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Research Article

A Functional MRI-Compatible Apparatus for Investigations of Brain Activity during Simulated Walking – A Pilot Study

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ABSTRACT

Understanding brain activity during walking and imagined walking is critical for accurate design of brain computer interfaces (BCIs) for patients with limited or no mobility. Functional magnetic resonance imaging (fMRI) has great potential for this purpose; however, during imaging, subjects must remain in a supine position, which limits studies to simple leg movements that minimize head motion such that fMRI data are not contaminated by signal artifacts. Here, we describe the design and testing of an MR-compatible apparatus that allows subjects to perform leg movements that closely resemble the kinematics of normal walking with minimal head motion.

Keywords: Magnetic resonance imaging; Brain computer interface; Kinematics

Abbreviations: BCIs: Brain Computer Interfaces; fMRI: Functional Magnetic Resonance Imaging; MR apparatus: Melting Point Apparatus; LAMRI: Locomotion Apparatus for Magnetic Resonance Imaging; CAD design: Computer-Aided Design; MR scanner: Magnetic Resonance Imaging Scan; Hz: Hertz; mm: Millimetre; AITF: Alberta Innovates Technology Future; CIHR: Canada Innovates Health Research; NSERC: National Science and Engineering Research Council.

INTRODUCTION

Walking is an intricate sensorimotor and cognitive task that involves the interaction of a number of dynamic processes in the brain, spinal cord and limbs [1]. An understanding of these interactions, the brain's activity during walking, is important when considering the design of brain-computer interfaces (BCIs) for individuals who have lost function of their legs and are unable to walk. One technology that has potential for this purpose is functional magnetic resonance imaging (fMRI), which indirectly measures neural activity throughout the entire brain at millimetre spatial resolution, by assessing localized increases in blood flow during tasks [2].

However, fMRI requires individuals to be in a supine position within a spatially confined environment (i.e., inside the MR scanner) during brain imaging. This poses several unique challenges to the study of brain activity during walking: supine rather that upright body position; mimicked stepping motions rather than true walking movements; and excessive head motion that occurs during leg movements in a supine position, leading to fMRI signal artifacts.

The biomechanics and kinetics of flexion and extension at the knee joint in a supine position have been investigated previously [3,4]. However, no studies have attempted to assess the kinematic features of such movements for the purposes of determining if they are a suitable proxy for walking or for stepping. Several apparatus designs have been proposed to allow simple leg movements while inside an MR scanner, including a single-leg, ankle flexion and dorsiflexion device [5,6] and a single-leg movement weight-resistant pulley system (to simulate the effects of gravity) [7].

Yet, because walking incorporates movement of the lower body at the hip, knee and ankle, these designs are limited in their ability to comprehensively examine the kinematics of simulated walking. A bipedal device that allows for hip, knee and ankle

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movement has been proposed [8]. However, the design requires several pneumatic pressurized cylinders to offer resistance, which is costly and makes the device somewhat cumbersome for MRI purposes.

These issues thus require a novel design of an apparatus to permit leg movements inside the MR environment that closely mimic walking and minimize any detrimental impact on brain image quality. We have designed an apparatus to meet these challenges. The apparatus is: 1) made of MRI-compatible materials; 2) cost-efficient; 3) light-weight and durable for easy insertion into and removal from the MR environment; and 4) permits stepping movements that closely mimic the kinematics of natural walking, with minimal head motion.

RESEARCH METHODOLOGY

Pre-design

Prior to constructing the apparatus, the magnitude of head motion that occurs during lower limb movements executed in a supine position was determined, and the kinematics of these lower limb movements were compared to those that occur during normal upright walking. This information was used to inform apparatus design.

Three healthy, male volunteers (aged 19-24) took part in this pre-design study, which was approved by the University of Calgary's Conjoint Health Research Ethics Board. Thirty-five reflective markers were affixed to the body at the left and right hip, knee and ankle joints, acromion, proximal and distal sternum, cervical vertebrae 7, along the legs, and to the head at the right and left glabella, and the left and right parietal bones. From the reflective marker positions, a number of lower limb locations were defined specifically.

