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# Smoothness Discriminates Physical from Motor Imagery Practice of Arm Reaching Movements

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## 1 **Abstract**

2           Physical practice (PP) and motor imagery practice (MP) lead to the execution of fast  
3 and accurate arm movements. However, there is currently no information about the influence  
4 of MP on movement smoothness, nor about which performance parameters best discriminate  
5 these practices. In the current study, we assessed motor performances with an arm pointing  
6 task with constrained precision before and after PP (n= 15), MP (n= 15), or no practice (n=  
7 15). We analyzed gains between Pre- and Post-Test for five performance parameters:  
8 movement duration, mean and maximal velocities, total displacements, and the number of  
9 velocity peaks characterizing movement smoothness. The results showed an improvement of  
10 performance after PP and MP for all parameters, except for total displacements. The gains for  
11 movement duration, and mean and maximal velocities were statistically higher after PP and  
12 MP than after no practice, and comparable between practices. However, motor gains for the  
13 number of velocity peaks were higher after PP than MP, suggesting that movements were  
14 smoother after PP than after MP. A discriminant analysis also identified the number of  
15 velocity peaks as the most relevant parameter that differentiated PP from MP. The current  
16 results provide evidence that PP and MP specifically modulate movement smoothness during  
17 arm reaching tasks. This difference may rely on online corrections through sensory feedback  
18 integration, available during PP but not during MP.

19

20

21 **Keywords:** motor imagery, movement smoothness, feedbacks, internal models, motor  
22 learning.

23

## 1 **Introduction**

2           Motor skill learning is a central process in everyday life, sustaining adaptation and  
3 efficiency of motor behaviors in constantly changing environments. Through physical practice  
4 (PP), movements are performed faster, more accurately, and require less energy consumption  
5 (Willingham, 1998). Even if continuous and extended practice is known to greatly and  
6 durably improve motor performance (Robertson et al., 2004; Kitago and Krakauer, 2013),  
7 positive effects of practice can also be observed within a single training session. A growing  
8 number of studies indeed observed that a few minutes of practice is sufficient to induce gains  
9 in motor performance (e.g., speed and accuracy) on a wide variety of motor tasks, such as  
10 sequential finger-tapping or arm-reaching tasks (Karni et al., 1998; Walker et al., 2003;  
11 Gentili et al., 2006, 2010; Spampinato and Celnik, 2017; Ruffino et al., 2021). This fast  
12 learning process, known as motor acquisition, is considered as the first step towards the  
13 formation of new and robust motor memories.

14           Although skill learning usually requires PP, alternative forms of practice also exist.  
15 Among these, motor imagery, that is the mental simulation of an action without associated  
16 motor output, has been largely documented. In fact, mental practice (MP) improves several  
17 aspects of motor performance, such as movement accuracy, speed, and force (Yue and Cole,  
18 1992; Yáguiez et al., 1998; Ranganathan et al., 2004; Gentili et al., 2006, 2010; Allami et al.,  
19 2008; Lebon et al., 2010; Grosprêtre et al., 2018; Ruffino et al., 2021). Performance increases  
20 following MP is associated with specific neural mechanisms at both cortical and spinal levels  
21 (Avanzino et al., 2015; Grosprêtre et al., 2019; Ruffino et al., 2019). Specifically, an acute  
22 session of MP induces use-dependent plasticity into the primary motor cortex (Bonassi et al.  
23 2017; Ruffino et al. 2019) and spinal circuitry (Grosprêtre et al. 2019). At the functional level,  
24 it is proposed that motor performance improvement following MP may reflect an update of  
25 internal forward models (Kilteni et al., 2018; Dahm and Rieger, 2019; Ruffino et al., 2021).

1 Basically, internal forward models are neural network that predict the future sensorimotor  
2 state (e.g., velocity, movement duration, position) given the current state, the efferent copy of  
3 the motor command, and the goal of the movement (Kawato et al., 2003; Wolpert &  
4 Flanagan, 2001). Kilteni et al. (2018) strongly supported this assumption by showing that the  
5 sensory consequences of imagined movements are predicted during motor imagery.

