in all sessions, right hand displacements were recorded using the experimental device (sampling rate: 60 Hz). Postural data were recorded using a seesaw force plate (techno concept; Posturwin software, version P3-03). This force plate was connected to the experimental device and an analogical signal was used to synchronize these two recordings. The recording of CoP displacement on the x-axis and y-axis began 600 ms before the hand movement procedure and finished 1000 ms afterwards. The onsets of hand and CoP movement were calculated from a 5% threshold of the maximal speed of each velocity signal. Hand and CoP—kinematics signals were filtered (fourth-order Butterworth with a 7 Hz low-pass cut-off frequency). The authors focused on the synchronization between the hand and the CoP velocity profiles and on the characteristics of CoP and hand kinematics (CoP maximal velocity [MV]; hand peak velocity [PV]; and time to hand peak velocity [TPV]). To further investigate the organisation of postural control, the CoP mean velocity was analyzed for different temporal intervals. Four temporal intervals were considered with respect to the onset of hand movement (t0): the baseline (from t0 −600 ms to t0 −150 ms), the APA period (from t0 −150 ms to t0), an initial control phase (from t0 to t0 +100 ms), and a final control phase (hand TMV to hand movement end). According to the literature, the interval from −150 ms to T0 was chosen to explore the anticipatory postural control [3,5]. A period of t0 to t0 +100 ms was chosen as an open-loop and a programmed phase that reflected pure feedforward mechanisms without any possibility for feedback motor corrections [7]. For these intervals, the mean velocity of CoP displacement was computed. Mathematically, this parameter was calculated as the integrated function of the CoP velocity, divided by the interval duration.

Pre-test differences between the two groups

We applied Student tests to evaluate the potential difference in the pre-test session between the two groups in the clinical test results.

Pre-post-test analyses

The 30 trials per session were averaged for each subject. All dependent variables were submitted to two groups (TG and CG) × two sessions (pre-test and post-test) analyses of variance (Anovas), with repeated measures on the two factors. Levene's test for homogeneity of variance was conducted prior to the analysis of each variable. Post-hoc analyses were conducted using Scheffe's test. All statistical analyses were carried out using an alpha level of 0.05.

Learning rate analyses

Data from the TG were averaged for all patients and between sessions and plotted on Fig. 5. For the CoP mean velocity during the APA and for the hand mean velocity, we calculated the gain per week, corresponding to the progression of each variable during one week, for the first week and the second week. Mathematically, this gain was calculated by the following formula:

$$\text{Gain} = ((\text{Perf. on Friday} - \text{Perf. on Monday})/\text{Perf. on Monday} \times 100)$$

Results

Homogeneity between the two groups before training

The analyses revealed no significant differences ($Ps > 0.245$) between the TG and the CG for age, weight, height and functional tests. This is summarized in Table 1.

Pre-test and post-test comparisons

Hand kinematics

For the hand movement time, results of the Anova revealed no group effect ($F(1,29) = 0.665$, $P = 0.427$), no session effect ($F(1,29) = 2.62$, $P = 0.116$) but a significant group × session interaction ($F(1,29) = 4.367$, $P < 0.5$). A decomposition of this interaction demonstrated that hand MT were lower in the post-test (1.34 ± 0.47 s) than in the pre-test session (1.95 ± 0.68 s) for the TG only.

The results for the hand mean velocity and hand reaction times mirrored those obtained for the hand movement times. Similarly, the Anovas revealed no group effect ($F(1,29) = 0.439$, $P = 0.511$ and $F(1,29) = 0.39$, $P = 0.846$, respectively), no session effect ($F(1,29) = 0.292$, $P = 0.367$ and $F(1,29) = 3.91$, $P = 0.057$, respectively) but a significant group × session interaction ($F(1,29) = 4.817$, $P < 0.5$ and $F(1,29) = 0.39$, $P = 0.846$, respectively). A decomposition of these two interactions demonstrated that mean velocities were higher in the post-test ($0.92 \pm 0.31\,\text{m.s}^{-1}$) than in the pre-test sessions ($0.63 \pm 0.2\,\text{m.s}^{-1}$) and reaction times were shorter in the post-test (0.446 ± 0.11 s) than in pre-test session (0.605 ± 0.244 s) for the training group only. These results are summarized in Fig. 3.

