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TECHNICAL NOTE

MEDICAL PHYSICS

Technical note: MR-compatible pedal ergometer with electromechanical pedal resistance and exercise triggering enhanced by visual feedback via video display

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[Correction added on 27 June, 2024, after first online publication: The copyright line was changed.]

Abstract

Background: During and after exercise, dynamic ^{31}P MR parameters are typically measured using an MR-compatible ergometer. Self-built equipment for local condition can be constructed where possible.

Purpose: To develop a pedal resistance ergometer with rocker arm based on a system that combines electric weight displacement, visual self-monitoring, and exercise triggering. The repeatability and reproducibility were tested.

Methods: The hardware and software for the ergometer were constructed from commercial components in a home laboratory. Twelve volunteers participated in the testing of the ergometer.

Results: A fully automated ergometer system was developed, allowing the pedal resistance to be adjusted during the examination. The system includes a self-monitoring and triggering mechanism that enables both the operator and subject to monitor pedal frequency and force. The operator can modify the pedal resistance as desired during the exercise. This self-monitoring solution is simple and cost-effective, requiring only a commercial potentiometer, an Arduino converter, and a conventional video projector with a personal computer (PC). Additionally, all system components are located outside the magnetic resonance (MR) room, avoiding interference with the MR system. Results of several test of the reproducibility/repeatability of power at three pedal resistance values (15%, 24%, 25% maximal voluntary force) were expressed both as a coefficient of variation ranging from 6% to 3.1% and as an intraclass correlation of coefficient ranging from 0.96 to 0.99. Similar values were also found for other dynamic parameters of ^{31}P MR spectroscopy. These findings are similar to published data obtained on different types of ergometers.

Conclusions: Based on more than 1 year of usage, the ergometer proved successful in handling stationary and variable loads, and can be easily operated by a single user.

KEYWORDS
construction, dynamic ^{31}P MR spectroscopy, MR compatible ergometer, self-monitoring

Abbreviations: ΔPCr, PCr signal drop; MVF, maximal voluntary force; P, exercise power; pH_{end}, pH at the end of exercise; Q_{max}, mitochondrial capacity; V_{PCr}, initial PCr recovery rate; τ_{PCr}, recovery time constant.

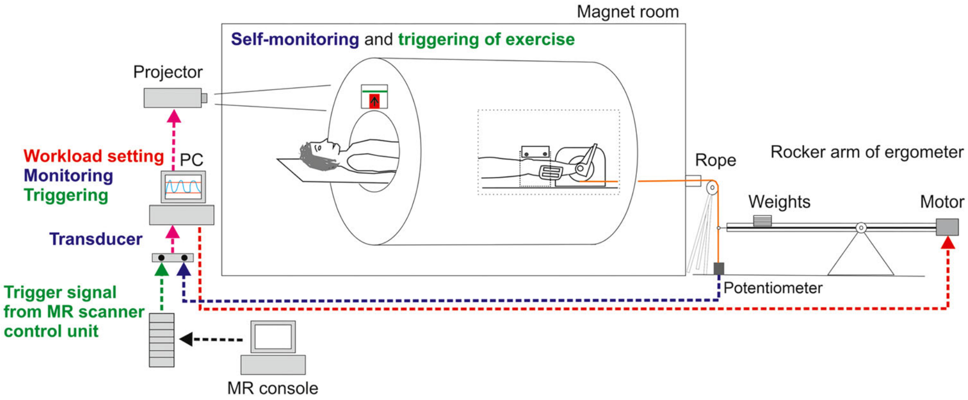

FIGURE 1 Overall schema of a custom MR-compatible pedal ergometer with electromechanical pedal resistance, visual self-monitoring and exercise triggering for the acquisition of MR spectra. PC, personal computer; MR, magnetic resonance.

1 | INTRODUCTION

Magnetic resonance (MR)-compatible ergometers have been shown to be effective in measuring dynamic phosphorus (^{31}P) MR spectroscopy (MRS) during and after exercise.[1–5] The devices are used to measure ^{31}P MR spectra as well as proton spectra and images inside the MR unit during physical stress or exercise.[6] The disadvantage of most MR compatible ergometers is their sometimes complicated mechanical construction and mainly the lack of communication between the examined subject and the operator controlling the experiment. Ergometers based on the pneumatic principle are also often used, however have another disadvantage. They often suffer from fluid or air leakages and need compressed air cylinders to keep them running.

