Evaluation of a Portable fMRI Compatible Robotic Wrist Interface

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***Abstract*— This paper presents evaluation of a portable fMRI compatible haptic interface to study the brain correlates of sensorimotor control during wrist motion. The interface is actuated by a shielded DC motor located more than 2 m away from the 3T MR scanner's bore. The achievable wrist torque of the interface is up to 2 Nm, and the interface provides sufficient bandwidth for human motor control experiments. Ergonomic and fMRI compatibility testing with a 3T MR scanner showed that the interface is MR safe, compatible with a strong static magnetic field and radio frequency emission, and its operation does not affect the quality of the acquired images.**

***Clinical relevance*— We present and evaluate an fMRI compatible robotic interface to study human wrist joint motor function.**

I. INTRODUCTION

Haptic interfaces that could be used in conjunction with functional magnetic resonance imaging (fMRI) enable neuroscientists and clinicians to investigate the brain mechanisms involved in performing tasks with arbitrary dynamics [1]. The application of novel materials and techniques, as well as advances of MR technology, have enabled deployment of mechatronic systems in MR environments [2], [3], [4], [5].

fMRI compatible haptic interfaces with different actuation principles and design configuration for human motor control experiments were introduced mostly with upper limbs movements. Investigating the control of movements with several degrees of freedom (DoF) can provide important information about how the nervous system coordinates movements involving multiple joints and deals with coupled and nonlinear dynamics [6], [7]. However, dynamic interactions between limb segments often cause head movements and thus result in motion artifacts on brain MR images [8], [9], [10]. Furthermore, the analysis of movements and muscle activity becomes significantly more complex with every additional DoF. This suggests investigating multi-joint movements only when the targeted neural processes require them [11], [12].

While brain imaging is one of the very few non-invasive windows available to observe the neural processes of sensorimotor control across the whole brain, it yields a noisy signal. Traditionally, due to safety and costs restrictions in the technology, brain imaging is better suited for answering relatively simple questions that can in most cases be equally well addressed on one joint rather than on multiple joint movements. For instance, using a wrist flexion/extension interface [13] in conjunction with fMRI and muscle electromyography (EMG), allowed us to investigate the neural basis of force vs. impedance control [14]. A simple tiny wrist flexion/extension 1-DoF interface for neonates [15] enabled us to describe the evolution of sensorimotor activity in the brain of preterm infants, from their birth to term corrected age [16].

These successful experiences motivated us to develop a portable MR compatible haptic interface to wrist flexion/extension movements, that can be used to study human motor control by combining haptic interaction, EMG and MRI. These movements are very suitable for MR imaging studies, as they can be carried out easily by subjects placed in the bore of the scanner, and are likely to generate little head motion. Furthermore, the motor commands for these movements can be investigated precisely using EMG by recording the activity of one group of antagonist muscles, e.g. flexor carpi radialis and extensor carpi radialis longus [17]. Our interface should be compatible with magnetic fields of up to 3T (both from a safety and image artifact perspective), and be adaptable to scanners with different geometries. The overall system should be easily transportable and easily removable if any interruption of the experiment is required.

In this paper, we evaluate with a human-participant a portable MRI compatible wrist interface capable of rendering high dynamic programmable torque output. The design of the interface was previously presented in [18]. The overall view of the developed interface is shown in Fig. 1A-C. The portable wrist interface is installed on the left side of the scanner examination table, so that a patient can be easily placed or removed from the scanner in case of emergency. Fig. 1D demonstrates the portability of the system.

II. DESIGN OVERVIEW

Design requirements. The following key design, ergonomics and safety factors for the fMRI compatible robotic interfaces were considered: portability, easiness of installation, user safety and possibility of fast evacuation, control capabilities.

