Assessing the repeatability of a Magnetic Resonance-compatible ergometer for ankle dorsiflexion

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Abstract

In the movement and sport sciences field, there is always the necessity to deepen the knowledge of the muscular functionality, especially with the new technological means at disposal of the scientists. The aim of this study was to assess the repeatability of the experiments conducted with a self-constructed Magnetic Resonance(MR) compatible ergometer, to be able to record the muscular physiological activity during the development of controlled muscular contraction. The recordings were planned on two sessions at 2 days of distance, to assess both the intra and inter experimental repeatability. 5 subjects (age 25.8 ± 0.8 years, medium weight of the subjects 81.8 kg) participated; the data from one subject were not used for the repeatability between subjects, as the subject itself assessed a low ankle mobility. Each trial consisted in 30 seconds of active plantar dorsiflexion movement and, for each resistance level (controlled by changing the number of elastic bands), 3 trials were done. On the second day, only the trials with the resistance provided by 2 elastic bands were recorded. The following analysis assessed that the found percentage coefficient of variation (CV) of the data was always lower than the critical value, chosen to be 5.0%, assessing that the ergometer grants a consistency in the recorded data throughout the trials. An ICC test between subject, however, assessed that the ergometer is susceptible to the different way to perform the movement by the subjects; this value could be done to the fact that no external pace was imposed to the subjects, and the subjects were free to pursue the trials with their own determined speed.

1. Introduction

The studies of muscular physiology and how the muscle works started with the Italian physician Luigi Aloisio Galvani, that in the years 1780-1783 started to apply electrical stimulation to frog thighs in form of electrical current [1], which showed that the muscles, also when extracted from the body itself, were contracting to the electrical current, while going back to non-excited state when the stimulation stopped. The studies on human muscular physiology went on, but still nowadays there is the necessity of deepen the knowledge of how the muscle in its integrity work during the muscular contraction. Therefore, Aalborg University, during of the Sport Technologies master course, concepted and build an ergometer for plantar dorsiflexion of angle joint. The particularity of this ergometer is that is magnetic resonance friendly (without the use of ferromagnetic materials), to be used inside a 3 Tesla (3T) MR machine. This will give the chance to use the functional magnetic resonance (fMR) as the machine could be used in cooperation with the 31P MRS protocols during muscle contractions to assess and compare the changes in the metabolism during controlled movements. The ergometer needed to be completed, as first step, using all MR-compatible material, and connecting the two measuring instruments, a force transducer (SSM-AJ-1000N, Interface) and a rotating-pin potentiometer, to the machine itself. The second part of the experiment was focused on assessing repeatability of the test conducted with the machine, taking in account the intra subject (how precise the machine can be while recording movements performed by the same subject) and inter subject (the capability of recording consistent data from the same movement performed by different subject) repeatability.

2. Material and methods

2.1 Description and completion of the machine

For the study, the choice of final materials was of fundamental importance; the ergometer was supposed to be completely non-magnetic. The ergometer was composed by two main water-cut plastic parts, and precisely:

- Foot plate 90 cm x 19 cm x 2 cm
- Base 60 cm x 38,6 cm x 2 cm

To connect this two main parts, smaller rectangular parts where used; the parts were all connected with brass screws and mats; brass is a metal alloy composed by copper and zinc, and it was chosen mainly because of its non-magnetic properties (figure 1).

Figure 1 Mounted ergometer, with the force transducer installed. It can be seen the place in which the potentiometer will be inserted.