CoP kinematics

For the CoP mean velocity during the APA ($\text{CoPMV}_{\text{APA}}$), results of the Anova revealed no group effect ($F(1,29) = 0.653$, $P = 0.426$), no session effect ($F(1,29) = 0.057$, $P = 0.453$) but a significant group × session interaction ($F(1,29) = 8.031$, $P < 0.01$). A decomposition of this interaction demonstrated that the $\text{CoPMV}_{\text{APA}}$ were higher in the post-test ($0.031 \pm 0.022\,\text{m.s}^{-1}$) than in the pre-test session ($0.024 \pm 0.01\,\text{m.s}^{-1}$) for the TG only.

By contrast, results for the CoP mean velocity during acceleration and deceleration phases (CoPMVAcc and CoPMVDec, respectively) revealed no significant effects. Interestingly, the results for the CoPMVAcc revealed a tendency in favour of a group × session interaction ($P = 0.075$) mirroring that observed for $\text{CoPMV}_{\text{APA}}$ ($0.033 \pm 0.022\,\text{m.s}^{-1}$ for the post-test and $0.027 \pm 0.011\,\text{m.s}^{-1}$ for the pre-test sessions). These results are summarized in Fig. 4.

Hand mean velocity and CoP mean velocity during the APA

As shown in the previous sections results demonstrated that the hand mean velocity and the CoP mean velocity during the APA were increased between the pre- and post-test. Here we measured these improvements across the different sessions. The gains for the hand mean velocity obtained during the first week (40.7% ± 58%) and during the second week (8.9% ± 18%) were different ($t = 2.42$; $P = 0.026$). By contrast, these gains for the CoP Mean Velocity during APA obtained during the first week (25.4% ± 37.7%) and during the second week (22.7% ± 46.1%) were not significantly different ($t = -1.01$; $P = 0.329$).

An illustration of TG improvements related to both hand and CoP parameters is presented in Fig. 5.

Results demonstrated that the $\text{CoPMV}_{\text{APA}}$ increased with the training sessions: the comparison between pre- and post-test revealed a significant difference (see above, the interaction group between session, in the CoP kinematics section). To further document the learning curve shown on Fig. 4, and determine whether it was monotonic or not, we compared the performance obtained in pre-test with those obtained in S3 (end of the first week), in S4 (beginning of the second week) and in S6 (end of the second week). These three comparisons revealed that the performance obtained in pre-test was different from that obtained in S3 ($t = -2.03$ $P = 0.053$ for a single-tailed analysis), and from that obtained in S6 ($t = -2.76$ $P = 0.011$) but not from that measured in S4 ($t = -1.5$ $P = 0.147$). These results suggest that the learning rate was discontinuous and the learning curve was not monotonic.