Portability and easiness of installation are particularly important for haptic systems to be used in fMRI environments, as good portability characteristics reduce the time required to transport and install the devices and therefore the cost for expensive and often limited imaging services decreases significantly. However, not many previous studies

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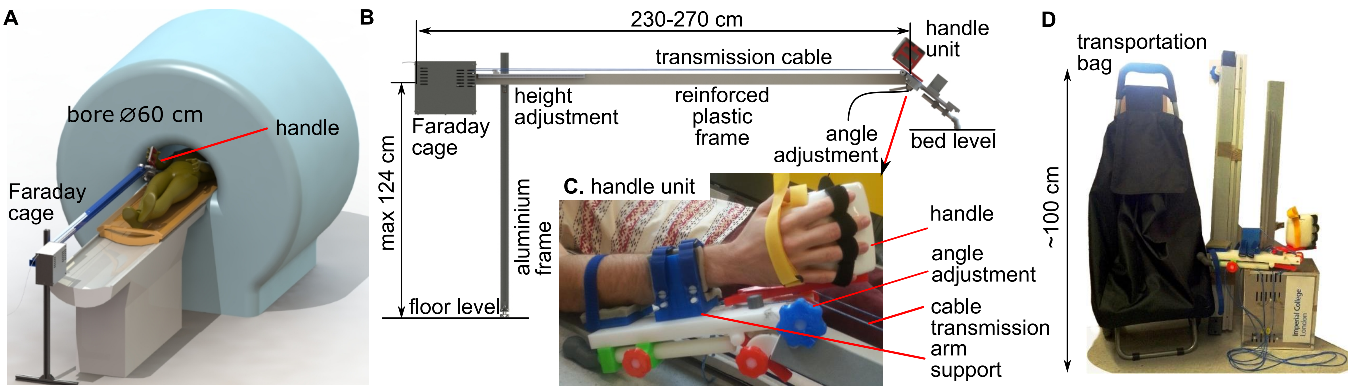

Fig. 1. Overview of the fMRI compatible haptic wrist interface design. **A**, a user during wrist interaction experiment in MR room using the designed interface (CAD); **B**, side view of the interface and its frame (CAD); **C**, a user during interface ergonomic tests; **D**, a photo of the disassembled interface and its travel trolley. The interface can be installed/uninstalled within 15 minutes; its total weight is 15 kg. The interface can be transported by one person and its installation requires two people.

describe the portability of the presented interfaces. Some existing systems involve big frames which makes them non-portable [19], [13], [20], [21]. Other interfaces require rigid attachment to the scanner's bed which is not desirable for portability [22], [23], [24], [25]. Many of these devices use aluminium frames which (1) may heat due to electric current induced by the strong magnetic field and (2) require time and effort to assemble and move the devices in the scanning room [20], [26]. The same limitations apply to interfaces with cable transmission which require special adjustments during installation in the scanning room [27], [28]. A critical safety factor related to the design is the possibility to perform safe and fast patient evacuation from the scanner in emergency cases which is not possible for interfaces with big frames [19], [13], [20], [26], [28].

Haptic interfaces to study human movements should have sufficient dynamic performance such as high bandwidth, low friction, and a simple to tune and robust controller. However, fMRI compatibility requirements generally limit the control performance. For instance, some interfaces are capable of applying forces only in one direction [29], [30], [31] or the force levels are too low when compared to human force capabilities [32]. Depending on the type of actuation the control quality and requirements can create additional application limitations. Using ultrasonic motors can yield compact interfaces, but such motors can hardly be used for slow movements and high holding torques limiting haptic transparency [22]. Interfaces with electro-rheological fluid actuators require high voltage power sources [31]. Devices with ultrasonic motors are not efficient for low velocity movements [24], [25], while interfaces with pneumatic actuation [33], [15], [34] are capable of reproducing only simple movement patterns, characterised by slow response time and require a compressed air source.

