Changes in brain activation patterns after physiotherapy program: A preliminary randomized controlled trial study after Postural Reconstruction® and stretching programs

Changements dans les patterns d’activation cérébraux : une étude préliminaire randomisée contrôlée après des programmes physiothérapeutiques de Postural Reconstruction® et de stretching

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Received 13 April 2015; accepted 9 September 2015
Available online 24 October 2015

Abstract

Postural Reconstruction® is a physiotherapy method that has been developed over the last two decades. Its main therapeutic objectives are to decrease pain levels, normalize joint alignment and posture and improve movement and function. The goal of this study was to substantiate the neuromuscular mechanism of action of Postural Reconstruction® by evidencing pre- vs. post-intervention changes in brain activation patterns during sustained ankle dorsiflexion. It concerns a single-centre, prospective, randomized, controlled, parallel-group trial. Sixteen healthy subjects (8 males and 8 females; age range: 20–23) were randomized into two groups: an interventional Postural Reconstruction® group (n = 8) and a control stretching group (n = 8). Both groups performed 10 weekly sessions. The Postural Reconstruction® sessions involved five manoeuvres and the stretching sessions involved five different exercises. Brain activation patterns were measured via single-photon emission computed tomography. Each subject received two 1480 MBq doses (3 months apart). We performed a voxel-wise statistical analysis (using Statistical Parametric Mapping software) to detect changes in brain activation within each group.

Results. – We observed statistically significant pre- vs. post-intervention changes in brain activation patterns in the Postural Reconstruction® group (a neuromuscular approach), but also in the stretching group (viewed as a mechanical approach). There were no significant intergroup differences in the pre- or post-intervention brain activation patterns.

Conclusions. – Our results suggest that the two different physiotherapy programmes have a neuromuscular mechanism of action and evidenced changes in brain activation patterns in young, healthy adults (i.e. free of CNS lesions) during the performance of ankle movements.

Keywords: Neuroimaging; Neuroplasticity; Posture; Rehabilitation

Résumé

La Reconstruction Posturale® est une physiothérapie qui a été développée au cours des deux dernières décennies. Ses objectifs sont la résolution des algies, la réaxation des segments, la normalisation de la posture, l’amélioration de la mobilité et de la fonction. Le but de cette étude était d’étayer le mode d’action neuromusculaire de la Reconstruction Posturale® en mettant en évidence des modifications pré- vs post-intervention dans les patterns

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http://dx.doi.org/10.1016/j.mednuc.2015.09.004
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d’activation cérébraux lors d’une dorsiflexion de la cheville. Il s’agit d’une étude prospective, monocentrique, randomisée contrôlée en deux groupes parallèles de sujets sains, 8 hommes et 8 femmes, (extrêmes : 20–23 ans) : un groupe expérimental de Reconstruction Posturale\textsuperscript{R} (n = 8) et un groupe témoin de stretching (n = 8). Dix sessions à un rythme hebdomadaire et 5 techniques pour chaque groupe. L’activation cérébrale a été mesurée par tomographie d’émission monophononique. Il a été administré à chaque sujet 2 \times 1480 MBq à 3 mois d’intervalle. Nous avons effectué des analyses statistiques en chaque voxel grâce au logiciel SPM pour détecter les changements d’activation cérébrale au sein de chaque groupe.

Résultats. – Des changements statistiquement significatifs pré- vs post-intervention dans les patterns d’activation cérébrale ont été observés dans le groupe Reconstruction Posturale\textsuperscript{R} (approche neuromusculaire), mais aussi dans le groupe stretching (considéré comme une approche mécanique). Il n’y avait pas de différence significative entre les groupes.

Discussion. – Nos résultats suggèrent que les deux programmes de physiothérapie ont un mode d’action neuromusculaire. Les changements ont été mis en évidence chez des jeunes adultes sains (non cérébroparcocités) lors d’un mouvement de la cheville.