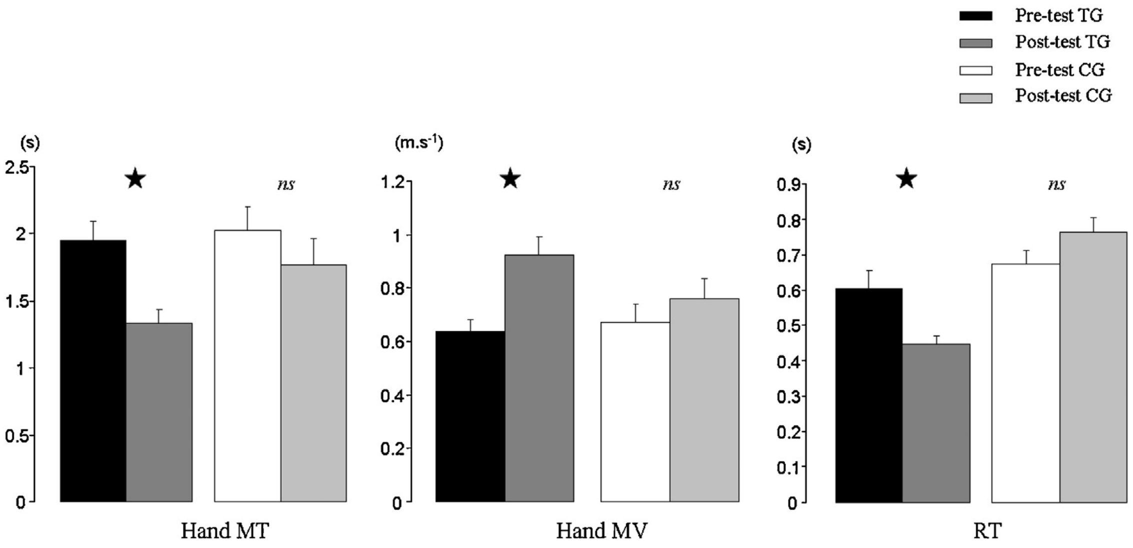

Figure 3 Hand movement time (s), hand mean velocity (s) and reaction time (s) for the training group (TG) and the control group (CG) in the pre- and post-tests. Vertical bars represent standard error.

Discussion

The objective of this study was to determine whether a virtual rehabilitation based program could induce some level of motor improvement especially in the coordination between posture and movement in a population of frail individuals. More specifically, we investigated whether these improvements could be explained by central changes and especially by better predictive capacities linked to their own movement.

Clearly, our results showed substantial improvement in the control of hand movement, as shown in the systematic increase in hand mean velocity. At this point, it is important to note that this increase was not associated with a decrease in the precision of the hand movement. Interestingly, we also observed an improvement in the control of the CoP (increased CoP velocity) especially during the APA phase. One may suggest that in the field of postural control increases in CoP-velocity can been seen to reflect increasing instability. However, from a physical viewpoint a high velocity does not necessarily mean that the system is unstable. It may be dynamically stable so this consideration can be controversial. In addition, this assertion is mainly valuable for quiet standing. During APA, the displacement of the CoP is not erratic as during quiet standing and is made in a main direction (see traces in Fig. 3 on [15], for instance). As such, there is a clear instability that is generated here but the conjugate displacement of the CoP and CoM is considered to prepare the system to counteract the perturbation due to the arm movement (forward displacement of the

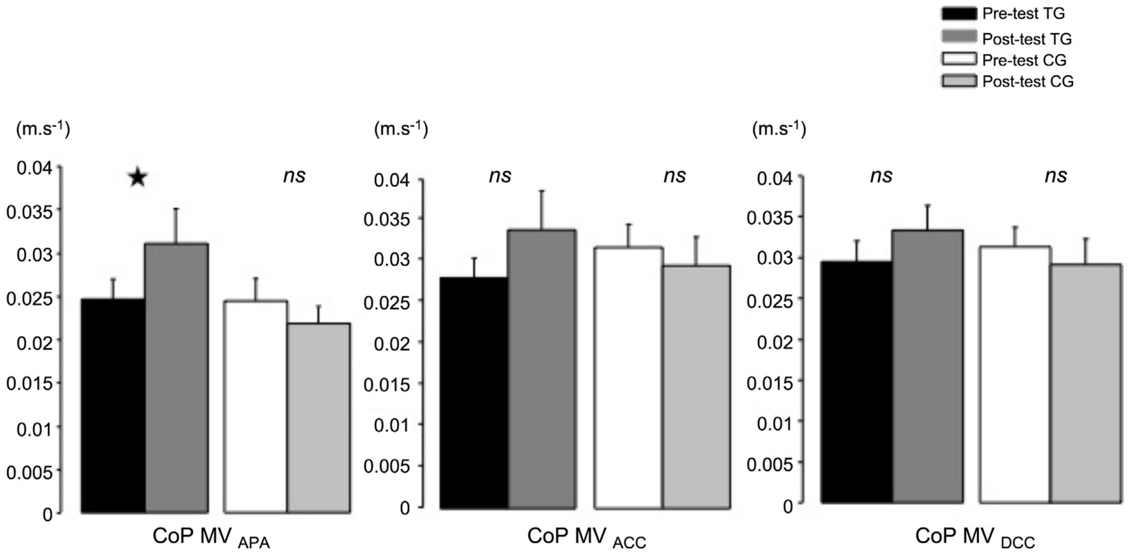

Figure 4 CoP mean velocity during APA, acceleration (ACC), and deceleration (DCC) phases, both for the training (TG) and the control (CG). Vertical bars represent the standard error.