While many of the described systems are potentially portable, few were designed to be installed fast and easily. Few of existing systems use conventional electromagnetic actuation enabling flexible control for larger range of velocities and frequencies [32]. Furthermore, few of the existing devices are designed for one DoF movements. However, the ability to draw clear conclusions from human motor studies with fMRI is at odds with the complexity of the involved movements: complex movements will be more difficult to investigate and correlate muscle to brain activity, and are prone to creating motion artifacts [26], [21], [23]. To overcome these potential shortfalls we developed a portable fMRI compatible wrist interface which can be used for a wide range of human motor control studies.

Design overview. The requirements described above were considered for the design of the fMRI compatible wrist interface is shown in Fig. 1. The frame, designed to support the actuation mechanism, is made adjustable, easily removable (is positioned on one side of the bed only). The components of the frame and transmission do not contain any ferromagnetic material to prevent any projectile risk with the main static magnetic field. The design enables fast assembly, disassembly and easy transportation. The actuation system consists of a DC motor with an optical encoder, a 2.1 m long cable transmission, and a a handle unit. Detailed description of the design can be found in [18].

The ergonomic design of the wrist handle unit allows comfortable, adjustable and safe wrist positioning and support facilitating natural and painless movement. Operation of the interfaces should not cause any significant movements of other body parts, which is critical for brain imaging studies [35]. To fulfil these ergonomic requirements an option to adjust inclination of the handle's rotational axis in the vertical plane was added (Fig. 1C).

The interface's system identification tests showed that the haptic interface provides sufficient dynamic bandwidth for human neuro-motor control experiments [18]. The closed-loop position control bandwidth was 0-3 Hz and the bandwidth for torque control was 0-30 Hz.

III. EVALUATING ERGONOMICS

To evaluate the ergonomics of the designed interface we asked five subjects to use the interface for 10 minutes of pre-programmed various motor control tests such as tracking position control, interaction with virtual wall, etc. The

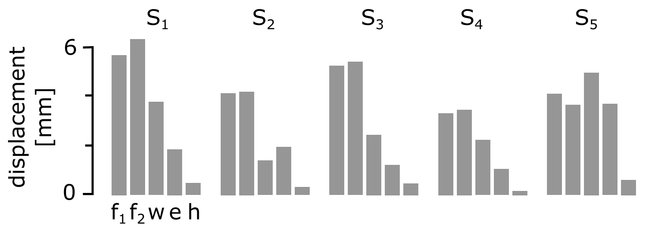

Fig. 2. Experimental results of movement artifacts for five subjects S_1-S_5 for index (f_1) and middle (f_2) fingers, wrist joint (w), elbow (e) and head (h). The displacements of each body part were expressed as root mean square deviations of the measured positions during using with the interface. The standard deviation of head movements was less than 0.6 mm.

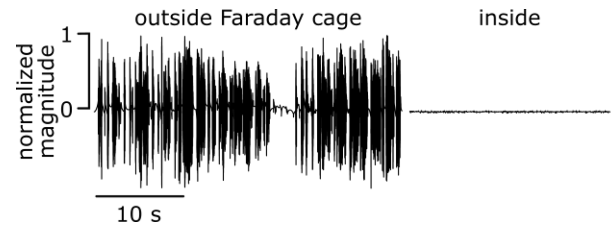

Fig. 3. Time history of the recorded radio signal outside and inside the Faraday cage. FM radio signal at 105 MHz was used as a source, and signal obtained after frequency demodulation (sound signal) was recorded. The signals were normalised with respect to the maximal magnitude.

interface was tested in two configurations: arm support with inclination (as shown in Fig. 1B) and flat arm support (handle is leveled with the main horizontal frame). All subjects preferred the forearm support with adjusted inclination. No discomfort or pain was reported. All tests were conducted in respect with the institutional ethics regulations (reference 12/LO/1247) and involved healthy right handed subjects who were members of our research group.

The validity of motor control studies with fMRI critically depends on avoiding motion artifacts. First, any head movements should be avoided or minimised. Second, to analyse brain activation specifically related to the movement of interest, i.e. wrist flexion/extension, movements in other parts of the body should be negligible.