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\textbf{Mots clés :} Neuro-imagerie ; Neuroplasticité ; Posture ; Réhabilitation

1. Introduction

Postural Reconstruction\textsuperscript{R} (PR) is an innovative neuromuscular physiotherapy paradigm that has been developed over the last two decades. It is based on the hypothesis whereby excessive residual tension in large sets of overlapping muscles involved in human stance may change the joint moment and thus contribute to movement pattern disorders \cite{1}. This can be viewed as analogous to building tension in the string of a bow; tension in the string causes bending and twisting of the bow (i.e. the spine and limbs).

Residual muscle tension (i.e. muscle tone) is not under voluntary control. Hence, PR uses manoeuvres based on scientific studies of neurorehabilitation \cite{2,3}. These manoeuvres implement a specific therapeutic tool (referred to as normalizing induction) to first increase the already excessive residual muscle tension and then (in the same treatment session) fatigue it, with a view to normalizing spinal and/or peripheral joint alignment disorders \cite{4,5}. Concomitant effects on pain, movement performance and function are expected \cite{6,7}.

The normalizing induction uses an irradiation process that is similar to motor overflow, i.e. a voluntary movement that triggers distant, involuntary contractions of contralateral homologous muscles or ipsilateral or contralateral non-homologous muscles \cite{8,9}. In everyday implementations of PR, the voluntary inducing movement is a complex motor task that is sustained for a relatively long period of time (10 to 30 min) and requires full concentration by the subject. For a given inducing motor task, the distant reaction is almost always the same in a given subject but may vary from one subject to another and may also affect the axial muscles.

The distant reactions are not related to central nervous system (CNS) damage or psychiatric disorders because they can be triggered in healthy subjects \cite{10}. The distant reactions characterized in the literature appear to have a central trigger (via cortical activation of motor overflow). However, a subcortical origin cannot yet be ruled out \cite{11}.

The progressive decrease in involuntary contractions induced by PR treatment suggests that the process involves brain plasticity. Hence, we hypothesized that PR’s mode of action might be related to changes in the spatial extent of brain activation.

The goal of the present study was to investigate the effect of PR on brain activation patterns during the performance of a simple, predefined motor task (sustained, active dorsiflexion of the right ankle) recorded with single-photon emission computed tomography (SPECT). Indeed, SPECT has already been used to image functional brain activation patterns during movement, language and memory tasks \cite{12–15}.

To avoid methodological bias and the possible misinterpretation of results, we sought to compare the putative changes in brain activation associated with PR (a neuromuscular approach) with those associated with stretching (viewed as a mechanical approach). According to many researchers \cite{16–18}, the effect of stretching is more likely to be due to the application of tensile stress to non-contractile, connective tissues in and around the muscle than to inhibition of the muscle’s contractile element.

We therefore decided to perform a pilot study in young, healthy adults (i.e. free of CNS lesions).

2. Experimental procedure

We performed a single-centre, prospective, randomized (allocation ratio: 1:1), controlled, parallel-group, proof-of-concept study.

2.1. Participants

The study population comprised physiotherapy students from the Institut de Formation en Masso-Kinésithérapie (France). The inclusion criteria were as follows: age between 18 and 35 (inclusive), negative pregnancy test (HCG Stat, from Roche Diagnostics, Meylan, France, who has a sensitivity of 1 mU/ml and able to detect a pregnancy as early as 10 days after fertilization), command of the French language and valid social security coverage.

The main exclusion criteria were as follows: a history of neurological or psychiatric impairments, recent musculoskeletal trauma, contraindications to neuroimaging (such as the presence of a pacemaker, ferromagnetic surgical clips, ocular implants, intraocular/neural metallic foreign bodies or hypersensitivity...
to the radiotracer or one of its excipients), breastfeeding and participation in another clinical trial.

Twenty-three eligible students volunteered to participate. Sixteen of the latter were chosen at random (using a block randomization design, an allocation ratio of 1:1 and the random number generator in R software) and constituted the study population (8 males and 8 females).

Given that this was a pilot study, the lack of literature data on the effect of intervention on our primary efficacy variable prevented us from calculating a precise sample size. Hence, the sample size was determined as a compromise between study feasibility, physiological variability and financial imperatives. However, the results of the present study should facilitate calculation of the sample size required in future trials. Each subject served as his/her own control.

