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MR COMPATIBLE DEVICE FOR ACTIVE AND PASSIVE FOOT MOVEMENTS

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ABSTRACT

The present paper presents a new MR compatible robotic device able to induce foot dorsiflexion and plantarflexion movements ('passive' patient mode), or to set and control for a series of parameters (force, amplitude) when the same movements are performed by the subject ('active' patient mode). Recent studies have demonstrated that the foot dorsiflexion is a critical component of the gait cycle; thus, ankle dorsiflexion/plantarflexion has been proposed as part of locomotor rehabilitation protocols, as well as a functional magnetic resonance imaging (fMRI) paradigm for defining brain activity relevant to gait. The principal aim of this work was to develop a robotic device to be used during fMRI testing, in pre- and post-locomotor therapy evaluations of cerebral activity. The same device can furthermore be used in the rehabilitation of neurological paretic patients, who need to practise foot movements and/or to relearn locomotor schemas.

Design criteria and implementation are described, as well as the final prototype. Great concern was given to choice of materials (for MR compatibility) and to anthropometric dimensions (for patient adapting). Furthermore pneumatic circuit and control software are illustrated. Finally preliminary results obtained from a fMRI exam on a healthy subject are pointed up.

Keywords: MR compatible, lower limb rehabilitation, robotics, neuroimaging

1 INTRODUCTION

Functional magnetic resonance (fMRI) is an in vivo imaging technique which allows the mapping of active processes within the brain, thus revealing the cerebral areas involved in a particular motor or cognitive task. Most fMRI studies measure changes in blood oxygenation over time. Because blood oxygenation levels change rapidly following activity of neurons in a brain region, fMRI allows researchers to localize brain activity on a second-by-second basis and within oxygenation occur intrinsically as part of normal brain millimetres of its origin. Besides, as changes in blood physiology, fMRI is a non-invasive technique that can be repeated as many times as needed in the same individual. It is then used both for clinical aims and for research purposes.

One of the main clinical applications concerns the detection of brain functional changes after rehabilitation programs in order to evaluate their efficacy. Robotics can greatly improve the accuracy of such medical evaluations, especially when the fMRI test is of motor type, i.e. where patient must achieve motor tasks or receive motor inputs during fMRI. For example, the motor rehabilitation of neurological paretic patients can be evaluated through the same fMRI motor task administered before and after the rehabilitation protocol: obviously, the force, the frequency and the amplitude of the limb movements must be identical in the two conditions. As

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the task usually requires the paretic patient greater efforts before his rehabilitation, a robotic device monitoring for these parameters is essential. Moreover, some patients have difficulty in executing an fMRI motor task because of their brain lesion. In such cases a robotic device inducing passive movement becomes crucial.

Currently MRI compatible devices for the movement of upper limbs have been developed: a force sensing system for monitoring wrist forces and moments exerted by patients during fMRI testing has been proposed in [1]; another device [2] moves the fingers of a hand with the purpose of studying brain activations due to passive hand movement. Furthermore brain activations due to elbow and finger active and passive movements, supported by custom-built devices, are illustrated respectively in [3] and [4].

However, while cerebral activations and modifications following training of the upper limbs have been more extensively investigated, less is known about the functional organization and reorganization of the lower limbs. In particular, investigations of the foot extension and flexion movements would be of special interest, as many works have shown that they are the most critical in studying locomotion ([5], [6]). Indeed, ankle dorsiflexion is a critical component of the gait cycle: The ankle dorsiflexes at heel strike upon initiation of the stance phase and throughout the swing phase. For these reasons, ankle dorsiflexion/plantarflexion has been proposed as a functional magnetic resonance imaging (fMRI) paradigm for defining brain activity relevant to gait; its validity has recently been demonstrated by some experimental works showing that foot extension and flexion alone generate a similar brain activation pattern to that associated with walking ([7], [8]). In [8] foot movement has been studied by limiting it to a single degree of freedom movement (only ankle dorsiflexion/ plantarflexion) thanks to a wooden device. This latter is manually activated by an operator and may be adjusted to fit different sizes and resistance so to permit a comfortable movement. Similar experiences are presented in [9] and [10], and [11].

[12] presents a fMRI compatible device for measuring torques generated from patients during voluntary isometric lower limb contractions. The device employs the same load cell described in [1], by placing it on a footplate that is positioned so to minimize head movements.

This article illustrates a MR compatible robotic device for active and passive ankle movement. Furthermore device validation on a healthy voluntary subject is presented.