6         Although PP and MP share common mechanisms, a number of dissimilarities also  
7 exist. Perhaps the main difference, at least the most visible, is that during MP there is no  
8 sensory feedback about movement (position velocity and acceleration), since the imagined  
9 segment **is** inert. In error-based motor learning process, external sensory feedback is  
10 necessary to update the prediction of the internal forward model, via the discrepancy between  
11 the predicted state and the actual state (Kawato et al., 2003; Shadmehr et al., 2010; Shadmehr  
12 & Krakauer, 2008; Wolpert et al., 2011). Better state prediction will, in turn, improves the  
13 controller and thus the motor output. In the case of a model-free motor learning process,  
14 external feedback directly improves the controller through reward predictions error  
15 (Criscimagna-Hemminger et al., 2010; Izawa and Shadmehr, 2011). The absence of external  
16 feedback during MP could explain why after PP the performance improvement is better than  
17 after MP (Ingram et al., 2019). This assumption is supported by the study of Bonnassi et al.  
18 (2017), which associated MP with peripheral nerve stimulation. The authors observed a better  
19 motor learning than after MP alone, and a similar motor learning than after PP. Thus, these  
20 results highlight the crucial role of peripheral feedback in the update of internal models and in  
21 the motor learning process. Theoretically, it is proposed that the difference between the  
22 prediction and the desired outcome based on stored movement representations would be  
23 returned as an input to improve the subsequent motor command via a “self-supervised  
24 process”, explaining motor performance improvement despite the external feedback during  
25 MP (Gentili et al., 2010, Ruffino et al. 2021).

1 Up to now, performance improvement after MP has been measured, and compared to  
2 PP, mainly on three parameters: force, accuracy, and speed. Nonetheless, other parameters are  
3 of importance for motor performance, such as movement smoothness that is enhanced after  
4 PP (Balasubramanian et al., 2015). Smoothness is related to the form of the velocity profile,  
5 which is singled-peaked with one acceleration and one deceleration phase. When the motor  
6 command is inaccurate a number of sub-movements are necessary to correct it, creating thus a  
7 non-optimal and clumsy movement (Kelso et al., 1979; Ketcham et al., 2002; Ketcham &  
8 Stelmach, 2004). Intriguingly, the effects of MP on this parameter are yet unknown.

9 In the current study, we sought to compare PP and MP, considering spatial, temporal,  
10 and smoothness parameters. We recorded movement-related trajectories on a graphic tablet  
11 from two training groups (PP and MP) and one control group (Ctrl, absence of practice). In  
12 line with the literature, we first hypothesized that PP and MP would similarly enhance arm  
13 reaching movements, with improvements for all parameters but with greater gains for PP.  
14 Alternatively, temporal parameters would similarly improve following PP and MP, as sensory  
15 feedback is not a prerequisite in that case, whereas spatial and smoothness parameters would  
16 be less improved after MP.

17

## 18 **Method**

### 19 *Participants*

20 Forty-five right-handed adults participated in this study after giving their informed  
21 consent. All were healthy and self-reported being free from neurological or physical  
22 disorders. The participants were randomly assigned into three groups: the Physical Practice  
23 group (PP, n = 15, 6 females, mean age:  $25 \pm 2$  years old), the Mental Practice group (MP, n =

1 15, 9 females, mean age:  $25 \pm 6$  years old), and the Control group (Ctrl,  $n = 15$ , 7 females,  
2 mean age:  $28 \pm 4$  years old).

3 Motor imagery vividness of the MP group was assessed by the French version of the  
4 revised Movement Imagery Questionnaire 'MIQR' (Lorant and Nicolas, 2004). The MIQR is  
5 an 8-item self-report questionnaire, in which the participants rate the vividness of their mental  
6 images using 7-point scales ranging from 1 (really difficult to feel/visualize) to 7 (really easy  
7 to feel/visualize), on two modalities (visual imagery and kinesthetic imagery). The average  
8 score obtained in the current study was  $42.1 \pm 9.5$  (maximum score: 56; minimum score: 8),  
9 revealing good imagery capabilities.