2.2. Group allocation

To avoid methodological bias and the possible misinterpretation of results, we decided to randomize the 16 participants to an interventional group (PR) and a control group (stretching sessions). Hence, in a second randomization, 4 men and 4 women were attributed to each of the two groups in a block randomization design (allocation ratio: 1:1) by using the random number generator in R software. The principal investigator enrolled participants and assigned them to interventions in the Service de Biophysique et de Médecine Nucléaire (University Hospital, France). The study’s objective and procedures were approved by an independent ethics committee and complied with the tenets of the Declaration of Helsinki (1964). All subjects provided their written, informed consent before participation in any study procedures.

2.3. Data collection

For each subject, the study was performed in three phases. Firstly, a clinical examination provided data on weight, height, blood pressure and heart rate. At baseline, SPECT was performed at rest and during activation (i.e. during sustained right ankle dorsiflexion). Secondly, the subjects participated in their allotted weekly physical therapy sessions over a 10-week period. Thirdly, a post-intervention SPECT was performed two weeks after the last physical therapy session. The overall study period (from first inclusion to the end of data collection for the primary outcome criterion) was 6 months.

2.4. The primary outcome criterion

The primary outcome criterion was defined as a change in the brain activation patterns observed with SPECT.

The SPECT examinations were performed by an experienced radiologist and in accordance with the nuclear medicine department’s standard clinical protocol. The “at rest” and “during activation” SPECT measurements were performed in that order at both the pre- and post-intervention time points.

There were no adverse or unexpected events in either group.

2.4.1. Measurement at rest (the baseline measurement)

The first “at rest” measurement enabled us to quantify changes in the brain activation patterns attributable to the motor task by comparison with post-intervention brain images. Fifteen mCi (555 MBq) of ethyl cysteinate dimer (ECM)-Tc99m (Neurolite®; Bristol-Myers Squibb Medical Imaging, Rueil-Malmaison, France) was injected intravenously while the participant was lying still in the supine position. The tracer update time was 90 seconds. Twenty minutes later a dual-head gamma camera (E-CAM, Siemens Healthcare, Erlangen, Germany) was used to image the brain. The acquisition parameters were as follows: collimator setting: fan-beam; total turnover: 2 × 180°; number of projections: 32; duration of each projection: 50 seconds; acquisition mode: stepper; zoom factor: 1; acquisition matrix: 128²; acquisition time: 27 min.

2.4.2. Measurement during activation

While in the supine position, the participant actively dorsiflexed his/her right ankle to the fullest extent possible. The following instructions were given: “Flex your right foot towards your shin as far as possible and hold that position. Do not move your left foot. The rest of your body must be relaxed”.

Next, 25 mCi (925 MBq) of ECM-Tc99m was injected 15 seconds after the start of the motor task. The ankle dorsiflexion had to be maintained for 90 seconds, to allow time for tracer uptake and binding. Electromyographic recording was used to control for the presence of involuntary co-contractions, which otherwise might have resulted in the activation of brain areas not involved in ankle dorsiflexion. A keypoint stimulator (Medtronic-Dantec Medical, Royal Portbury, UK), dispersive electrodes (18 cm in length and 20 mm in width-Medtronic, catalogue number 9013507231) and four surface recording electrodes (15 cm in length and 20 mm in width-Medtronic, catalogue number 901350211) were used for EMG recording. The electrodes were placed on the centre of the quadriceps and on the centres of the paravertebral muscles on either side of the third lumbar vertebrae. A camcorder with a timer was used to film the measurement session.

After the 20 min required for elimination of the tracer from the salivary glands, the gamma camera acquired a second set of images during a 27-minute period. The same measurement protocol was used post-intervention for measuring brain activation patterns at rest and during sustained ankle dorsiflexion.

The volume of brain areas activated in ankle dorsiflexion (the sensorimotor cortex, the premotor cortex, the supplementary motor area (SMA), the basal ganglia and the cerebellum) was quantified and assessed in a statistical analysis.