The main purpose of this study was to develop and test a novel design for an MR-compatible ergometer that combines pedal resistance and self-monitoring. A secondary aim of this study was to test the entire ergometer by measuring the reproducibility and repeatability of dynamic ^{31}P MR spectroscopy.

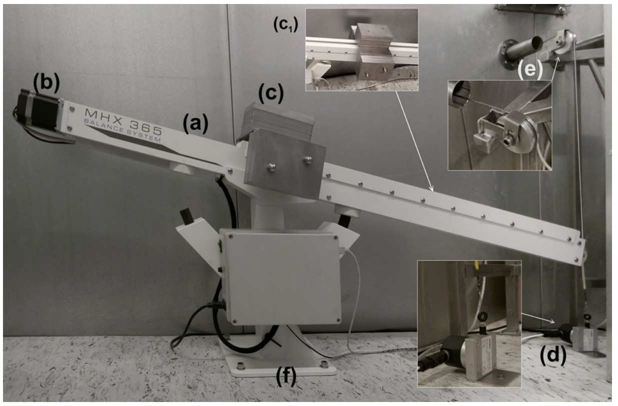

FIGURE 2 (a) The rocker arm (2 m in length); (b) electromotor for the movement of weights; (c) the weights on a small sliding trolley in the zero position and in the position (c1) corresponding to the load 56 kg at the end of the arm; (d) the potentiometer monitoring the position (height) of the rocker is placed on the ground at the level of the attachment of the ergometer cable to the rocker; (e) next to the rocker is a steel pulley structure; (f) the entire structure of the rocker is fixed to the floor with four screws (for details see Supplement 2).

2 | METHODS

2.1 | Construction of the ergometer

The overall schema of the ergometer is shown in Figure 1. Technical details of the construction are described in the Supplement. The ergometer consists of three main parts:

1. Pedal with knee fixation and receiving coil placed inside the magnet (see Supplement 1);
2. Electromechanical adjustment of workload.

The electromechanical resistance of the pedal is determined by the displacement of a set weight mounted on the rocker arm (see Figure 2). The total weight of the weights is 56 kg. The required weight for the exercise can be set by means of a small sliding trolley on the rocker. The weight is secured in the desired position provided by a long screw driven by a 2-phase hybrid stepper motor at the opposite end of the rocker arm. The position of the weight on the rocker arm is controlled by a computer (see also Supplement 2).

3. Control system and self-monitoring by the examined subject.

Pedal depression during the ^{31}P MR examination is measured by a potentiometer cable guided from the end of the rocker arm to a potentiometer placed on the floor under the rocker arm (see Figure 2d).

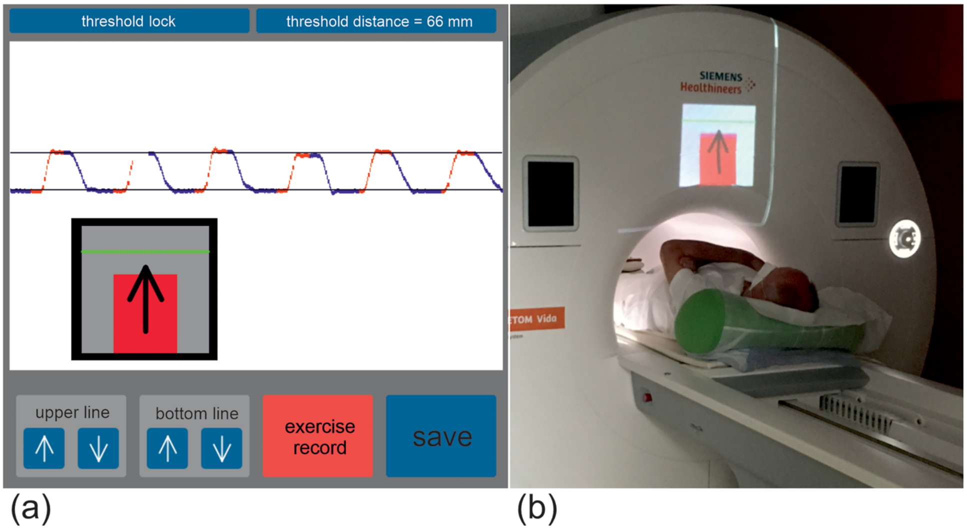

FIGURE 3 Displays for operator and exercising subject.