The device here described stems from the requirement of better assessing cerebral changes following a rehabilitative locomotor program recently designed by our research group, which makes use of a robotic gait orthosis ([13], [14]). Literature presents several robots for gait rehabilitation (for a review see [15]). Pre- and post- locomotor training fMRI testing will occur on patients, thus there is the necessity of a robotic device which consents identical testing conditions. Testing protocol demands both “active” (voluntary) and “passive” (imposed) foot movement, hence a novel device was necessary.

The apparatus consents either to induce appropriate ankle plantarflexion/ dorsiflexion in one or both feet or to record angles and forces while the patient achieves the same movement. It is entirely MR compatible.

2 METHODS

2.1 DESIGN CRITERIA

Design criteria are many and stem from different necessities: these are mainly physiological and anthropometric requirements, experimental protocol constraints and need of MR compatibility.

Physiology imposes induced movement to follow certain angular laws in time. Furthermore angles may not become larger than physiological ones for safety reasons: maximum dorsiflexion must be stopped at 25° and plantarflexion at 35°.

Physiological ankle joint must always be corresponding to device joint: for this anthropometric data have been studied to adapt foot position for patients between 95 percentile man and 5 percentile woman (data from [16]).

Experimental protocol requires two different kinds of modes: “active patient mode”, where device only records data from patient voluntary movement without creating disturbs, and “passive patient mode”, where device imposes appropriate movement. Complete dorsiflexion/plantarflexion cycles should occur with a frequency of circa 0.5 Hz for 12s followed by 12s of rest for the chosen testing time.

Finally real-time monitoring during fMRI testing entails MR compatibility, which brings to choice of totally amagnetic materials.

2.2 IMPLEMENTATION

Final device (picture in Fig.1a and CAD drawing in Fig. 1b) consists in a box containing regulation systems and providing support for patient’s legs, two pedals which may be coupled and a pneumatic actuator that moves pedals – and thus patient feet.

Pedals (1) may be coupled or independent by means of spins: this permits movement imposing on one or both feet, as protocol requires. Patient feet are strapped to the pedals and a small cushion positioned on contact point provides better comfort. A T-bar (2) connects pedals to pneumatic actuator (3) if pins are inserted: as cylinder moves also pedals rotate

around joint axis and the angle range may be limited by properly positioning pins in two appropriately drilled angular sectors (4). Current foot – or feet – angular position is measured by a custom-built analogue optical encoder (5): a parallelogram structure connects the rotor component to the T-bar (2). Recorded signal is transmitted to electronics positioned outside MR room by means of optical fiber. Box (6) contains height regulation system as well as providing support for patient legs: during use a proper padding furthermore covers it.

Chosen materials are aluminium, bronze, brass and Derlin. In particular bearings are Teflon coated brass L-shape bearings and all parts which require low friction contact couple Derlin and aluminium components.

Fig. 2 depicts main necessary anthropometric adaptations. Device must be suitable to patients with different sex, height and weight but patient ankle joint must always be corresponding to device joint. Distance (h) should therefore vary between 50 and 70 mm and (l) between 70 and 90 mm for adaptation to patients from 95-percentile man to 5-percentile woman. Moreover maximum angles are 25° in dorsiflexion (α_d) and 35° in plantarflexion (α_p). Contact surface – and thus force exchange - between foot and pedal corresponds to padding: its position (d) should also vary between 100 and 150 mm.

Each adaptation occurs thanks to a proper component. Distance (d) changes by means of a slot (Fig. 3a) where screws holding padding may move.

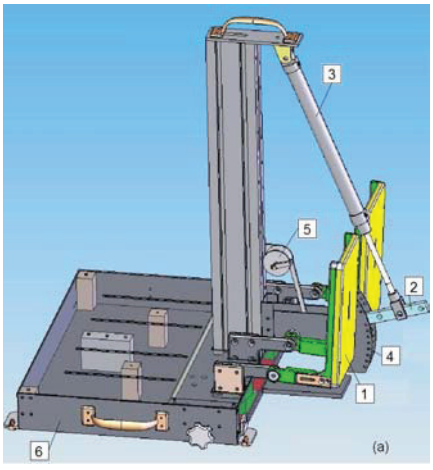

Figure 1 Device CAD drawing with numbered components (a) and picture with paddings and straps (b).