To evaluate these two factors, we used a visual motion tracking system (VICON Motion Tracking System, VICON, Oxford, UK) acquiring data at 100 Hz to measure movement of the five subjects' arm and head when interacting with the wrist interface. Five visual markers were placed on the right hand of a subject at the wrist joint (near the distal end of the radius bone), elbow joint (near the medial epicondyle of the humerus bone), head (centre of the frontal bone), and index and middle fingers (between distal and middle phalanges). One more marker was attached to the handle of the interface to measure the actual handle motion. The hand of each subject was fixed to the handle with the help of adjustable straps.

In the test the motor generated 1 Hz periodic torque flexing and extending the handle and the subject's wrist with a magnitude of approximately 40°, for about 2 minutes. The three dimensional position of each marker was recorded and root mean square deviation values were calculated. The results are shown in Fig. 2. For the calculation of the standard deviations for the index and middle fingers the position measurements of the finger markers were subtracted from the handle marker position measurements to obtain the displacements relative to the handle motion, which should be zero in the ideal case when the hand motion follows the handle's motion perfectly. As reported, for most of the subjects the relative finger movements with respect to the handle were about 6 mm, for the wrist joint the movement was about 4 mm, for the elbow joint - less than 2 mm, which are much smaller than the actual handle motion that exceeded 90 mm. The head motion for all subjects did not exceed 0.7 mm across all recordings.

In summary, the possibility to adjust the interface configuration for more comfortable hand positioning in the arm support provides sufficient user-interface interaction quality for the subjects, and makes the interface effective for fMRI motor control studies.

IV. MRI EVALUATION

RF compatibility. Prior to the tests at the MR imaging facility we checked whether the built Faraday cage was filtering out the RF so that that RF emission from the scanner did not influence the interface. For this test we used radio FM receiver set to receive signals at 105 MHz outside and inside the Faraday cage. Received signals were recorded for both cases and their plots are shown in Fig. 3. Clearly the RF emission was not detected when the receiver was inside the cage.

MR compatibility. Compatibility tests were carried out with a Philips Achieva 3.0 T TX scanner (Best, Netherlands) located at St Thomas hospital in London, UK. First we performed MR compatibility tests to verify that the interface is safe to be used inside the magnetic environment and does not deteriorate the image.

In the first recording during MR compatibility tests the motor was controlled by a micro-controller located inside the Faraday cage. Current steps of ± 2 A equivalent to 1.2 Nm were applied to the motor. During the test 24 slices of data were acquired using a gradient-echo EPI (echo planar imaging) sequence with an in-plane acquisition matrix of 256×256 and a cylindrical water-filled phantom, under two conditions: interface running and interface OFF. No distortion of the images was observed linked to either field inhomogeneity or speckles/strips image artifacts related to RF interference. The signal-to-noise ratio (SNR) for the two recordings was 28.3 dB (interface OFF) and 28.6 dB (interface ON). Statistical comparison of the images did not detect any significant differences.

Then, an MR compatibility test was performed with a healthy subject (male, right handed, age 28). $T2$-weighted images were acquired using a turbo spin-echo (TSE) sequence, with the haptic interface controlled from outside the scanner room using the optical fiber USB cable and specially designed software. Examples of the acquired images (at z=26) for the cases when the wrist interface was ON (active movements of the right wrist) and OFF (no movement) are