10

### 11 ***Experimental Device***

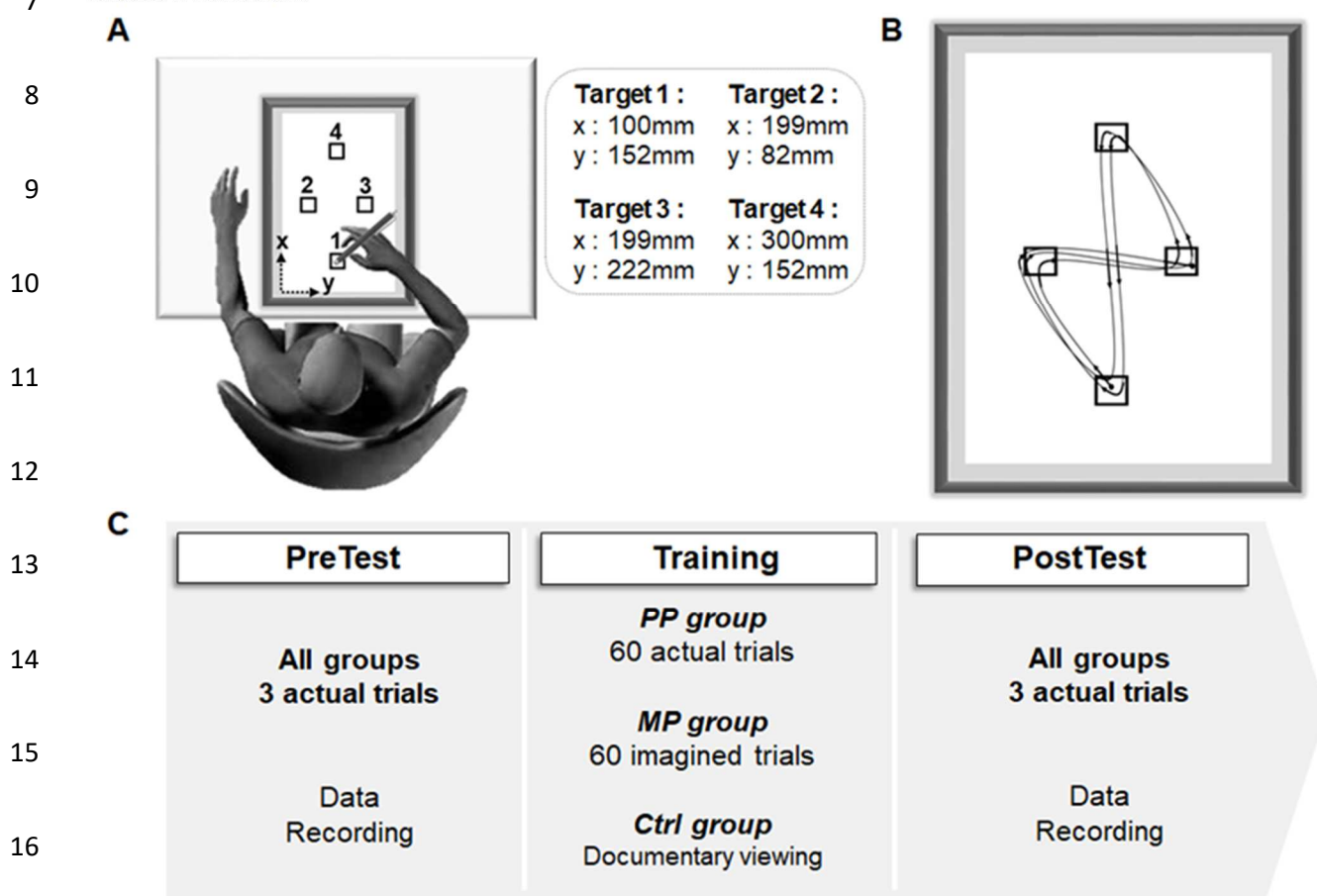
12 The participants were comfortably seated on a chair in front of a graphic tablet  
13 (Intuos4, XL, Wacom, Krefeld, Germany), on which four square-targets (1x1 cm) were  
14 presented (see Fig.1A). The distance between the participants' sternum and the first target  
15 (T1) was 10 cm. One trial included 10 successive target-to-target movements in the following  
16 order: 1 – 2 – 3 – 4 – 1 – 2 – 3 – 4 – 1 – 2 – 3. The participants were instructed to reach each  
17 target with a pencil as accurately and as fast as possible (Fig.1B). Accuracy was imposed  
18 during the experiment: participants were instructed to reach each target in the specified order  
19 to complete a trial. If the participant missed a target, the trial was aborted and performed  
20 again.