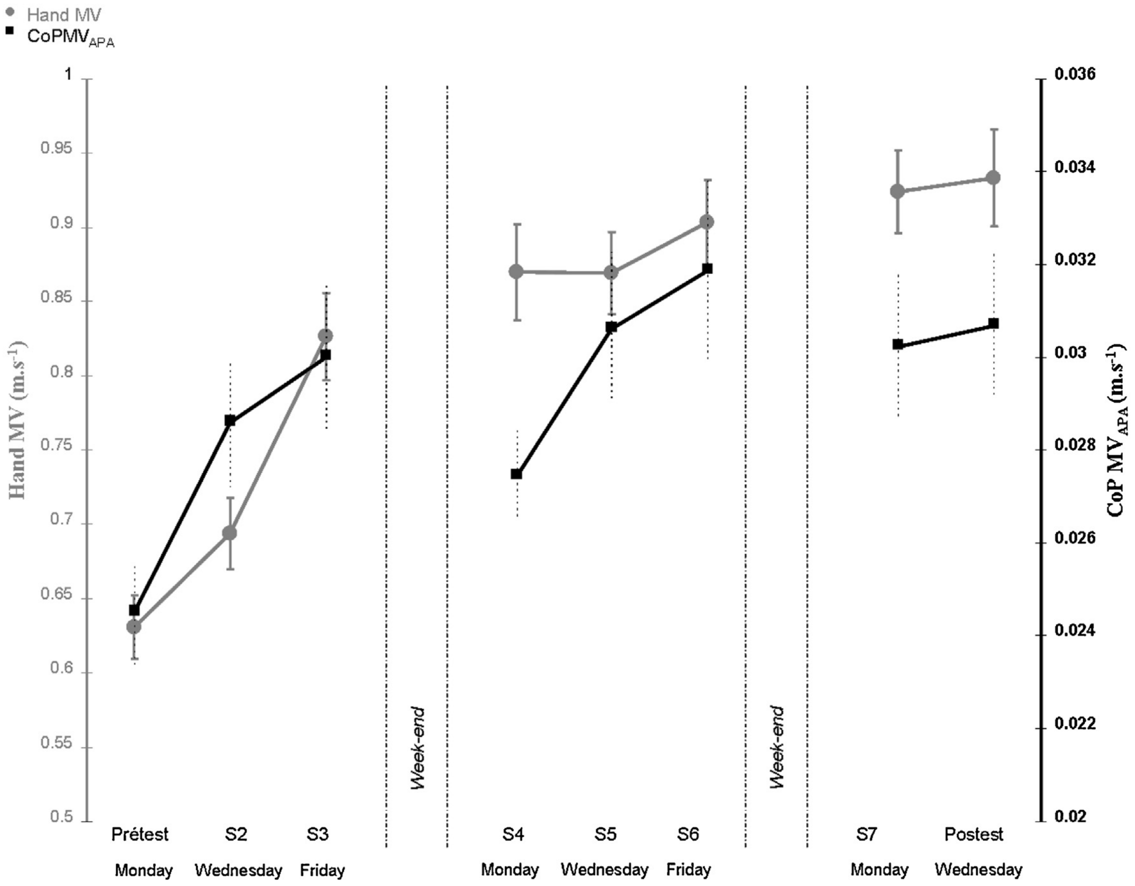

Figure 5 Hand mean velocity (calculated for the entire hand movement) and CoP mean velocity during APA (m.s^{-1}) in function of the session for training group patients. Vertical bars represent the standard error.

CoM). Finally, as APA occur before the hand movement it is considered that it reflects an anticipatory aspect of the human motor behavior, and feedforward control (without sensory feedbacks). In consequence, an increase of APA generally reflects an improvement of the feedforward processes and central changes [18]. In consequence, the COP-velocity was used in our study as a measure for the effectiveness of APA and hence increased velocity as improvement of APA in the course of training (see also [2] for the computation of APA using the CoP kinematics). These changes are important, because in our task, the patient's attention is mainly focused on the game and not on his postural control, especially during its initial phases. These could occur with training, which enhances the estimation of the self-generated perturbations (and their sensory consequences). This optimization mechanism has already been highlighted in normal older adults [14]. Our results clearly demonstrated that anticipatory and predictive processes could be improved in frail older adults with substantial functional impairments.