The force transducer was S - Shaped and a hole was found on the bottom brace of the S. Through the hole in the bottom brace, the inelastic rope was passing by and a knot was created to make the connection safer. The distance between the base of the transducer and the connecting part was fixed at 4.5 cm, a distance that granted an optimal initial pretension to the elastic band. On the plastic base of the ergometer, there was a triangular shaped device with a hole in it, in which the inelastic rope coming from the force transducer passed through; to stop the rope in the connecting device, two solutions were chosen a series of 3 knots was made at the external side of the device, and, in the internal side, a brass screw was pushed with force into the hole. This can be seen on the right side of figure 1, and more in detail, in figure 2. On the other side of the transducer (the one pointing to the footplate), a T – shaped plastic device was attached with the use of a brass screw and, to tighten it, a stainless-steel mat was used. The T- shaped plastic part was used to connect the force transducer to the footplate by using elastic bands; the bands were passing through two elliptical carved holes in the foot plate and they were secured to a 3D printed plastic cylinder (Ø2 x 12,5 cm)as it can be seen in figure 2.

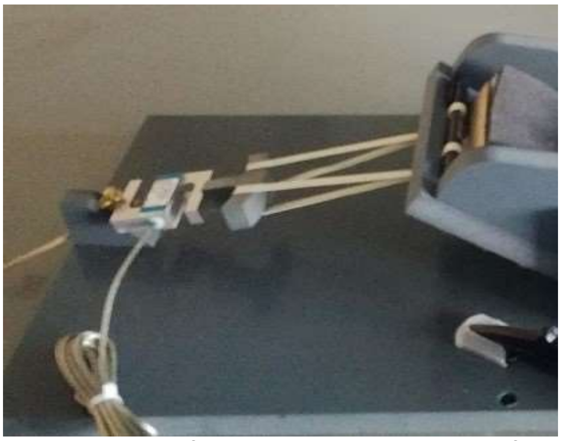

Figure 2: detail of the connection between the force transducer; from left to right it can be seen the inelastic rope, the plastic connecting part, the transducer, the t-shaped element and the elastic bands, connected to the foot plate.

The inelastic rope was then moved until the desired initial tension on the elastic bands were as desired, and the rope was then fixed at the found length. As it can be seen from figure 2, the footplate was connected to the force transducer by a series of elastic bands, and from the dimensions of the t-shaped element was possible to use from 1 to 4 bands, without incurring in overlapping of the bands. Moreover, at the beginning of the experiment it was possible to choose, at the beginning of the completion phase, between 4 different type of elastic band, with different initial length and resistance.

2.2 Tests on the resisting components

To assess which elastic band was the best solution for the experiment, a series of tensile test, inside the elastic behavior part, on all the 4 different bands available were done. The criterion that were used to choose the best band were two, the actual stiffness and the initial length of the bands. The initial length of the band was the most important of the two criterion, in order to grant a good ; therefore, a short white band (1,26 mm x 10,50 mm x 148,55 mm) was chosen, and, on the T-shaped connecting device, was possible to install from 1 to 4 elastic bands at a time, making possible to control and modifying the resistance of the system. This band, however, was not the optimal choice according to the stiffness, but granted a bigger ROM for the experiment, which was the most important thing for the further development of the experimental procedure.

2.3 Set up for data acquisition

On the side of the ergometer, the potentiometer, used to record the angle performed by the subject, was settled up, in a hole carved in the white rotating pin in the ergometer; to make it as adherent as possible a thin layer of white sellotape have been applied to the rotating surface of the potentiometer.
The signal from the force transducer, which was connected with a 15 meters long electrical cable, needed to be amplified in order to be strong enough for the recording; therefore, a system composed with an amplificatory (SGI-SMI2000) has been set up, giving the chance to amplifying the signal of a factor of 4k.
The signal from the potentiometer, in the other hand, did not need the amplification, therefore, it was connected directly to the AD board used to convert analog data in digital data; on the same AD board, the force transducer signal after the amplification has been converted and sent to the recording computer.
The data were later recorded by a LabView (version 15.0) self-developed program and saved in .bin format for further analysis in MatLab (version 2017b).