The joint center of the knee was taken as the midpoint between the reflective markers affixed to each side of the knee. The ankle joint center was taken as the midpoint between reflective markers affixed to the left and right malleoli. Joint centers for each hip were calculated using Tylkowski's approach [9] (i.e., 11% of the inter-ASIS distance medially, 12% distally, and 21% posteriorly, from each anterior superior iliac spine). Locations of the ankles, knees, hips, head and chest were defined using a Euler coordinate system [10].

Kinematic data for the head and knee were collected at 120 Hz using eight Kestrel Motion Analysis photogrammetric cameras and the Cortex software program (Motion Analysis Corporation ™, Santa Rosa, CA). Five trials consisting of five movements of each leg were performed for each of two conditions (alternating knee flexion/extension in a supine position on a physiotherapy training table and normal upright walking), with rest breaks between trials. Supine knee flexion and extension were performed such that the heel remained in contact with the table. Five rates of supine knee flexion/extension (40, 50, 60, 70, and 90 per min) were investigated, paced by an audio metronome.

Upright walking was self-paced. Kinematic data were imported into Matlab (The Mathworks®, Natick, MA) and low-passed filtered at 5 Hz. To permit comparison of kinematic data across conditions, the time segment of each movement from heal strike to heal strike was normalized from 0 (beginning of movement) to 100 (completion of movement). Maximum translation of the head in each direction during supine leg movements was computed using the positions of the head reflective markers during movements.

Apparatus design and construction

An apparatus (which we call the Locomotion Apparatus for Magnetic Resonance Imaging - LAMRI) was designed in the form of a portable bed table that could be easily inserted into and removed from the MR scanner. The computer-assisted design of the apparatus is shown in Figure 1 and was based on the dimensions of the MR scanner bore and the existing patient table, as well as the information gathered from the pre-design phase. The constructed apparatus is also shown in Figure 1.

All materials were non-ferromagnetic. The table board was constructed from pine, as it is light, durable and strong. The pedals and pulleys were made of Lexan, due to its very low coefficient of friction for both the pulley-rope and pedal-board interfaces, with brass rod and nylon bolts. Aluminium was used for the pulley mounts, with brass countersunk screws. Ribs were attached onto the backside of the board to provide a stable base and to distribute the participant's weight across the entire board due to the concavity of the existing MR table.

Torso restraints were incorporated to restrict upper body movement. Slits were made in the top half of the board (i.e., towards the head) for strap restraints to crisscross the body and go around the abdomen. Modular handholds (to accommodate various arm lengths) were included so participants could brace themselves against torso movement while performing leg movements. During MRI, the participant's head is inside the imaging coil, and thus the existing head restraints were used.

To simulate the force of gravity experienced during walking, pedals that slide within a near frictionless track were connected to pulleys with weights attached (Figure 1). Because the force of gravity is specific to a participant's mass, a weighting system based on the participant's anthropometric data was required. Specifically, leg segment mass (thigh and shank) were calculated as a percentage of total mass based on anthropometric data, equating to 17% body weight for each leg [10]. A rope was fastened to the end of the base plate, and the groove of the pulley was positioned at a 90-degree angle. This permitted modular weights consisting of salt in a fabric bag to be attached to the pulley system.

To record the timing of a participant's stepping movements, MR-compatible button pads (Lumina, Cedrus Corp., San Pedro, CA) were incorporated into the design so that at the end of the stepping movement a button was pressed (Figure 1). Upon flexion, the foot pedal slides past a spring-loaded depressor (towards the end of the board near the feet), releasing the response button. When participants extend their legs, the spring-loaded mechanism is pressed, which depresses the response button. A picture of a participant in the apparatus on the MR scanner bed is shown in Figure 2.