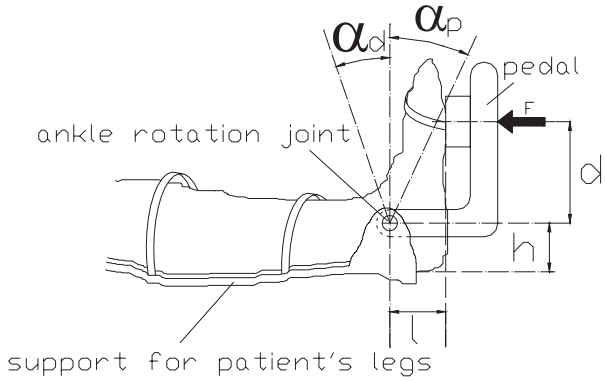

Figure 2 Main anthropometric regulation requirements.

Horizontal coincidence between patient ankle joint and device joint is obtained by means of slots (Fig. 3b) where pedal distance (l) from joint changes. In order to achieve vertical coincidence between joints (distance (h)), operator manually activates a lead screw, which drives a regulation system of overlaid Derlin wedges (Fig. 4).

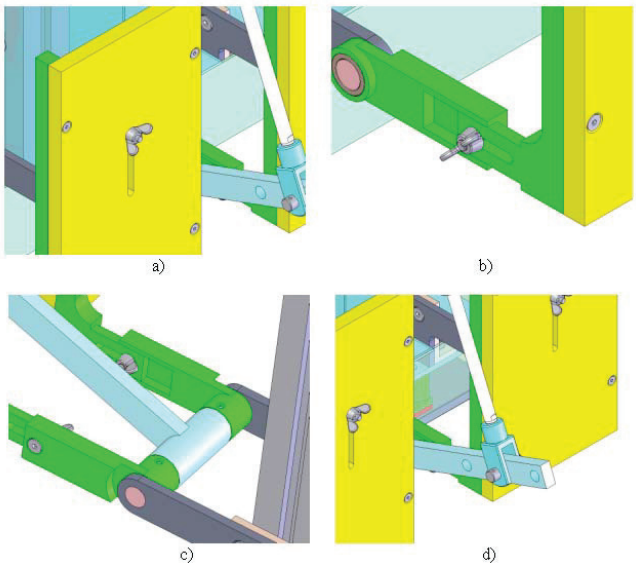

Figure 3 Main device regulations: foot padding position (a), horizontal ankle joint position (b), coupling of one or both feet with T-bar (c), position of actuator constraint for obtaining different torques (d).

Wedges (1) are hidden inside box (2), under patient leg support. Upper wedges are connected to whole pedal-actuation system (3) whereas lower wedges are fixed on a Derlin sled (4), which is brought in horizontal motion by a lead screw system. Latter system consists of female screw (5), connected to sled, and screw (7) connected to a knob (6) for operator activation. When knob (6) is rotated, screw (7) rotates and female screw (5) translates horizontally, driving connected sled (4) and lower wedges. Thanks to proper Derlin lateral slides (8), upper wedge movement is guided and thus whole pedal and actuation system (3) moves vertically.

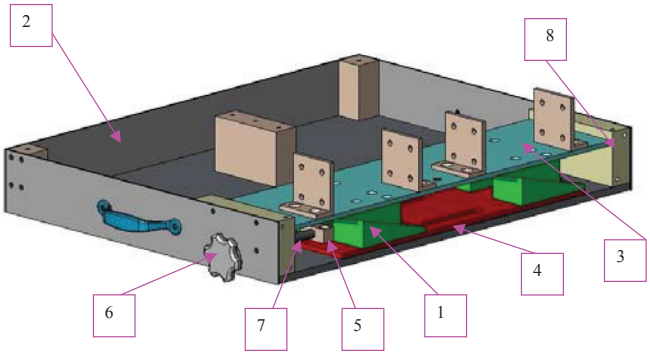

Figure 4 Lead screw and wedge system for regulating vertical ankle joint position.

Furthermore it is possible to choose between single foot movement and two feet movement by placing or removing pins (Fig. 3c) which couple pedals to the T-bar.
Finally the lever arm of transmitted force – thus the generated torque – may vary by differently attaching actuator rod on T-bar thanks to proper holes (Fig. 3d).
Kinematical analysis of pedal system was necessary to choose best constraint positions for mechanism components. In particular the position of the pneumatic actuator is strictly correlated to the force arm and thus to the generated torque. Fig. 5 depicts final kinematical scheme.