In total, each subject received two 1480 MBq doses (3 months apart). These doses were approved by the French National Agency for Healthcare Product Safety (Paris, France).

2.5. The physical therapy interventions

2.5.1. The interventionnal programme: Postural Reconstruction®

The PR group participated in 10 weekly, 30-minute individual sessions (all led by the same practitioner). In the PR paradigm, the treatment tool is referred to as “normalizing
induction”, i.e. an irradiating, voluntary movement designed to induce involuntary contractions (referred to as “evoked responses”) [4,5]. Inductions are complex motor tasks performed with the greatest available range of motion. Not all full-range movements provoke a measurable evoked response; hence, some inductions must include certain combinations of movements (e.g. shoulder abduction and medial rotation) or avoid them (e.g. the dissociation of movement of the little toe and foot abduction). In some cases, the evoked response will occur if a conflicting factor (such as stiffness of the opposing muscles) interferes with the normal range of movement or the movement’s trajectory. The inductions are selected after morphological examination of the patient in all three spatial planes [19]. Clinically, the evoked responses translate into transient aggravation of the pre-existing, localized, morphological impairment. The induction is maintained until there is a decrease in or disappearance of the evoked response. In clinical terms, this decrease corresponds to a reduction of the morphological feature that was previously aggravated. The inductions are performed with a specific breathing pattern and a focus on exhalation. Five inductions were used during the PR sessions. Two are described here (Fig. 1):

- a combination of shoulder abduction and internal rotation [20,21] and;
- dorsiflexion of the toes of the left foot against resistance while in the sitting position [22]. It is important to note that neither of the two manoeuvres required right ankle dorsiflexion.

Dorsiflexion of the toes of the left foot against resistance while in the sitting position causes an involuntary, uncontrollable forward movement of the head. Electromyograms (EMGs) recorded in preliminary experiments revealed moderate activation of the right C4 paravertebral muscles and intense activation of the ipsilateral sternocleidomastoid muscle.

The combination of shoulder abduction with internal rotation causes uncontrollable aggravation of the ipsilateral thoracic curve, which is through to reflect accentuation of spinal convexity. In preliminary experiments, the EMGs evidenced involuntary contractions of the contralateral paraspinal muscles (T12-L1).

2.5.2. The control programme: stretching

The stretching group participated in 10 weekly, 30-minute group sessions (all led by the same practitioner). In each

Fig. 1. a: dorsiflexion of the toes of the left foot against resistance, while in the sitting position. The electrodes were placed (from the top to the bottom of the screen in the figure) on the submental muscles, the right and left paravertebral muscles over C4 and the clavicular head of the sternocleidomastoid muscle; b: shoulder abduction combined with internal rotation. Motor irradiation is enhanced by combining active, assisted, medial rotation of the shoulder with active abduction of the arm (with the greatest possible range of motion). The electrodes were placed (from the top to the bottom of the screen in the figure) on the right and left rhomboid muscles and the right and left paraspinal muscles over T12-L1.

session, each stretching posture was performed five times alternately on each body side, in line with Taylor’s recommendations [18,23]. The stretching postures were intended to stretch the hamstrings, the triceps surae, the adductors, the iliopsoas and, lastly, the posterior muscles of the trunk and legs (Fig. 2). Passive stretching was chosen for the control group because of its action on the elastic component of muscle structure [24,25]. The stretch was performed slowly, in order to avoid activation of the myotatic (stretch) reflex. Each stretch was held for 10 seconds [26,27]. There was a 2-minute rest period between each stretch.

2.6. Image processing

To perform a voxel-wise statistical analysis, images have to be registered in a common space. To this end, all four images acquired for each patient were firstly rigidly aligned and then averaged. This average image was used to estimate an affine transformation and thus map all four individual images onto the SPECT template provided in the Statistical Parametric Mapping package (SPM – Wellcome Department of Imaging Neuroscience, London, UK; http://www.fil.ion.ucl.ac.uk/spm). Lastly, the intensities of the warped images were normalized (by estimating the scaling factor that minimized the sum of squared intensity differences with the SPECT template) and then smoothed with a Gaussian kernel (full width at half-maximum: 12 mm). All processing steps were performed with Medipy software (University, France; https://piiv.u-strasbg.fr/traitement-images/medipy).