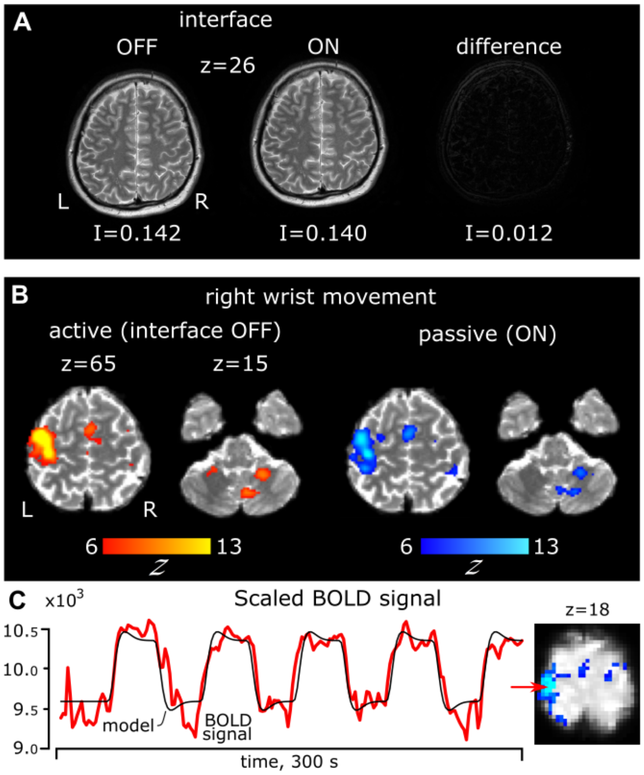

Fig. 4. **A**, anatomical T2 scans of the brain (at z=26) for the cases when the interface was OFF (left), ON (middle) and the image difference (right). Normalized image intensity I is reported for each scan. **B**, recorded brain activity (at z=65 and z=15) for the case when the human subject moved the wrist and the interface was OFF (left) and for the case when wrist was moved together with running haptic interface (right). **C**, the sampled Blood oxygen level (BOLD) dependent signal (red) can closely fit the Hemodynamic response function model (black).

presented in Fig. 4A. Visual inspection of the images did not show any differences. The difference between the images is shown on the right panel of the Fig. 4A. The difference image was obtained by subtracting the corresponding pixel intensities from the anatomical brain image when the interface was OFF and from the cases when the interface was activated. The normalized mean pixel intensity of the difference image was 0.012 (where 0 corresponds to black and 1 to white pixels) while the original brain images' intensity was about 0.14 or more than ten times larger.

fMRI test. To complete the evaluation, an fMRI compatibility test was performed to verify that expected brain responses are adequate for active condition (subject voluntary wrist movements while the interface if OFF) and for passive condition (subject's wrist movements controlled by the running interface). In the passive condition the controller of the DC motor was used in the torque control mode to track the reference 1 Hz periodic sinusoidal torque, as it was used in the ergonomics validation test.

The tests were performed in the same environment as the MR compatibility test with the same subject. The fMRI data was acquired using a gradient-echo EPI (GRE-EPI) sequence with parameters: TR: 1500 ms; TE: 30 ms; FA: 90°; resolution ($x \times y \times z$): 3.5×3.5×5 mm; 22 slices; SENSE factor: 2. Images were acquired during alternating periods of 30 s rest and 30 s right wrist extension/flexion. The total recording time was 300 s. Each state was repeated five times, as a result 100 data points were acquired for each of the conditions (rest and movement). In the passive condition (the interface was ON), the handle pushed the wrist to flex and extend and the subject was instructed to follow the handle's movements. We verified that in the passive condition the subject did not cause significant unintentional resistance torques to the handle which could cause differences with respect to the brain images acquired in the active condition.[1]

The General Linear Model (GLM) as implemented in FEAT (fMRI Expert Analysis Tool v5.0.8, FSL image processing package) was used to carry out fMRI analysis [36]. Data were preprocessed using standard steps comprising motion correction, slice-timing correction, non-brain tissue removal, spatial smoothing (Gaussian kernel 5 mm FWHM), global intensity normalization, and high-pass temporal filtering (cut-off 60 s). The results of the fMRI analysis are presented in Fig. 4B. The brain images on the left show the identified activation rendered as red-yellow gradient (z=65 and z=15) representing the fMRI data when the interface was OFF. The remaining images on the right of Fig. 4B show the identified patterns of activation in blue gradient when the interface was ON. In both experimental conditions, characteristic and significant clusters of brain activity were identified in the contralateral (left) peri-rolandic region (comprising the primary motor and somatosensory cortices), the midline supplementary motor area, and ipsilateral peri-rolandic region and cerebellum. Fig. 4C presents the time series measurements of Blood oxygen level (BOLD) dependent signal in the test when the wrist interface was activated for 30 s for five times. The wrist movements are associated with significant increases in the measured BOLD signal in the brain area marked with a red arrow on the right panel of Fig. 4C.