2.3 Calibration of measuring instruments

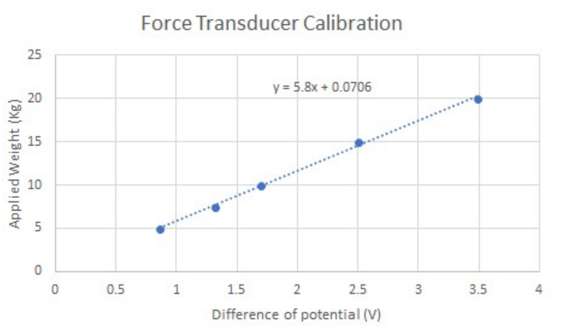

Figure 2 : calibration graph for the force trandsucer, whit showed the linear correlation between applied weight (kg) and recorded difference of potential (V)

A calibration for both the measuring instruments (figure 3) was found to be of crucial importance, to determine the linear behavior and the equation of linear regression to convert the voltage data in actual recording. Therefore, a series of known weights (5, 7.5, 10, 15 and 20 kilograms) were applied on the force transducer, and for each weight the maximum difference of potential was recorded; the same procedure was followed for the potentiometer, with the use of movements inside of controlled range of motions, and precisely 95, 105, 115, 125 and 135 degrees. After recording these peak difference of potential, a graph, representing the difference of potential as a function of the weight (for the force transducer) and range of motions (for the potentiometer) was created; from each of the graphs, the equation of linear regression (Y = mx+q), was found. This was considered a crucial step in the process of assessing the repeatability of the ergometer; if the two instruments did not show a linear behavior, the instruments would not have been suitable for the designed use; furthermore, the instruments were projected to record data just as difference of potential, so there was the necessity of converting the data in actual force and angle data.

Figure 3: On the left, the force transducer; on the right, the potentiometer with the layer of tape, which was necessary to assess a perfecct adhesion to the rotating pin.

3. Statistical Analisys

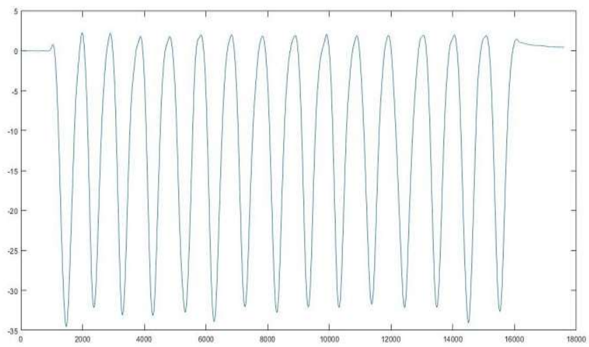

Figure 4: representation of actual recorded data from the force transducer

The first step of the analysis was extracting peak maximum forces and peak moments from each trial of each subject. Each recording contained a certain number of peaks, depending on the subject pace and on the level of resistance chosen; the peak was considered starting from 0 to the highest value recorded for each complete movement.
The main statistical data of interest have been the calculation of the percentage Coefficient of Variation (CV), with the following formula

$$CV = \left(\frac{SD}{AVERAGE}\right) * 100$$

in which SD is the standard deviation, and "average" is the average of the trial taken in consideration. It was chosen to use the percentage CV in order to have a concrete indication and a concrete index for the understanding if the recorded values could be considered consistent. The critical value was chosen to be 5.0 %, as a critical value to determine the consistency of the data. Moreover, a single ANOVA test to assess the difference between the value from the first trial day to the second one has been performed, and an ICC (Intra Class Correlation) test were performed, to assess how variable were the recording
The CV tests were performed in multiple ways, and they were following this scheme:

- **CV Intra-subject** (calculated between the trials done by each subject);
- **CV intra-trial and inter-subject** (calculated for each trial from each subject and level of resistance, from which the average has been extracted);
- **CV inter – day** (calculated between the average of the trials from the two different days, within the trials of the second level of resistance);
- **ANOVA test** (between the trials of the two days, using the average of the results and calculated subject by subject);
- **ICC test (Intra class correlation test):** this test has been performed to assess the inter subject correlation, which means the correlation between the measurements between the subjects.

The previous sequence of analysis was used to analyze the two variables considered of interests for the purpose of this study, and precisely the developed force (recorded by the force transducer) and the angle developed during the trial, recorded with the use of the potentiometer.