2.7. Statistical analysis

All statistical analyses were performed using the SPM8 software package (running on Matlab 7.10; MathWorks, Natick, MA, USA). Descriptive statistics were used to characterize the group samples. In activation studies, we considered the difference in intensity between images recorded during activation and images recorded at rest; this differential image is referred to as the activation map. The pre-intervention brain activation patterns (but not post-intervention activation patterns) were obtained by performing a one-sample t-test on the activation maps of all individuals (i.e. the two groups’ maps were pooled). Pre-intervention vs. post-intervention differences within each group were obtained by performing a one-sample t-test on the differences between the pre-intervention activation map and the post-intervention activation map for each individual. Lastly, intergroup comparisons of pre- vs. post-intervention differences in the activation maps were performed by applying a two-sample t-test. All statistical tests were performed in the absence of any covariates, although global normalisation with SPM’s analysis of covariance routine was used to account for changes in intensity across subjects. With a cluster spatial extent of 5 voxels, the threshold for statistical significance of \( P \) (uncorrected) was set to \(< 0.001\) for the analysis of pre-intervention brain activation.

![Fig. 2. The five passive stretching postures, for stretching the hamstrings (a), the triceps surae (b), the adductors (c), the iliopsoas (d) and the posterior muscles of the trunk and lower limbs (e). Les 5 techniques d’étirement passif des muscles ischio-jambiers (a), des triceps suraux (b), des adducteurs (c), des iliopsoas (d) et des muscles postérieurs du tronc et des membres inférieurs (e).]
patterns and < 0.005 for the analysis of pre- vs. post-intervention differences in brain activation patterns.

This threshold enables the deletion of irrelevant, isolated clusters with fewer than 5 voxels and thus provides a cleaner map. The choice of a value of 5 is somewhat arbitrary (we could have chosen 10) but this is the default setting in xjView (the software we used to visualize the results).

Statistical maps were analysed with xjView software (http://www.alivelearn.net/xjview8/), which enabled us to identify the brain regions associated with the detected clusters.

Only the statistician was blinded to the group assignments. He received two datasets but did not know which dataset corresponded to which group.

3. Results

Fig. 3 shows the disposition of the study population: enrolment, allocation, follow-up and analysis.

The study participants’ individual characteristics are summarized in Table 1. The data were not distributed normally and so are reported as the median [1st–3rd interquartile range]. There were no significant differences between the two study groups in terms of age (range: 20–23), weight, height or resting heart rate ($P > 0.05$ in Mann-Whitney U tests).

Electromyographic recordings of the quadriceps and paraspinal muscles and video recording confirmed the absence of involuntary movements during the SPECT acquisitions.

3.1. Pre-intervention brain activation patterns during sustained right ankle dorsiflexion

Certain brain areas were activated before any intervention ($n = 16$; one-sample $t$-tests without any covariates; statistical threshold, $P < 0.001$ (uncorrected); cluster size > 5 voxels). They were variously located in the left hemisphere (the posterior limb of the left internal capsule, the lentiform nucleus and the thalamus; the left temporo-occipital junction; the left sub-gyral frontal lobe and the cingulate gyrus; the left superior frontal gyrus (Brodman area (BA) 6 and the SMA) and the precentral gyrus) and the right hemisphere (the right postcentral gyrus and the parietal inferior lobe) (Fig. 4).