Statistical analysis of fMRI data and visual inspection of the images showed that in both cases activation was nearly identical and that usage of the wrist interface did not alter or adversely affect the ability of fMRI to identify significant clusters of brain activity.

V. CONCLUSION

The presented fMRI-compatbile robotic wrist interface is easy to transport and set up (weight $\leq$15 kg, length $\leq$90 cm, $\leq$15 minutes installation time), and can be adapted to different scanners with magnetic fields up to 3T. It can be used to provide a high quality haptic environment at 200 Hz with simultaneous recording of muscle and brain activity. An fMRI evaluation with a participant demonstrated that the device provides a comfortable interaction with a bandwidth over the capabilities of wrist movements, does not cause

[1]Based on the error between the recorded reference and measured DC motor currents during the test, we calculated the root mean square of the resistance torque. The mean absolute resistance torque at the handle in the active condition was about 20 mNm, which is of the same order as the mean levels of identified interface friction.

image artifacts, and can be safely used to induce robust patterns of brain activity relating to sensorimotor processing.

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REFERENCES

[1] R. Gassert, E. Burdet, and K. Chinzei, "Opportunities and challenges in mr-compatible robotics," *IEEE Engineering in medicine and biology magazine*, vol. 27, no. 3, pp. 15–22, 2008.

[2] R. Gassert, A. Yamamoto, D. Chapuis, L. Dovat, H. Bleuler, and E. Burdet, "Actuation methods for applications in MR environments," *Concepts Magn. Reson. Part B Magn. Reson. Eng.*, vol. 29B, pp. 191–209, oct 2006.

[3] R. Gassert, D. Chapuis, H. Bleuler, and E. Burdet, "Sensors for Applications in Magnetic Resonance Environments," *IEEE/ASME T. Mechatronics*, vol. 13, pp. 335–344, jun 2008.

[4] V. Hartwig, N. Carbonaro, A. Tognetti, and N. Vanello, "Systematic review of fmri compatible devices: design and testing criteria," *Annals of biomedical engineering*, vol. 45, no. 8, pp. 1819–1835, 2017.

[5] M. Fleury, G. Lioi, C. Barillot, and A. Lécuyer, "A survey on the use of haptic feedback for brain-computer interfaces and neurofeedback," *Frontiers in Neuroscience*, vol. 14, p. 528, 2020.

[6] R. Shadmehr and F. Mussa-Ivaldi, "Adaptive representation of dynamics during learning of a motor task," *J. Neurosci.*, vol. 14, pp. 3208–3224, may 1994.

[7] E. Burdet, R. Osu, D. W. Franklin, T. E. Milner, and M. Kawato, "The central nervous system stabilizes unstable dynamics by learning optimal impedance.," *Nature*, vol. 414, pp. 446–9, nov 2001.

[8] J. M. Hollerbach and T. Flash, "Dynamic interactions between limb segments during planar arm movement," *Biol. Cybern.*, vol. 44, pp. 67–77, may 1982.

[9] T. Lemmin, G. Ganesh, R. Gassert, E. Burdet, M. Kawato, and M. Haruno, "Model-based attenuation of movement artifacts in fMRI.," *J. Neurosci. Methods*, vol. 192, pp. 58–69, sep 2010.