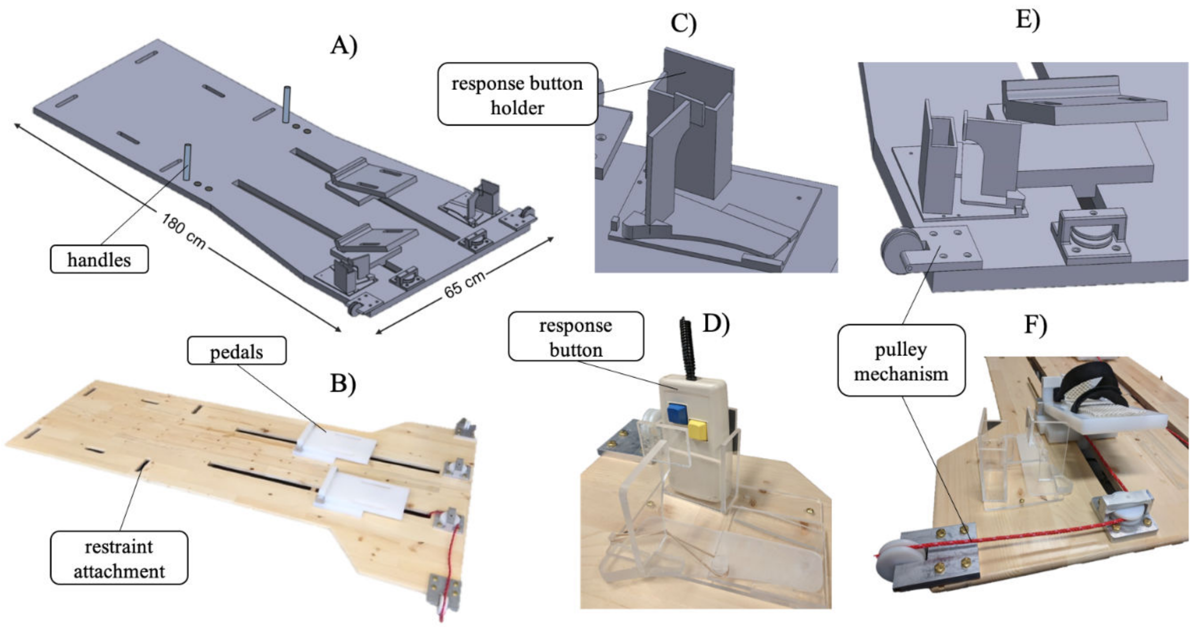

Figure 1: A CAD design of the MR apparatus including dimensions to assist with scale. This figure shows A) the dimensions and handholds, B) the pedals and their tracks, C) response button holders to time stamp stepping and hand holds for participants, D) the response button switch, E) pulley system in CAD and F) pulley system after fabrication.