4. Results

The results will be presented in separate tables, divided according by the different calculation of the chosen statistical tests.

4.1 CV intrasubject

SUBJECT	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Mean CV**
1	2.47	2.08	0.84	0,99	**1.59**
2	1.28	0.88	2.83	2.49	**1.87**
3	1.45	1.12	1.57	1.71	**1.46**
4	2.20	3.45	0.79	0.80	**1.81**
5	1.38	2.72	1.21	2.82	**2.04**

SUBJECT	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**	**Mean CV**
1	0.67	0.78	0.94	0.55	**0.73**
2	0.91	0.57	3.24	3.14	**1.96**
3	0.92	2.89	1.97	1.84	**1.90**
4	1.48	0.80	0.67	0.61	**0.89**
5	6.67	2.10	0.71	1.16	**2.66**

Table 1: CV intrasubject for peak force (**up**) and recorded angles (**down**)

The mean of the intrasubject relative CV for the peak force has been found to be equal to **1.76** %, while the CV for the recorded angles was **1.64**% (table 1).

4.2 CV intra-trial and inter-subject

To perform this analysis, the CV was calculated for each single trial, of each person and for each resistance level performed by the subject. The results were paired and grouped by resistance level, and for each single trial the average of CV have been extracted.
Moreover, a mean of the result was extracted, and then the overall mean for all the resistance levels was found. For this analysis, a subject was excluded, because he assessed a low mobility of the ankle before the trial.

	1st trial	**2nd trial**	**3rd trial**	Mean
1 band	2,72	1,11	1,22	**1,68**
2 bands	1,06	1,25	1,34	**1,21**
3 bands	2,67	2,53	2,80	**2,69**
4 bands	2,69	2.44	1.25	**2,12**

	1st trial	2nd trial	3rd trial	Mean
1 band	1.13	1,28	1,51	**1,31**
2 bands	0,84	1,33	1,57	**1,25**
3 bands	3,37	3,35	3,72	**3,48**
4 bands	2,68	2,81	3,09	**2,87**

Table 2: CV intra trial/inter subject for peak force (**up**) and recorded angles (**down**)

The mean of the CV for the angle was found to be **1,92** %, while for the peak force was slightly higher, with a value of **2.23** % (table 2)

4.3 CV Inter – day

In this case, the percentage CV inter-day was calculated using as basis of the calculation the average from the trials with two bands, both for day 1 and day 2. The CV was calculated subject by subject, with the use of data from all the 5 subjects involved.

	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5
Peak Force	**1,06**	**3,30**	**2,53**	**0,55**	**2,78**
Peak Angle	**0,71**	**0,54**	**3,15**	**1,79**	**1,56**

Table 3: CV inter-day for peak force and recorded angles

It has been found that the CV inter day, for what concerns the peak force, was **2,04** % while for the peak angle was **1,55** % (table 3).

4.4 ANOVA Test

To give a better understanding on the repeatability between days, an ANOVA single test was performed between the averages of the 2 bands data in the two days. It was chosen to use a p-value of 0.05 to assess the reliability; with a value higher than that, the values were not considered acceptable and therefore the data too different (table 4):

	P Val	Meaning
Sub 1	$P < 0.05$	No difference
Sub 2	$P < 0.05$	No difference
Sub 3	$P > 0.05$	Difference
Sub 4	$P > 0.05$	Difference
Sub 5	$P < 0.05$	No difference

Table 4: ANOVA test results and meaning of the results

4.5 ICC test

The test was using, as data set, the average of the recording for each subject from day one; in this test, a subject was excluded from the calculation because he reported a low ankle flexibility. This test was calculated just for the angle values, because the experimental procedure gave too much relevance to the individual way to perform the exercise, which made clear that the force data were already too different and not consistent between subjects. The results are the following (table 5):

	1 band	2 bands	3 bands	4 bands	Mean
ICC value	**.601**	**.736**	**.591**	**.662**	**0.646**

Table 5: ICC test results and mean of the correlation value

5. Discussion

The present study had the main goal to assess if the self-constructed ergometer could grant or not consistent measurements during a series of consecutive analysis.