The potentiometer generates an electrical signal proportional to the deflection of the rocker arm. The analogue electrical signal from the potentiometer is then fed to the Arduino module in the control room. Synchronisation pulses from the MR system are also fed into this Arduino module, which defines the beginning of the dynamic ^{31}P MR sequence. The Arduino module integrates these two signals into a single universal serial bus (USB) output, which is ultimately routed to the personal computer (PC) in the control room. The operator can control the progress of the exercise according to the information on the monitor, and the examined subject steps on the pedal according to the commands on the display (see Figure 3 and also Supplement 3).

The novelty of the design lies in its use of a rocker arm to set pedal resistance. Rocker arm of the ergometer is located behind and along the wall of the MR room. Next to the rocker is a steel pulley structure that guides the rope from the ergometer pedal to the rocker (1.5 m from the magnet). For details, see Figure 2 and also Supplement 2.

The second novelty is computer-controlled triggering and a self-monitoring exercise system (see Figure 3 and video[7]). The custom PC program controls the examination and records the signal from the Arduino module, providing visualizations on two program displays. The first display, designated for the operator in the control room (3a), presents the pedal movements. It features a bar graph that shows the current pedal pressure, desired pedal pressure (indicated by a green line), and a trigger signal (represented by an arrow). For more detailed information, please refer to the accompanying video. The entire protocol's running pattern, including rest time, exercise time, recovery time, cadence, arrow display time, etc., can be easily modified prior to initiating the program. Recording and exercise initiation occur automatically upon detecting the initial synchronization pulse of the MR sequence. The second display (3b) is intended for the subject under examination. To assist with successful pedal depression, a moving arrow limit is projected onto the front wall of the MR scanner using a common home video projector (as depicted in Figure 3b). This projection allows the subject to clearly understand when and how forcefully to press the pedal, offering a comprehensive overview.

2.2 | Subjects

Two groups of subjects participated in the study. The first group consisted of five healthy recruited volunteers (mean age = 44.0 ± 4.2 years; mean body mass index (BMI) = 21.3 ± 1.8 kg/m^2; moderate physical activity, 3 women). Prior to commencing the experiment, the subject inside the magnet is instructed to step on the pedal of the ergometer once. The operator progressively augments the resistance on the pedal by adding more weight to the rocker arm. The weight that the subject can no longer lift corresponds to the maximum voluntary force (MVF). Each volunteer underwent two MR examinations, each with exercises at 15% and 24% MVF. The second group of seven subjects (mean age = 31.2 ± 3.0 years; mean BMI = 23.6 ± 2.0 kg/m^2; moderate physical activity, four women) performed the same protocol at 25% MVF over three rounds as part of one examination. The interval between exercises was at least 15 min.

All participants provided their informed consent in agreement with the regulations of the relevant ethics committee.

TABLE 1 Mean values, coefficients of variation, and intraclass correlation coefficients of consistence were calculated for the following parameters: Exercise power (P), relative PCr signal drop (ΔPCr), recovery time constant (τ_{PCr}), pH at end of exercise (pH_{end}), initial PCr recovery rate (V_{PCr}), and mitochondrial capacity (Q_{max}). Maximum voluntary force (MVF) 15%, 24% (reproducibility), and 25% (repeatability) were tested.

Mean values ± SD	P (W)	ΔPCr (%)	τ_{PCr} (s)	pH_{end}	V_{PCr} (mmol/s)	Q_{max} (mmol/s)
15% MVF	1.5 ± 0.4	15 ± 2	39 ± 18	7.04 ± 0.04	0.19 ± 0.08	0.46 ± 0.18
24% MVF	3.2 ± 1.3	27 ± 10	38 ± 10	7.01 ± 0.07	0.30 ± 0.13	0.59 ± 0.21
25% MVF	4.4 ± 1.8	33 ± 12	51 ± 21	6.89 ± 0.20	0.27 ± 0.01	0.55 ± 0.10
Coef. of variation	**P**	**ΔPCr**	**ΔPCr**	**pH_{end}**	**pH_{end}**	**V_{PCr}**
15% MVF	6.0	8.4	14	0.30	11	10
24% MVF	4.6	10	12	0.55	5.1	6.3
25% MVF	3.1	9.3	8.4	0.57	10	11
Intraclass correlation coef.	**P**	**ΔPCr**	**pH_{end}**	**pH_{end}**	**V_{PCr}**	**Q_{max}**
15% MVF	0.96	0.20	0.47	0.48	0.83	0.89
24% MVF	0.98	0.81	0.52	0.26	0.97	0.95
25% MVF	0.99	0.91	0.89	0.87	0.89	0.89