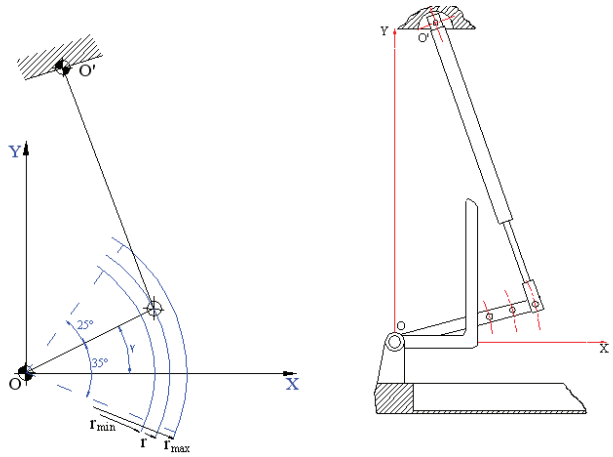

Figure 5 Kinematic scheme.

T-bar is rotated (angle γ) by 20° with respect to horizontal when ankle is in null flexion position: this consents whole range of dorsiflexion/plantarflexion motion without need of free space under the device. This choice consents to place the apparatus directly on the bed where patient lays inside MR room, without requiring other supports (e.g. a table or cart). The position of upper cylinder constraint (O') has been consequently chosen to keep generated torque as constant as possible both during motion and despite different actuator positions on T-bar.
Fig. 6 shows a picture of the prototype worn by a healthy volunteer subject during fMRI testing.

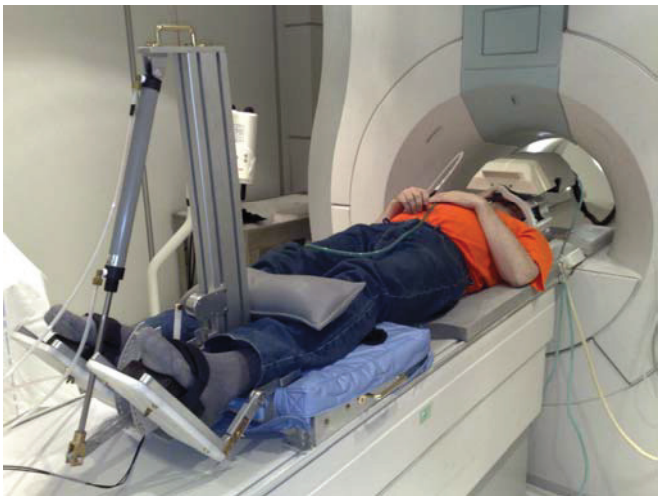

Figure 6 fMRI testing on voluntary healthy subject with MR compatible device.

3 PNEUMATIC CIRCUIT

A pneumatic circuit (Fig.7), positioned outside from MR room, controls the device.
The circuit consists of three main parts: "passive mode" circuit, "active mode" circuit, and "emergency management" circuit.
Air from supply source passes through a filter (1) and a locked pressure reducer (2) that cuts pressure to 4 bars: it then splits (node N) and flows to the three "sub-circuits".

3.1 "PASSIVE MODE" CIRCUIT

In "passive mode" the device must impose the movement to the patient's foot. Air from (N) passes through a pneumatically controlled bistable valve (3): if valve (3) is switched by a signal from emergency circuit, it cuts supply out and discharges the air from the circuit. Supply pressure is measured at valve (3) outlet for self-diagnostics of the system by means of pressure transducer T1. While this mode is selected from PC, electrovalve (4) is active. Air enters through OR valve (7) and reaches electrovalves (8) and (9), connected to the MR compatible cylinder (10) chambers and alternatively activated by the control software. Air pressure is measured by means of T2 and T3, so to calculate the force imposed on patient's feet. Outlet air from valves (8) and (9) passes respectively through flow regulators (11) and (12) before exhausting, so to allow actuator velocity control.

3.2 "ACTIVE MODE" CIRCUIT

In "active mode" the device must let the patient free to voluntarily achieve foot movement without feeling resistance. Air from (N) passes through another pressure reducer (5) which establishes pressure to the necessary value for balancing device weight. While this mode is selected from PC, electrovalve (6) is active and air passes through OR (7), since valve (4) is inactive. The downstream circuit is the same as above, although in this case valve (9) is always active and valve (8) is always inactive.

3.3 "EMERGENCY MANAGEMENT" CIRCUIT

For safety reasons, circuit presents redundant emergency buttons, which cut supply, stop the machine and discharge the circuit. OR valves (15) and (17) put all emergency signals together and command the pneumatically switched main emergency valve (3), which cuts air and discharges the circuit. Emergency signal may come: from the patient (inside MR room) by means of a bellow (B), placed in patient's hand, which – if pushed - sends low pressure signal to low-high pressure valve (16), supplied by air coming from (N); from operator (outside MR room) by means of PC emergency button (always displayed on screen) which commands electrovalve (13) or by means of plunger activated valve (14), positioned on operator's panel. Working conditions may be restored only manually by means of push button valve (18): this brings valve (3) back to its normal position and newly connects air from (N) to the circuit. Valve (18) can not switch valve (3) if any emergency signal is still running.