3.2. Pre- vs. post-intervention differences in the Postural Reconstruction group

Differences were observed in the left hemisphere, the right hemisphere and the cerebellum ($n = 8$; one-sample $t$-tests without any covariates; statistical threshold, $P < 0.005$)
uncorrected; cluster size > 5 voxels): the left lingual and inferior occipital gyrus; the left inferior temporal gyrus and fusiform gyrus; the left middle temporal gyrus; the left anterior cingulate and orbitofrontal gyrus; the left superior temporal gyrus; the left parahippocampal gyrus; the left inferior frontal gyrus; the left lentiform nucleus, internal capsule and thalamus; the left inferior parietal lobule and supramarginal gyrus; the left precuneus; the left inferior parietal lobule, Brodmann’s area (BA) 40 and 7; the left precentral gyrus = 33 voxels (peak Montreal Neurological Institute (MNI) coordinate: 30 −6 48; t-statistics peak intensity: 5.07); the left precentral gyrus = 216 voxels (peak MNI coordinate: 34 −28 60; t-statistics peak intensity: 5.03); the left SMA; the right superior temporal gyrus; the inferior orbitofrontal gyrus; the right inferior occipital gyrus; the right caudate and lentiform nucleus; the right inferior parietal lobule and supramarginal gyrus; the right superior and middle frontal gyr; the right cingulate gyrus and precuneus = 472 voxels; the left cerebellum = 27 voxels (peak MNI coordinate: 54 −52 −42; t-statistics peak intensity: 4.5); the left cerebellum = 47 voxels (peak MNI coordinate: 14 −64 −32; t-statistics peak intensity: 4.37); the left cerebellum and vermis; the right cerebellum = 235 voxels (peak MNI coordinate: −28 −38 −32; t-statistics peak intensity: 11.69); the right cerebellum = 7 voxels (peak MNI coordinate: −2 −52 −40; t-statistics peak intensity: 4.07); the right cerebellum = 198 voxels (peak MNI coordinate: −20 −96 −24; t-statistics peak intensity: 5.98) (Fig. 5).

3.3. Pre- vs. post-intervention differences in the stretching group

Differences were observed in the left hemisphere, the right hemisphere and the cerebellum (n = 8; one-sample t-tests without any covariates; statistical threshold, P < 0.005 uncorrected; cluster size > 5 voxels): the left lingual and inferior occipital gyrus; the left lentiform nucleus; the left middle temporal gyrus; the left tempo-occipital junction; the left middle frontal gyrus; the left inferior frontal gyrus; the left middle frontal gyrus; the left middle frontal gyrus, BA 6 and precentral gyrus; the left thalamus; the left precuneus; the right middle temporal gyrus; the right superior temporal gyrus; the right medial part of superior frontal gyrus; the right medial frontal gyrus; the right superior frontal gyrus; the right superior and middle frontal gyr; the right SMA; the right precentral gyrus and opercula; the right precentral gyrus; the left pre- and postcentral gyr; the right inferior parietal lobule; the right postcentral gyrus; the right caudate nucleus; the vermis; the left cerebellum; the right cerebellum = 24 voxels (peak MNI coordinate: −38 −60 −48; t-statistics peak intensity: 5.39); the right cerebellum = 20 voxels (peak MNI coordinate: −28 −54 −42; t-statistics peak intensity: 9.07) (Fig. 6).

4. Discussion

4.1. Pre-intervention brain activation patterns

The results for brain area activation during active ankle dorsiflexion movement prior to the intervention agree with the literature data [28,29]. To the best of our knowledge, only one study has explored brain area activation during sustained ankle dorsiflexion [30]. The activated areas included the bilateral paracentral lobule and the precuneus (which are mainly located in the left hemisphere), BAs 1, 2, 4 and 7, the bilateral lingual gyrus (which is mainly located in the left hemisphere), BAs 17 and 18, the right cuneus, BAs 18 and 19, the right inferior occipital gyrus (adjacent to the lateral occipitotemporal gyrus and lingual gyrus) and the vermis.
4.2. Post-intervention brain activation patterns

In our study, changes in brain activation patterns were seen in both the PR group and the stretching group. One can speculate that the interventions had effects on the afferent input and then the efferent motor response when performing the task. Taken as a whole, our results raise questions about the physiological mechanisms underlying these two types of physiotherapeutic intervention. Both the PR group and the control group displayed significant pre- vs. post-intervention differences in activated brain areas. However, there were no significant intergroup differences in brain activation patterns either before or after the intervention.

To investigate the reproducibility of brain perfusion SPECT imaging over time, we also compared the pre- vs post-intervention baseline scans within each group and the corresponding statistical map revealed no significant change at the threshold \( P < 0.001 \), which is in accordance with several already published studies [31–33].