2.3 | MR spectroscopy

The MAGNETOM Vida whole-body 3T MR scanner (Siemens Healthcare, Erlangen, Germany) equipped with dual-channel $^{1}H/^{31}P$ (11 cm diameter, Rapid, Germany) was used. Volunteers were examined in a supine position with the coil fixed underneath the calf muscle. MRI localiser sequence for verification position of coil under musculus left and right gastrocnemius and one non-localised ^{31}P MRS spectrum with 16 acquisitions was acquired at rest (delay [TE*] = 0.4 ms, repetition time [TR] = 15 s, flip angle [FA] = 90°, vector size = 1024, bandwidth 2kH; BIR-4 adiabatic pulse with duration 5 ms, shim on water signal half-width FWMH = 30–35 Hz). Most of the ^{31}P MR signal came from m. gastrocnemius and soleus due to the detection depth of the surface coil (max ~5 cm).

Dynamic ^{31}P MR spectra were obtained with: TR = 2 s, 1 acquisition, 420 measurements, flip angle = 72°). Resistance of the pedal ergometer was set to 15%, 24% (reproducibility measurement), and 25% (repeatability measurement) of the maximal voluntary force (MVF). The exercise protocol consisted of a 2-min rest period, followed by a 4- or 6-min exercise period at 25% of the maximum voluntary force (MVF), and finally, a 6-min recovery period. During the exercise period, plantar flexion was performed once every 2 s between signal acquisitions. ^{31}P MR spectra were processed in jMRUI software. After phasing the spectra, the peaks were fitted as single Lorentzians, except the adenosine triphosphate (ATP) signals, where the γ- and α-ATP were fitted as Lorentzian doublets and β-ATP as a triplet. The β-ATP signal was used as a concentration reference, assuming a ATP concentration of 8.2 mM in the muscle tissue.[1,8]

The following dynamic parameters were calculated using published equations: PCr signal drop (ΔPCr), recovery time constant (τ_{PCr}) obtained from fitting the recovery curve of PCr during the post-exercise period, pH at the end of exercise (pH_{end}), initial PCr recovery rate (V_{PCr}) calculated as the concentration drop of PCr during exercise divided by τ_{PCr}, and mitochondrial capacity (Q_{max}) calculated as V_{PCr} divided by (1 + KM/[ADP]), where KM was assumed to be 30 μM, as explained in more detail in.[2,3] Exercise power (P) was calculated based on total cumulative weight lift and exercise time.

2.4 | Statistical methods

Repeatability of the measurement was assessed as the coefficient of variation (CV) of the calculated metabolic parameters. The intraclass correlation coefficient of consistence (ICC) was used to assess reliability of the Shrout and Fleiss method.[9] Differences between the first and second MR examinations were evaluated by Bland-Altman plots. A range of agreement was defined as mean bias ± 1.96 standard deviations. Statistical analysis was performed using R software.

3 | RESULTS

The functionality of the entire ergometer was tested using two exercise protocols involving constant pedal resistance and continuous load change in a step-by-step manner.

1. In the first test, dynamic ^{31}P MR spectra were repeatedly measured in the group of 5 healthy subjects at 15% and 24% MVF. In the second test, the group of seven subjects was examined at 25% MVF.