[10] M. Kühne, M. Eschelbach, A. Aghaeifar, L. von Pflugk, A. Thielscher, M. Himmelbach, K. Scheffler, A. Peer, *et al.*, "An mr-compatible haptic interface with seven degrees of freedom," *IEEE/ASME Transactions on Mechatronics*, vol. 23, no. 2, pp. 624–635, 2018.

[11] A. Erwin, M. K. O'Malley, D. Ress, and F. Sergi, "Kinesthetic feedback during 2dof wrist movements via a novel mr-compatible robot," *IEEE T NEUR SYS REH*, vol. 25, no. 9, pp. 1489–1499, 2016.

[12] S. Menon, A. Soviche, J. Mithrakumar, A. Subbarao, and O. Khatib, "A novel haptic fmri interface for five-axis force and motion neuroimaging experiments," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 899–905, IEEE, 2017.

[13] R. Gassert, R. Moser, E. Burdet, and H. Bleuler, "MRI/fMRI-compatible robotic system with force feedback for interaction with human motion," *IEEE/ASME T. Mechatronics*, vol. 11, pp. 216–224, apr 2006.

[14] M. Haruno, G. Ganesh, E. Burdet, and M. Kawato, "Differential neural correlates of reciprocal activation and cocontraction control in dorsal and ventral premotor cortices.," *J. Neurophysiol.*, vol. 107, no. 1, 2012.

[15] A. G. Allievi, A. Melendez-Calderon, T. Arichi, A. D. Edwards, and E. Burdet, "An fMRI compatible wrist robotic interface to study brain development in neonates.," *Ann. biomed. eng.*, vol. 41, pp. 1181–92, jun 2013.

[16] A. G. Allievi, T. Arichi, N. Tusor, J. Kimpton, S. Arulkumaran, S. J. Counsell, A. D. Edwards, and E. Burdet, "Maturation of Sensori-Motor Functional Responses in the Preterm Brain.," *Cereb. Cortex*, oct 2015.

[17] A. Melendez-Calderon, L. Bagutti, B. Pedrono, and E. Burdet, "Hi5: A versatile dual-wrist device to study human-human interaction and bimanual control," in *Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst.*, pp. 2578–2583, sep 2011.

[18] I. Farkhatdinov, A. Garnier, and E. Burdet, "Development and evaluation of a portable MR compatible haptic interface for human motor control," in *IEEE WorldHaptics 2015*, pp. 196–201, jun 2015.

[19] R. Moser, R. Gassert, E. Burdet, L. Sache, H. Woodtli, J. Erni, W. Maeder, and H. Bleuler, "An MR compatible robot technology," in *Proc. IEEE ICRA*, vol. 1, pp. 670–675, 2003.

[20] S. Li, A. Frisoli, L. Borelli, M. Bergamasco, M. Raabe, and M. W. Greenlee, "Design of a new fMRI compatible haptic interface," in *Proc. of IEEE World Haptics 2009*, pp. 535–540, IEEE, mar 2009.

[21] S. Menon, G. Brantner, C. Aholt, K. Kay, and O. Khatib, "Haptic fMRI: combining functional neuroimaging with haptics for studying the brain's motor control representation.," *Proc. Ann. Int. Conf. IEEE Eng. Med. Biol. Soc.*, pp. 4137–42, jan 2013.

[22] M. Flueckiger, M. Bullo, D. Chapuis, R. Gassert, and Y. Perriard, "fMRI compatible haptic interface actuated with traveling wave ultrasonic motor," in *40th IAS Annu. Meet. Conf. Rec. 2005*, vol. 3, pp. 2075–2082, IEEE, 2005.

[23] M. A. Ergin, M. Kuhne, A. Thielscher, and A. Peer, "Design of a new MR-compatible haptic interface with six actuated degrees of freedom," in *5th IEEE RAS/EMBS Int. Conf. Biomed. Robot. Biomechatronics*, pp. 293–300, aug 2014.