Some mechanical and technical consideration need to be done concerning the completion of the machine, especially about the use and integration of the rotating potentiometer inside the machine.

In order to grant a perfect recording on the angles by the potentiometer, the potentiometer needed to be in perfect adherence with the white rotating part of the ergometer, to grant a perfect recording of the angular movement. The hole already carved in the rotating part had a bigger diameter than the rotating part of the potentiometer; to solve this difference and make the parts more adherent, a layer of sellotape has been applied to the potentiometer; moreover, an elastic band has been tightened around the cable coming out from the potentiometer and wrapped around the plastic sustain part, as extreme solution. This solution, however, was not ultimate, as it tended to lose connectivity between the two devices during the use, which resulted in small differences in the data recording, visible just in the further data analysis and not during the recordings. A definitive choice could have been, for example, by gluing (with hot glue or silicone) the potentiometer inside the pin. In this way, the connection will last for a longer time, with the undesired side effect that it will be harder to

extract the device in case of damage.
Some improvements could have been similarly done to the force transducer; for example, the t- shaped device connected to the transducer was big enough just to permit the connection of only 4 bands of the chosen type, which has restricted the choice of the level of resistance; with a bigger t-shaped element, the choice of level of resistance could have been improved. Another weak point of the connection of the transducer was found when just one band was connected with the footplate and the transducer; in that situation, the only band was tending the transducer in just one direction, making the transducer inclined in the direction opposite as the band and It is unknown which effect this could have on the measurement. The connection with the base, however, can be considered safe and not influencing the result of the measurement; the inelastic rope has been chosen in order to not interfere with the measurements, and the 3 knots in series granted a good stability to the system. The last security measure that was used was a clamp used to anchor the machine to the test table, which not influenced at all the recordings but granted the usability of the machine and the security for the user.
The most important part of the experiment was the calibration of the two instruments used, the potentiometer and the force transducer and this was required for two main reasons. The first, and most important result of the calibration, was assessing if both instruments were acting with a linear correlation in correspondence of the applied weight or angular movements. The linear behavior of the instruments was a fundamental requirement in order to expect the repeatability of the recording with the machine itself; if the linear relation was not found, any further analysis was non-significant and not possible to be made; both the instruments were found to have a linear behavior and therefore, the whole experiment was considered possible. The second output is that it was possible to extract the equation of regression, which made possible to convert the electrical output (both instruments were recording just a difference of potential) in actual measurements, respectively Newton (for the force transducer) and range of motion, in particular angles (for the potentiometer).
The result shows that the values of the coefficient of variation are lower than the chosen critical value, which was chosen to be 5,0 %. This can be considered a sign that the values recorded can be considered consistent and repeatable through the same subject, and this makes understand that the instrument itself is reliable.
On the other hand, the values from the ICC between the subjects, compared with the higher values (thus still under the critical value) of the CV inter subject raise some consideration. The mean ICC value is quite low (0. 646). Usually, to be considered correlated, the value from a correlation test should be equal or higher than 0.750
This difference can be due basically to two reasons. The first one is the experimental design; it was chosen not to control the movement from outside, for example with the imposition of a pace with a metronome, for example. This choice was made because during the pilot test was seen that the movement and the pace of the metronome was forcing the subject to sudden acceleration or deceleration to follow the pace, and that could have been a chance of disturbing the movement itself, misleading to wrong recordings. The second reason could be considered a construction factor; looking the data, it appears that usually the last subject conducting the experiment express the biggest variance among the results; this could be due to the instability of the connection between the instrument and the machine that could become more instable after a long use. This will be solved by gluing the potentiometer to the rotating pin, or creating a pin able to better control the movement of the inelastic rope connecting the force transducer to the machine.

6. References

[1] De viribus electricitatis, 1971