We also observed two different learning curves for hand and postural controls. The hand mean velocity increased continuously across the training session whatever the rest period between two training sessions to reach a plateau quite rapidly. Whereas, the learning curves for the CoP mean velocity during the APA was rather discontinuous. For the latter parameter, our analysis showed that the retention was subtotal after a break of 72 hours (during the week-end) whereas there was no loss after 48 hours. These two different learning curves suggest that retention and learning processes were not identical for these two types of motor improvements. Discontinuous improvements observed for the control of the CoP during APA, showing a non-monotonic learning curve, could indicate an involvement of lower learning processes. These may reflect the updating of internal models involved in estimating the consequences of self-generated perturbations during coordination between posture and movement. By contrast, the continuous increase of hand velocity could be explained by more explicit processes, since an immediate feedback (i.e., knowledge of results) was given to the patients each ten trials. From a clinical point a view, this last point should encourage clinicians to extend the training course duration, even if reaching movement improvements seems acquired, in order to automate these anticipatory postural abilities.

One may wonder what kind of motor learning is involved during our training protocol, especially with regards to the improvements of the CoP control during the APA phase. A detailed analysis of the learning rates for the CoPMV$_{APA}$ revealed substantial but incomplete retentions following each week-end and decelerated learning rates with sessions. This pattern seems typical of fast motor skill learning

[4,6] and especially motor adaptation. Indeed, during our fast arm raising training, participants did not learn a new motor sequence but rather learn unconsciously to better anticipate and predict for the upcoming perturbation associated in this case with the arm raising movement. Despite some cortical areas may be involved in this fast learning process especially in the posterior part [4], it is difficult to firmly conclude about their participation. However, for this type of motor adaptation the cerebellum at least has been shown to be involved in the processing of sensory-motor errors that measure the discrepancy between the predicted perturbation and actual feedbacks, perhaps on trial by trial basis [8,9]. This interpretation is clearly in the vein of the role played by the cerebellum in the storage of internal models [12,13,24,25]. To sum-up we suspect here a form of simple fast sensory-motor realignment that does not fit with the learning of a complex new motor sequence.

Since we observed rapid improvements but did not measure how long they could last (even if we could observe a subtotal retention from week to week), one may suggest that the generalization of our results could be an important limitation, notably with respect to the prevention of falls (note that this application was not our primary goal). However, we feel that our approach is important for several reasons. By focusing only on self-generated perturbations associated with voluntary movements, we demonstrated that some levels of improvements are possible in the anticipatory and programmed part of motor activities for impaired elderly individuals and in a reduced amount of time. Consequently, we reaffirmed here that the trainability of predictive processes could be an important avenue for rehabilitation of elderly individuals. Indeed, our results suggest that internal models can be rapidly updated. This feasibility is critical with respect to the main literature in the field of rehabilitation in elderly individuals. To our knowledge, main researches in this field did not focused on these predictive processes. Some studies demonstrated that APA were impaired for elderly individuals but they did not investigated how they could be (re)-learned [2,11,27]. We tried to make a step further in this way. In this vein, prevention of falls has mainly been investigated through the prism of ''balance recovery reactions'' (see [16] for a review) suggesting that the emphasis was laid on reactive and not on predictive processes.

Finally, one other possible limitation with our paradigm may be that attention focused on the upper extremity component of the task may vary with the overall task difficulty, depending on what surface and stance the participant is asked to maintain. The more challenging surfaces and stances may result in participants attending more to balance to maintain an upright position. For instance, APA decrease when the base of support is reduced [21]. In consequence, further investigations in various postural contexts should be made. In the context of age-related changes affecting the brain, neuronal viability and neuronal vulnerability [23], our results suggest that some level of motor (re)-learning is maintained in frail patients with low functional reserves. Hypo-kinetic behaviour could aggravate motor impairment and lead to the development of learned non-use [22]. Rehabilitation therapies should take into account these possibilities.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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