[24] F. Sergi, A. C. Erwin, and M. K. OMalley, "Interaction Control Capabilities of an MR-Compatible Compliant Actuator for Wrist Sensorimotor Protocols During fMRI," *IEEE/ASME T Mechatronics*, vol. 20, pp. 2678–2690, dec 2015.

[25] A. Erwin, M. K. O'Malley, D. Ress, and F. Sergi, "Development, control, and MRI-compatibility of the MR-SoftWrist," in *2015 IEEE Int. Conf. Rehabil. Robot.*, pp. 187–192, aug 2015.

[26] A. Hribar, B. Koritnik, and M. Munih, "Phantom haptic device upgrade for use in fMRI.," *Med. Biol. Eng. Comput.*, vol. 47, pp. 677–84, jun 2009.

[27] D. Chapuis, R. Gassert, G. Ganesh, E. Burdet, and H. Bleuler, "Investigation of a cable transmission for the actuation of MR compatible haptic interfaces," in *Proc. IEEE Int. Conf. Biomed. Robot. Biomechatronics*, pp. 426–431, 2006.

[28] B. Vigaru, J. Sulzer, and R. Gassert, "Design and evaluation of a cable-driven fmri-compatible haptic interface to investigate precision grip control.," *IEEE Trans. Haptics*, vol. PP, p. 1, oct 2015.

[29] A. Khanicheh, A. Muto, C. Triantafyllou, B. Weinberg, L. Astrakas, A. Tzika, and C. Mavroidis, "fMRI-compatible rehabilitation hand device.," *J. Neuroeng. Rehabil.*, vol. 3, p. 24, jan 2006.

[30] L. M. Di Diodato, R. Mraz, S. N. Baker, and S. J. Graham, "A haptic force feedback device for virtual reality-fMRI experiments.," *IEEE T Neural Syst. Rehabil. Eng.*, vol. 15, pp. 570–6, dec 2007.

[31] A. Khanicheh, D. Mintzopoulos, B. Weinberg, A. A. Tzika, and C. Mavroidis, "MR_CHIROD v.2: magnetic resonance compatible smart hand rehabilitation device for brain imaging.," *IEEE T Neural Syst. Rehabil. Eng.*, vol. 16, pp. 91–8, feb 2008.

[32] M. Hara, J. Duenas, T. Kober, D. Chapuis, O. Lambercy, H. Bleuler, and R. Gassert, "Design and compatibility of a high-performance actuation system for fMRI-based neuroscience studies," in *Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst.*, pp. 2437–2442, oct 2010.

[33] N. Yu, W. Murr, A. Blickenstorfer, S. Kollias, and R. Riener, "An fMRI compatible haptic interface with pneumatic actuation," in *2007 IEEE 10th Int. Conf. Rehabil. Robot.*, pp. 714–720, IEEE, jun 2007.

[34] H. Sharini, N. R. Alam, H. Khabiri, H. Arabalibeik, H. Hashemi, A. Azimi, and S. Masjoodi, "Novel fmri-compatible wrist robotic device for brain activation assessment during rehabilitation exercise," *Medical engineering & physics*, vol. 83, pp. 112–122, 2020.

[35] Z.-M. Li, L. Kuxhaus, J. A. Fisk, and T. H. Christophel, "Coupling between wrist flexion-extension and radial-ulnar deviation.," *Clin. Biomech.*, vol. 20, pp. 177–83, feb 2005.

[36] S. M. Smith, M. Jenkinson, M. W. Woolrich, C. F. Beckmann, T. E. J. Behrens, H. Johansen-Berg, P. R. Bannister, M. De Luca, I. Drobnjak, D. E. Flitney, R. K. Niazy, J. Saunders, J. Vickers, Y. Zhang, N. De Stefano, J. M. Brady, and P. M. Matthews, "Advances in functional and structural MR image analysis and implementation as FSL.," *Neuroimage*, vol. 23 Suppl 1, pp. S208–19, jan 2004.