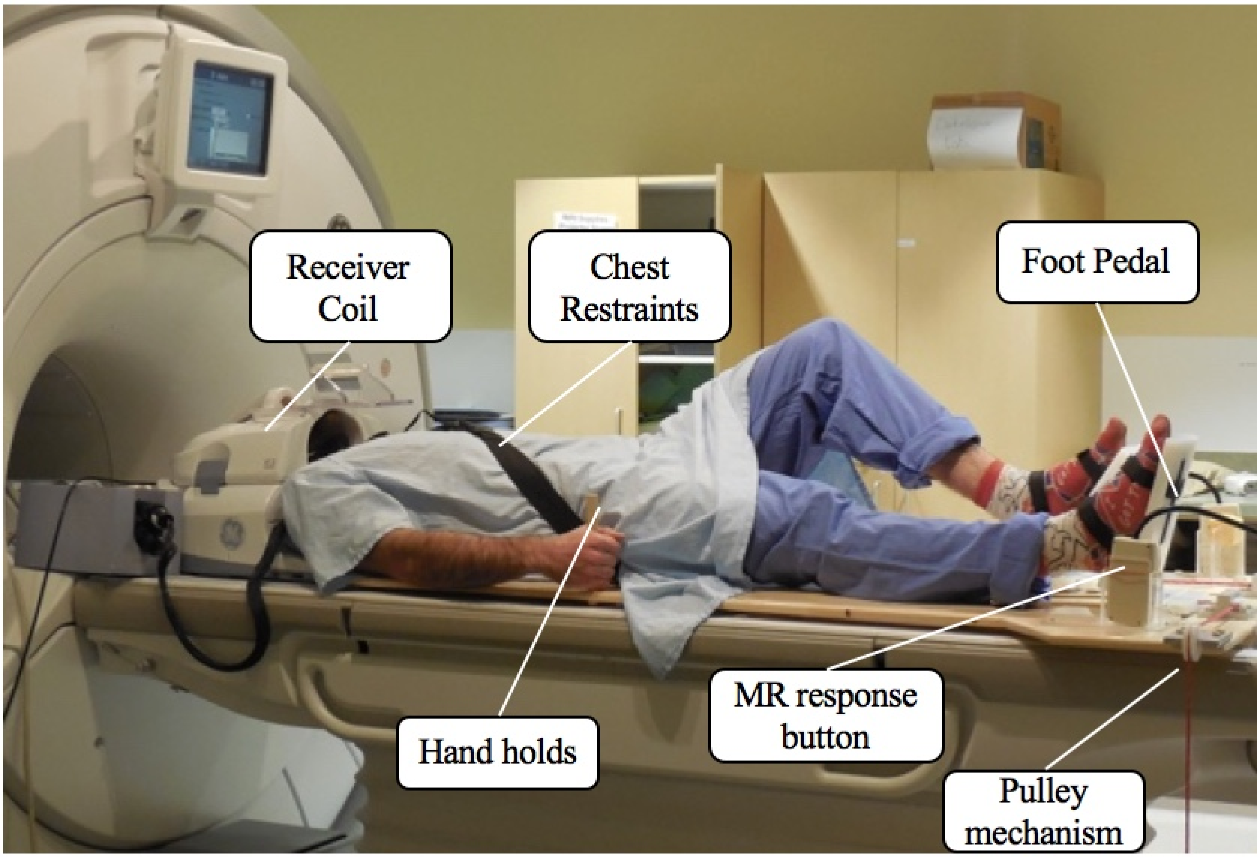

Figure 2: MR apparatus in the MR scanner with participant positioned for stepping movements. This device is modular within the scanner for individuals of varying height and weights.

Pilot testing of the apparatus

Pilot testing of the apparatus outside the MR environment was performed to compare knee kinematics and head motion to the data acquired in the pre-design phase. The same three individuals who participated in the pre-design phase participated in the pilot testing of stepping movements using the apparatus.

Task and data collection methodologies were the same as in the pre-design phase, with the exception that only one movement rate (50 steps per minute) was investigated (this rate was determined to be optimal, see Results section; while 50 steps/min is approximately half of the normal walking pace (~100 steps/min) [11], this rate minimizes head motion).

Additional pilot testing of the apparatus was conducted during an MRI session to ensure fMRI data quality was not compromised and to assess head movement as determined using the software, MCFLIRT [12].

FMRI data were collected using a 3 Tesla Discovery MR-750 scanner equipped with a 12-channel receive-only phased array head coil (GE Healthcare, Waukesha, WI) and a gradient-recalled echo planar imaging sequence (repetition/echo time=2000/30 ms, flip angle=70°, 150 total volumes, 64 × 64 matrix, 3-mm isotropic voxels). Pacing of leg movements was accomplished using a visual stimulus, where a computer-generated avatar "walked" on screen at a rate of 50 steps/min. and participants were instructed to pace their movements with the video image [13].

RESULTS

Table 1 shows the pre-design maximum head displacement for each participant, averaged over the five right leg movement trials, at each pace.

Head displacement exceeded 2 mm for all rates of movement and in all directions, with greatest displacements along the x-axis (i.e., in the sagittal plane), but was least for a stepping rate of 50 steps/min. During supine leg movements using the LAMRI inside the MR scanner, head movement was less 2 mm in all direction (Table 1).

Table 1: Maximum head displacements during supine leg movement trials (pre-design), and with the LAMRI inside the MR scanner, averaged over all trials and participants (N=3). A stepping rate of 50 steps/min yielded the lowest head displacement during the pre-design phase and was thus selected as the prescribed rate for the apparatus inside the MR scanner.

Steps per min	x (mm)	y (mm)	z (mm)
40	7.2 ± 0.4	3.0 ± 1.0	2.2 ± 0.6
50	4.0 ± 0.6	2.9 ± 0.1	2.2 ± 0.2
60	5.6 ± 0.8	4.4 ± 0.8	2.9 ± 0.6
70	7.9 ± 1.2	3.9 ± 0.4	3.6 ± 0.2
90	7.1 ± 1.3	6.4 ± 4.2	4.6 ± 2.3
50 (with LAMRI in MRI)	1.3 ± 0.4	0.7 ± 0.5	0.3 ± 0.2

Pre-design knee flexion angle as a function of time (normalized over a complete trial) for upright walking and supine movements at a rate of 50 steps/min are shown in Figures 3A and 3B, respectively, for each participant averaged over all trials. Maximum knee flexion angle was 74° during executed walking at approximately 75% of the stride, while maximum knee flexion angle during supine movements was 48° at approximately 65% of the stride.