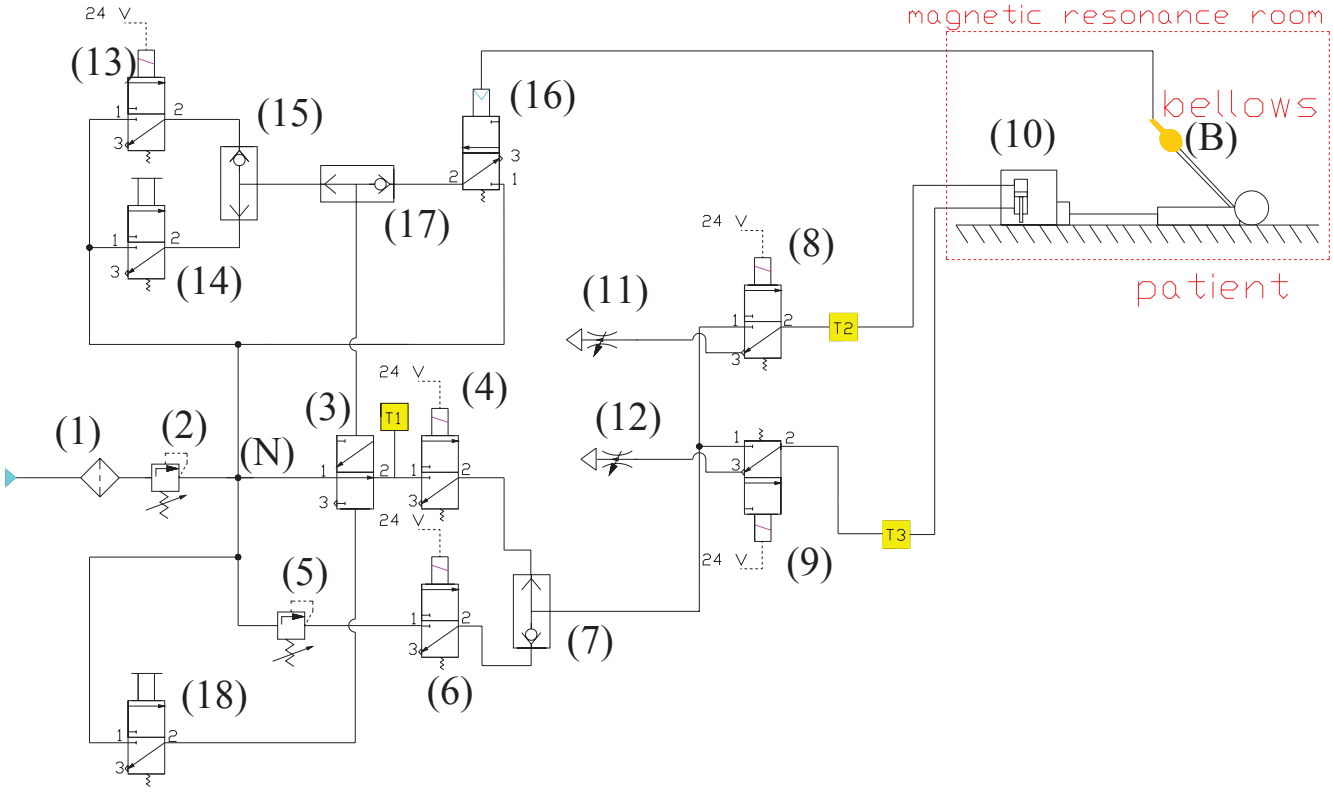

Figure 7 Pneumatic circuit schematics.

4 SOFTWARE AND CONTROL STRATEGY

Control software was expressly developed for this application. Main issues were user-friendly interface and intrinsic safety, so to avoid unwanted device movements. Fig. 8 depicts main software logic by means of a flowchart.

At the start, software makes a general test of the whole system (auto-diagnosis block): in particular it verifies signals from pressure transducers and from the optical encoder. When self-diagnostics is complete, the first screen-page is displayed, where operator can choose between "device regulations" and "testing".