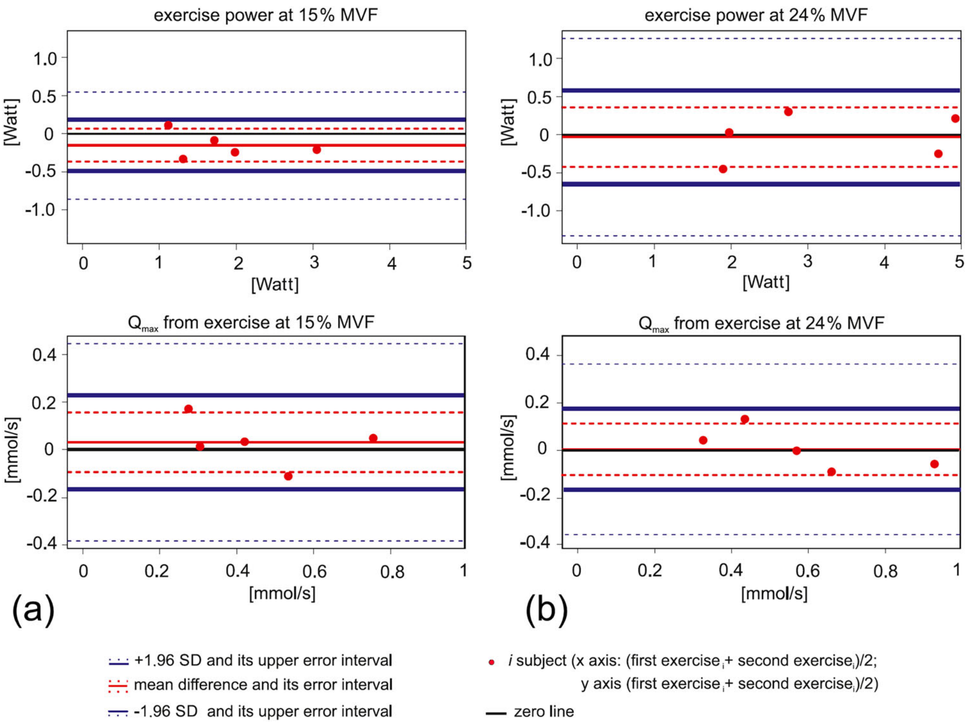

FIGURE 4 Bland-Altman plots of exercise power (P) and Q_{max} values measured at two pedal resistance values (15% and 24% maximum voluntary force [MVF]). Full red lines represent mean differences and blue lines border the limits of agreement ($\pm$1.96 standard deviation of differences).

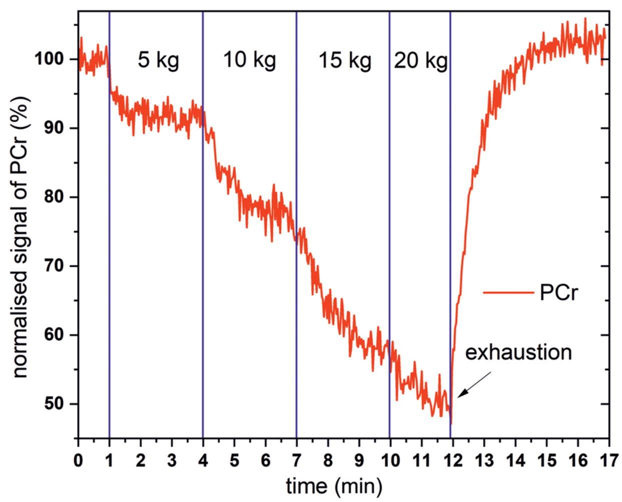

FIGURE 5 Time dependence of the PCr signal during exercise. After resting for 1 min, the subject starts pedalling at a rate of 1x every 2 s with 5, 10, 15, and 20 kg counterweights as endpoints. An estimated maximum voluntary force (MVF) value of 20 kg was used to optimise the dynamic ^{31}P MR spectroscopy (MRS) protocol.

The following dynamic ^{31}P MR parameters were calculated: mean values, coefficients of variation, and intraclass correlation coefficients of consistency (see Table 1).

MVF 15% and 24% with 6-min exercise was chosen due to analogy with our older study[2] where our old mechanical ergometer and commercial pneumatic ergometer was compared. The MVF of 25% with 4-min exercise was chosen in view of future clinical studies where these parameters will be planned used.

2. Bland-Altman plots of Q_{max} and exercise power achieved satisfactory reproducibility at 15% and 24% MVF (see Figure 4), confirming agreement between both experiments.
3. The ergometer enables a continuous change in pedal resistance, eliminating the need to interrupt the exercise. Monitoring changes in dynamic ^{31}P MR parameters over time in this way is helpful in determining the physical limits of the participant, and is thus of potential use in biochemical and biomechanical studies.[10] Figure 5 shows the results of MVF based on a gradual increase in pedal resistance and a single contraction during exercise.

4 | CONCLUSION

Based on more than 1 year of usage, our novel MR-compatible ergometer—which combines a simple method of electromechanical pedalling resistance, visual self-monitoring and computer-controlled exercise triggering—proved adept at measuring ^{31}P MR spectra in the calf muscle during various exercise protocols, including continuous load changes. The system is robust, user-friendly, and only requires one operator. CV and ICC coefficients characterising the agreement and reproducibility of parameters P (W), ΔPCr (%), τ_{PCr} (s), V_{PCr}, and pH_{end} in experiments with different MVFs were highly satisfactory (see above). These ICC and CV values are comparable to previous values obtained using a custom mechanical ergometer and a commercial pneumatic ergometer,[2] and improve upon values obtained using an elastic-band ergometer.[11] For more details see Supplement 5.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict to disclose.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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