21

### 22 ***Experimental procedure***

23 The experimental protocol included two *test* sessions (PreTest and PostTest) and one  
24 *training* session (Fig. 1C). During the *test* sessions, all the participants performed 3 actual  
25 trials as fast and accurately as possible. During the training session, the participants of the PP

1 were trained as fast and accurately as possible to the task, while those of the MP group were  
 2 instructed to imagine themselves performing the task as fast and accurately as possible,  
 3 combining kinesthetic and visual (first-person perspective) imagery modalities. Both training  
 4 groups performed 60 trials, divided into 6 blocks with 1-min rest between blocks to avoid  
 5 mental fatigue (Rozand et al., 2016). The Ctrl group watched a non-emotional documentary  
 6 (“Home”, directed by Y. Arthus-Bertrand, 2009) for 30 min (the approximate time of both  
 7 training sessions)



18 **Fig. 1.** **A.** Participants’ position and targets location on the graphic tablet. **B.** One trial included 10 successive  
 19 track movements between the targets, as fast as possible without missing any target (1 – 2 – 3 – 4 – 1 – 2 – 3 – 4  
 20 – 1 – 2 – 3). **C.** Experimental procedure. The protocol included 2 test sessions of 3 actual trials (data recording  
 21 for each trial) and one training session. During the training session, the Physical Practice (PP) group physically  
 22 executed 60 repetitions of the 10 movements, and the Mental Practice (MP) group mentally simulated 60  
 23 repetitions of the 10 movements. The Control (Ctrl) group watched a non-emotional documentary.



1

2 ***Kinematics recording and analysis***

3 We recorded movement kinematics at 100Hz using a graphic tablet (Intuos4 XL,  
4 Wacom, Krefeld, Germany). The spatial resolution in the present experiment was less than 1  
5 mm. Data processing was performed using custom programs written in Matlab (Mathworks,  
6 Natick, MA). Position signals in the horizontal plane (X, Y) were low-pass filtered using a  
7 digital fifth-order Butterworth filter (zero phase distortion, Matlab ‘butter’ and ‘filtfilt’  
8 functions) at a cut-off frequency of 10 Hz.

9 We computed five parameters for each trial: i) movement duration (MD), i.e., the total  
10 time elapsed between the moment when the pencil exited the first target and entered the final  
11 target; ii) distance, i.e., the total two-dimensional displacement; iii) mean velocity (Vmean),  
12 i.e., the average inter-target movement speed; iv) maximal velocity (Vmax), i.e., the average  
13 of maximal inter-target movement speed; and v) number of velocity peaks (NbPeaks), i.e., the  
14 number of local maxima detected on velocity profiles. We used this parameter to quantify  
15 movement smoothness (Brooks et al., 1973; Fethers and Todd, 1987; Balasubramanian et al.,  
16 2015); the smaller the number of peaks, the smoother the movement.