For safety reasons, operator is initially forced to choose "device regulations" option: this assures that foot movement parameters are well suited to the patient. Operator can manually adjust dorsiflexion and plantarflexion speeds (by means of flow regulators (11) and (12) in Fig. 7) as well as maximum consented angles (by appropriately positioning spins (5) in Fig. 1): software displays current settings when parameter button is pressed. This regulation is also useful for optical potentiometer sensor testing.

Only after regulation has occurred operator may enter "testing" and select between "active patient" mode or "passive patient" mode.

In "passive patient" mode operator can change movement frequency and cycling time from the default values defined by standard protocol. Patient name must be inserted for data saving during testing.

During both "active patient" and "passive patient" modes, screen displays angular displacement, angular speed and exchanged force. Operator may save all records as data arrays versus time with the chosen name. Furthermore emergency button is always displayed during testing: this permits operator to cut supply pressure and discharge the circuit at any moment.

5 fMRI SUBJECT AND METHODS

A voluntary healthy subject was scanned while performing an active and passive blocked motor paradigm using described device. Paradigm was 12s of plantarflexion/dorsiflexion with frequency 0.5 Hz followed by 12s of rest for total acquisition time lasting 6.6 minutes.

Data acquisition was performed on a 1.5 Tesla INTERA™ scanner (Philips Medical Systems) with a SENSE high-field,

high resolution (MRIDC) head coil optimized for functional imaging. The resting state functional T2-weighted images were acquired using echoplanar (EPI) sequences, with a repetition time (TR) of 2000 ms, an echo time (TE) of 50 ms and a 90° flip angle. The acquisition matrix was 64 x 64, the field of view (FoV) 200 mm. A total of 200 volumes were acquired; each volume consisted of 19 axial slices, parallel to the anterior-posterior (AC-PC) commissure line; the slice thickness was 4.5 mm with a 0.5 mm gap. Two scans were added at the beginning of functional scanning and the data discarded to reach a steady-state magnetization before acquiring the experimental data.

In the same session, a set of three-dimensional high-resolution T1-weighted structural images was acquired for each participant. This data set was acquired using a Fast Field Echo (FFE) sequence, with a repetition time (TR) of 25 ms, ultra-short echo time (TE) and a 30° flip angle. The acquisition matrix was 256 x 256, the field of view (FoV) 256 mm. The set consisted of 160 contiguous sagittal images covering the whole brain. The in-plane resolution was 1 x 1 mm and slice thickness 1 mm (1 x 1 x 1 mm voxels).

BOLD imaging data were analyzed using the Brain Voyager QX software (Brain Innovation, Maastricht, Holland); a plug-in extension of this software was used to compute blind source deconvolution and power spectrum IC analyses (ICA plug-in) which corresponded to a C++ implementation of the fast-ICA algorithm ([17]). Functional data underwent the following pre-processing steps: 1) slice scan time correction, using a sinc interpolation algorithm; 2) 3D motion correction: all volumes were aligned spatially to the first volume by rigid body transformations, using a trilinear interpolation algorithm; 3) spatial smoothing by using a Gaussian kernel of 4 mm FWHM; 4) temporal filters (i.e. linear trend removal and non-linear trend removal using a temporal high-pass filter [frequency pass = 0.008 Hz]) were applied to remove drifts due to scanner and other low frequency noises 5) low-pass temporal filtering (FWHM = 2.8 s) to achieve modest temporal smoothing.

After preprocessing, a series of steps were followed in order to allow for precise anatomical location of brain activity. First, slice-based functional scan was co-registered on his own 3D high-resolution structural scan. Second, the 3D structural data-set of was transformed into Talairach space. Third the functional time course of each run was transformed into Talairach space and the volume time course created.

To circumvent the influence of movement artefacts functional images were measured by independent component analysis (ICA), a statistical technique that separates a set of signals into independent uncorrelated and non-Gaussian spatio-temporal components (IC). The fMRI brain image at each time point is treated as a mixture of spatial independent components; sICA extracts the different components, each with its unique time course, maximizing their spatial statistical independence. Fig.8 shows the flowchart of the prototype control software.

6 DISCUSSION

6.1 DEVICE PERFORMANCE

Fig. 9 depicts theoretical torques generated by the device with a 25mm bore pneumatic cylinder during plantar- and dorsi-flexion. The different curves depend on the distance (r) between the cylinder rod and the ankle joint (i.e. the radius of the force).

Torque values may vary by changing supply pressure and/or cylinder bore: equivalent force imposed to the foot may consequently vary between 20 and 500N.