Upon further visual inspection it was noted that executed walking also had a small peak at 15%, which was associated with lifting of the leg at the initiation of the stride. Supine knee flexion angle as a function of time using the LAMRI (outside the MR scanner) is shown in Figure 3C.

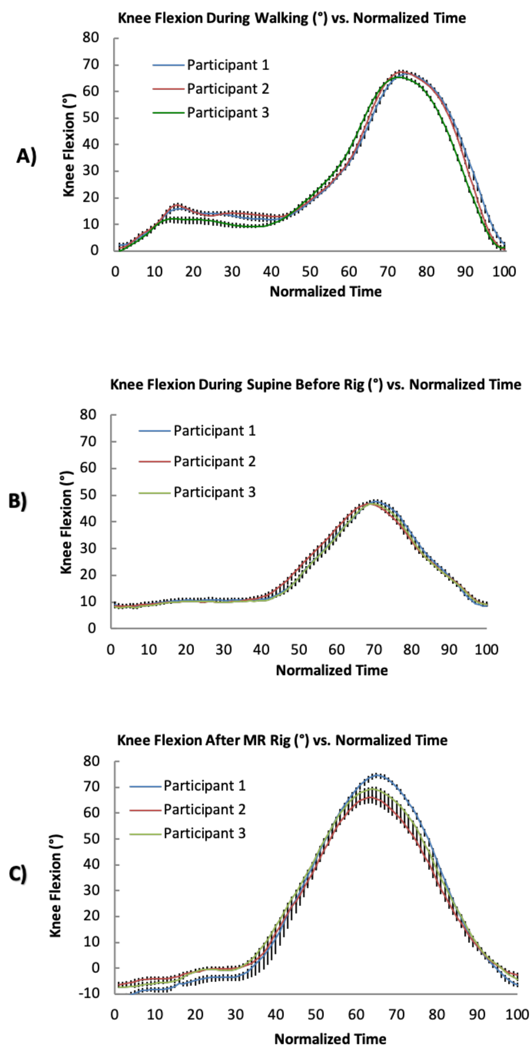

Figure 3: Knee flexion angle over the course of a stride for A) upright walking, B) supine before apparatus and C) using the apparatus.

Visual inspection shows that maximum knee flexion angle, time of maximum angle, as well as the presence of an initial small peak at the beginning of the motion, all closely resemble that of upright walking.

DISCUSSION

An MR-compatible device was constructed to permit simulated stepping while lying inside an MR scanner. The design significantly reduced head movement during stepping tasks and generated knee flexion kinematics that were more similar to that of upright walking than without the apparatus. The MR apparatus was intentionally designed to be modular so it could be adjusted for people of different heights and weights. The MR apparatus allows for hip, knee and ankle flexion/extension; thus, it can be used to assess all three actions associated with stepping. This design offers a relatively inexpensive means to use fMRI to study brain activity associated with lower body flexion/extension that mimics stepping.

The study, however, had some limitations. The calculation of the knee and hip joint centers were somewhat subjective. Tylkowski's method is cited as being more accurate than Andriacchi's; however, it is still associated with approximately 1.90 cm of discrepancy from true radiographic hip joint center [9]. A combination of Tylkowski's and Andriacchi's method is superior to either one alone. This combined approach uses Tylkowski's frontal plane proportions and Andriacchi's sagittal plane ones, generating hip center results within 1.07 cm of the true radiographic hip joint center [9-13].

CONCLUSION

Only the right step was analyzed for similarity between upright walking and supine knee flexion. Given the symmetry at the knee joint during walking, it is likely that similar findings would be obtained for the left leg comparisons. In addition, data were collected on a small sample of young, healthy males, possibly limiting the generalizability of the findings to older or female populations.

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