It is important to note that a lasting localized change in activation patterns for a specific movement was obtained by physical therapy interventions which did not involve the said movement at all. This experimental design was chosen in order to rule out bias due to motor learning [34].

To the best of our knowledge, the present study is the first to have recorded changes in brain activation patterns during ankle movement following the performance of rehabilitation sessions in healthy subjects (without any practice or training in the experimental motor task). Katiuscia Sacco et al. [35] used an fMRI motor imaging paradigm to evidence pre- vs. post-training differences in functional connectivity during ankle dorsiflexion in normal subjects [35]. However, these changes were observed after a week-long period of locomotor attention training.

**Fig. 4.** Brain activation during right ankle dorsiflexion before the intervention \((n = 16; \text{one-sample } t\text{-tests without any covariates; statistical threshold, } P < 0.001 \text{ uncorrected; cluster size } > 5 \text{ voxels})\).  
*Activation cérébrale lors de la dorsiflexion de la cheville droite avant l’intervention \((n = 16 ; t\text{-test pour échantillon unique sans covariable ; seuil statistique, } p < 0.001 \text{ non corrigée ; taille de cluster } > 5 \text{ voxels})\).*
We were not surprised to observe changes in brain activation patterns following PR because this technique is based on a neuromuscular paradigm [36, 37].

Our results indicate that changes in activation patterns occurred in the stretching group. In retrospective, this is not so surprising [38–40]. One can hypothesize that stretching modifies afferent pathways – most probably by increasing the discomfort threshold rather than changing viscoelastic properties per se [24] and thus the efferent motor response. If intervention can modify afferent inputs from the mechanoreceptors in both contractile and non-contractile components of muscle, this would explain why brain activation patterns can be re-organized by stretching.

Our findings may have some important implications for rehabilitation in practice. It is generally accepted that stretching has only moderate effects on muscle length [24], muscle stiffness [24], the risk of sports injuries [41], and delayed-onset muscle soreness [42]. Nevertheless, with the above-mentioned therapeutic objectives in mind, many therapists and coaches remain committed to stretching exercises. This conservatism suggests that patients and athletes do gain some sort of benefit. Could this benefit be based on a physiological response related to an induced change in brain activation patterns? Similarly, are there links between the normalization of joint alignment, posture restoration, the improved function observed in PR and the activation pattern modification evidenced here?

4.3. Study limitations

The study design must be considered in the light of PR’s preliminary state of advancement, since researchers are still in the early stages of using valid, reliable instruments to document the method’s putative effects.
In PR, a trained practitioner has to choose and perform the most appropriate induction manoeuvres. PR is therefore incompatible with the self-care principle that is often encouraged in physical therapy. In contrast, stretching enables self-care. Hence, in an attempt to reduce potentially confounding procedural differences between the two interventions, the stretching sessions were led by a practitioner.

Given that this was a preliminary study, only healthy subjects were assessed. This was made possible by the fact that PR can also be applied to asymptomatic individuals. This is also true for stretching, which explains in part why we choose that technique for the control group. The study sample was composed of young adult volunteers (range: 20–23). In view of this narrow age range, our results cannot be extrapolated to populations of healthy older adults or populations of symptomatic individuals.

Lastly, it is possible that the relatively short treatment period (10 weeks) was not long enough to produce statistically significant differences in activation patterns when comparing the two interventions. The absence of a statistically significant difference between PR and stretching might also be due to the small sample size.

This explains why assessing pre- vs. post-intervention changes within each group is of value and perhaps why we did not observe a significant intergroup difference.

We tried to show the brain’s plasticity under the influence of a physiotherapy technique, rather than a “snap-shot” of ankle dorsiflexion. The two-week interval after the last physiotherapy session enabled the persistence of effects to be assessed. The risk of methodological bias due to this time interval is very low because if a specific activity had biased the results, it would have had to be performed by all 16 subjects during the two-week period.