Real exchanged forces depend on patient interaction: however pneumatic actuation has been chosen also for its intrinsic compliance, which assures that forces stay under certain imposed values. This is a main issue for safety.

Device can be regulated to adapt joint position to physiological ankle joint for patients between 95-percentile man and 5-percentile woman. Angular displacement reaches maximum values of 25° in dorsiflexion and 35° in plantarflexion: these may be mechanically reduced by means of pins.

Experimental tests gave good results for what regards MR compatibility: chosen materials do not disturb testing magnetic field.

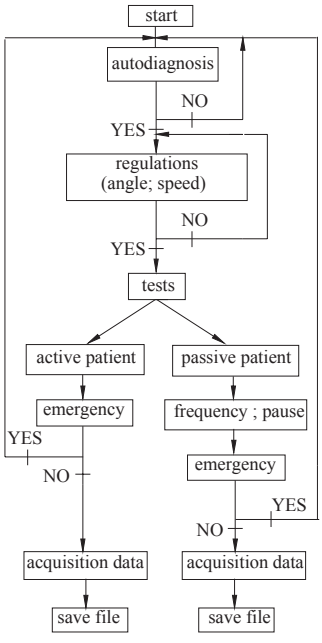

Figure 8 Control software main flowchart

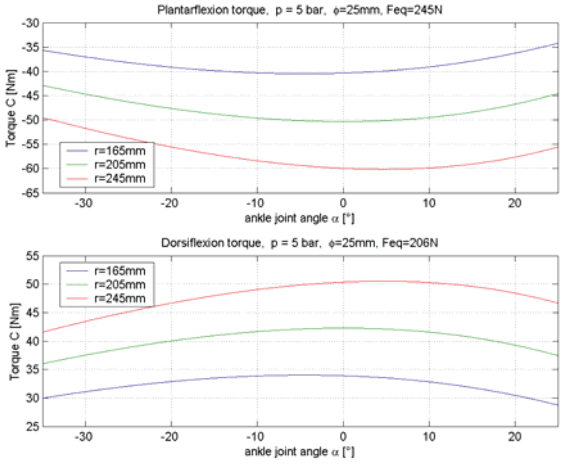

Figure 9 Theoretical torques imposed by pneumatic actuator during ankle range of motion for different values of force lever arm (r).

6.2 fMRI PRELIMINARY RESULTS

We extracted 40 IC with the ICA plugin and correlated each IC timecourse with the stimulation protocol and the 6 motion parameters resulting from the 3D motion correction algoritm. For each paradigm, the four IC found to be more correlated with the stimulation protocol (Fig. 10) and those more correlated with motion parameters (Fig 11) were mapped.

The passive stimulation-related IC (Fig. 10), although in some measure affected by motion noise, shows as expected a robust sensorymotor, supplementary motor and cerebellar activity plus some temporal and parietal clusters. The mean M1 timecourse shows that the activity in this area is strongly correlated with the stimulation paradigm.

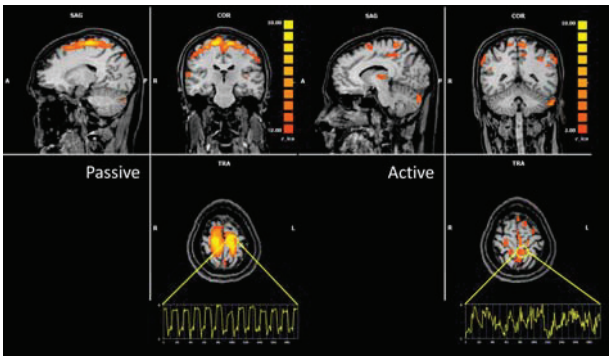

Figure 10 ICA motor components relative to Active (left) and passive (right) stimulation. Boxplots show the mean timecourse of a circular roi placed in the activated left sensorymotor area. Z-ica scale, Images obtained with Brainvoyager QX 1.9.

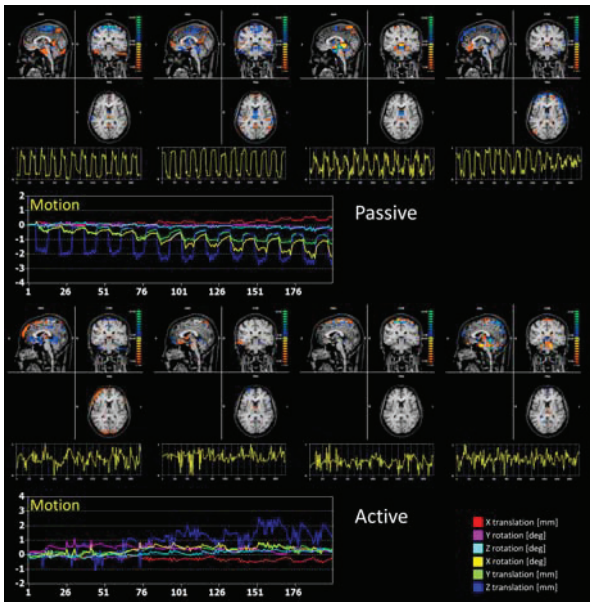

Figure 11 ICA most movement-related noise components relative to passive (upper images) and active (lower images) stimulation. Boxplots show the mean component timecourse and the six parameters motion of the subject head. Z-ica scale, Images obtained with Brainvoyager QX 1.9.

The active stimulation-related IC (Fig. 10) is less affected by motion noise and shows a less robust sensorymotor and supplementary motor activity, a cerebellar activation plus some thalamic, frontal and cingulated clusters. The mean M1 timecourse shows that the activity in this area is less correlated with the stimulation paradigm as well as with motion parameters.

The power analysis of motion-related ICs (Fig. 11) shows that the passive movement can induce stronger motion-related artefacts in the fMRI images than the active one. This is proved by the mean RMS signal that is significatively higher in the passive motion noise IC timecourses than in the active ones (Two sample t-Test, P=0.022 uncorrected).

The visual inspection of the motion graphs confirms that the passive movement induces a severe cumulative as well as periodic translation on the Z-axis and a similar rotation on the X-axis.

7 CONCLUSION

MR compatible device for active and passive foot movement has been developed and tested in MR environment and on a volunteer healthy subject. Device is entirely MR compatible and also optical angular encoder gave good compatibility

results. Device achieves imposing required movements and recording voluntary patient movements without interfering.
Better fixing patient's head may certainly reduce the recorded movement artefact in the fMRI brain activation due to subject translation and a rotation. Literature [12] presents an interesting solution where patient leg is bent. In such configuration it is likely that most of the z-axis translation of patient – and consequently of his head - is absorbed by leg movement instead, which would not generate such signal disturbs.
The main use of the device is in the fMRI assessment of motor rehabilitation efficacy, as it requires precise and controlled tasks in order to create identical pre- and post-treatment conditions and, with some patients, at least a partial help in performing the movement. However, given its RM compatibility, the device can actually be applied in every fMRI examination where either the patient cannot autonomously move his feet, or the control and standardization of movement parameter are essential (e.g. in research contexts). For instance, another relevant clinical fMRI application concerns the pre-surgical localization of eloquent brain areas, i.e. identify where motor and linguistic functions are placed in the patient's brain. Some patients requiring a brain surgery have difficulty in executing an fMRI foot motor task because of their tumor; on the other hand, a precise localization of their cerebral motor function is crucial for pre-surgical planning. Here again, a robotic device inducing passive foot movement becomes of great help. Finally, in research laboratories, fMRI is used to understand the workings of the normal human brain, including sensory and motor functions. In group studies, standardization of task parameters within participants is required. In repeated study designs, a robotic device provides the possibility of studying the effect of different controlled parameters on cerebral activations.
Besides its primary use in fMRI testing, presented device can be fruitfully applied in the rehabilitation of neurological paretic patients, who need to practise foot movements and/or to relearn locomotor schemas. Indeed, given that foot dorsiflexion/plantarflexion is crucial in deambulation, locomotor rehabilitation protocols have started to include specific foot movement exercises (e.g., [18]). The active/passive modes of the device allow its use in various types of motor therapies. For example, within Active Movement Training therapies (AMT), the 'active patient mode' allows the practice of the dorsi/plantar-flexion exercises; the possibility of setting the 'passive patient mode' at different degrees (according to the patient's motor capabilities) allows to include also patients with scarce motor functions, previously excluded from this type of therapy, who can gradually pass from the passive to the active mode on the bases of their ongoing motor improvements. Within Constrained-Induced therapies, the healthy foot can be immobilized with the device, while exercising the paretic foot. In the context of Passive Movement Training therapies, the passive movement of the plegic foot is helpful for the proprioceptive inputs to motor cerebral networks ([19]). In the context of recent Motor Imagery rehabilitation protocols, the passive foot movement can be accompanied by cognitive exercises with a locomotor attention focus.
The fundamental advantage is that the same device can be used both inside and outside the RM scanner, thus allowing to directly correlating patient's progresses in rehabilitation with his cerebral functional changes.

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