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Fig. 6. Pre- vs. post-intervention differences in the stretching group. Differences were observed in the left hemisphere, the right hemisphere and the cerebellum \( (n = 8; \text{ one-sample } t\text{-tests without any covariates; statistical threshold, } P < 0.005 \text{ uncorrected: cluster size } > 5 \text{ voxels}) \).

Différences pré- vs post-intervention dans le groupe stretching. Des différences ont été observées dans l’hémisphère gauche, l’hémisphère droit et le cervelet \( (n = 8; \text{ t-test pour échantillon unique sans covariable ; seuil statistique, } p < 0.005 \text{ non corrigée ; taille de cluster } > 5 \text{ voxels}) \).
The “evoked” motor task studied here (ankle dorsiflexion) was relatively simple, when compared with the normalizing induction motor tasks applied in everyday PR practice. Even though the amplitudes of the inducing movements in PR are physiologically normal, these movements are never spontaneously performed in everyday life. In the present study, the inducing motor task did not involve the right ankle. The choice of the right ankle was arbitrary and did not take account of the participant’s handedness. We chose ankle dorsiflexion over plantar flexion because the former movement (but not the latter) puts tension on the posterior muscle system. Hence, in most cases, the range of movement in plantar flexion is greater than that of dorsiflexion. Plantar flexion is also easier to perform. In our everyday practice, we find that dorsiflexion is more difficult for patients because it is restricted by posterior muscle tension. Hence, dorsiflexion is more likely to be influenced by a short course of PR and any changes in activation patterns should be more visible. In the literature, neuroimaging studies of activation patterns for ankle plantarflexion-dorsiflexion have generally involved dynamic and often repetitive movements [43–46]. However, the study cited above [30] (which used echo planar MRI to identify the brain areas activated during sustained ankle active dorsiflexion) also analyzed ankle plantarflexion. The results showed that although ankle plantarflexion excited fewer cortical areas than ankle dorsiflexion did, it excited more subcortical areas. In view of these recent data, it might have been better to explore plantarflexion because the latter appears to involve subcortical structures to a greater extent.

The present study constituted a pilot neurological investigation of upright, bipedal stance. Only contractions of the ankle, dorsiflexor and plantar flexor muscles are needed to maintain the body’s centre of gravity within the support base [47]. These muscles are directly involved in postural activity. Furthermore, the dorsiflexors are also involved in the gait cycle (in heel-on and throughout the swing phase). Research has shown that ankle dorsiflexion produces much the same brain activation pattern as gait does [48–50]. The physiotherapy exercises performed in the present study changed the activation patterns for ankle dorsiflexion, even when the movement was not performed. Accordingly, one can hypothesize that upright stance and gait might also be affected by PR and stretching.

In recent years, the outcomes obtained by certain rehabilitation interventions have been explained by brain plasticity [51–54]. However, most of the disorders studied and interventions used have been related to the field of neurorehabilitation. In the present study, we demonstrated that musculoskeletal rehabilitation procedures (PR and stretching) are associated with changes in brain activation patterns. This is a noteworthy finding for musculoskeletal rehabilitation, which supposedly involves soft tissue plasticity.

To the best of our knowledge, the present study is the first to have recorded changes in brain activation patterns during ankle movement following the performance of rehabilitation sessions in healthy subjects (without any practice or training in the experimental motor task).

Future studies of the effects of these interventions on brain plasticity should be performed with larger samples, older adults and longer treatment periods. Given that the results of this preliminary study concerned asymptomatic participants, further work should assess patients with muscle and joint disorders. Investigation of the effect on PR on brain activation patterns while standing is currently being considered. Our study results not only argue in favour of the suggested neuromuscular mechanism of action of PR but also raise questions about the mechanism of action of other kinds of rehabilitation.

Disclosure of interest

The authors declare that they have no competing interest.

Acknowledgments

We are grateful to Professors Christine Tranchant and Christian Marescous (Faculty of Medicine, University of Strasbourg) for assistance with the clinical trial and critical review of study proposal, respectively.

Funding: The study was funded by Strasbourg University Hospital (material support), the University of Strasbourg, France (financial support) and the Physiotherapie Schule Ortenau, Germany (financial support).

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