17 For each parameter, we calculated the gain between PreTest and PostTest. To  
18 systematically represent gains with positive values, we calculated gains for MD, NbPeaks,  
19 and distance as follows:

$$20 \quad Gain(\%) = \left( \frac{PreTest}{PostTest} - 1 \right) \times 100$$

21

22 and for Vmax and Vmean as follows:

$$Gain(\%) = \left(1 - \frac{PreTest}{PostTest}\right) \times 100$$

2

### 3 *Electromyographic recording and analysis*

4 To verify that muscles were not activated during mental training (MP group),  
 5 electromyographic (EMG) activity of the biceps brachii (BB) and the triceps brachii (TB)  
 6 muscles of the right arm were recorded during each imagined trial and compared to EMG  
 7 activity at rest (10-second recording before training). We used pairs of bipolar silver chloride  
 8 circular (10-mm diameter) surface electrodes. We positioned the electrodes parallel to muscle  
 9 fibers, over the middle of the muscles belly with an inter-electrode (center-to-center) distance  
 10 of 20 mm. The reference electrode was positioned on the medial elbow epicondyle. After  
 11 shaving and dry-cleaning the skin with alcohol, the impedance was below 5 k $\Omega$ . EMG signals  
 12 were amplified (gain 1000), filtered (with a bandwidth frequency ranging from 10 Hz to 1  
 13 kHz), and converted for digital recording and storage with PowerLab 26T and LabChart 7  
 14 (AD Instruments). We analyzed the EMG patterns of the muscles by computing their  
 15 activation level (RMS, root mean square) using the following formula:

$$RMS = \sqrt{\frac{1}{MD} \int_0^{MD} (EMG)^2 dt}$$

17

### 18 *Statistical analysis*

19 We performed the analyses on motor gains to reduce variability between participants,  
 20 especially at PreTest. We primarily checked the normality of the data (Shapiro-Wilk test), the  
 21 equality of variance (Levene's test), and the sphericity (Mauchly's test).

1           First, we used unilateral one-sample t-tests compared to the reference value 100 to  
2 check whether motor performances improved between Pre and PostTest, for each parameter  
3 and each group. Cohen's d was reported for each test and the statistical significance threshold  
4 was set at 0.05. To control for multiple comparisons, we applied the Bonferroni correction  
5 method to adjust the P values computed for each parameter (three one-sample t-tests per  
6 parameter).

7           To compare gains between groups, we then performed one-factor ANOVAs with  
8 *Group* as a between-subject factor and planned comparisons using orthogonal contrasts  
9 analysis for each parameter (Howell, 2012). We constructed a contrast matrix to test the  
10 following *a priori* assumptions: i) MP and PP led to better gain when compared to an absence  
11 of practice, i.e., Ctrl group (contrast C1), and ii) PP led to better gain when compared to MP  
12 (contrast C2).

13           To identify the parameters that best discriminated the groups, we finally realized a  
14 stepwise generalized linear discriminant analysis. This exploratory data analysis first  
15 consisted in the identification of discriminant parameters, and then in the creation of functions  
16 that combined these discriminant parameters. The resulting functions were used as a linear  
17 classifier to investigate the data organization according to the categorical predictors (i.e.,  
18 groups) and the independent variables (i.e., parameters). To test if the discriminant functions  
19 classified the experimental observations in their respective groups better than chance (i.e., if  
20 the combinations of identified factors were indeed relevant to group discrimination), we used  
21 the Press Q statistic (Hair et al., 1998).

22           Also, to ensure that participants of the MP group did not activate their muscles during  
23 MP, we used Friedman's ANOVAs, comparing the EMG activity of each imagined block  
24 with the rest condition, for each muscle (BB and TB).

25

## 1 Results

### 2 *Summary data*

3 Table 1 reports the mean values and the mean gains for the five kinematic parameters.

	PreTest	PostTest	Gain (%)	
	Mean (SD)	Mean (SD)	Mean (SD)	
<i>PP</i>	<i>MD (s)</i>	4.87 (0.97)	4.17 (0.78)	17.31 (15.26)
	<i>Distance (cm)</i>	162.01 (5.35)	163.19 (6.61)	-0.61 (4.23)
	<i>Vmean (cm/s)</i>	32.61 (8.07)	37.79 (8.42)	13.31 (11.81)
	<i>Vmax (cm/s)</i>	71.98 (22.12)	81.37 (26.18)	10.39 (10.34)
	<i>NbPeaks</i>	5.63 (2.14)	4.18 (1.47)	37.07 (29.37)
<i>MP</i>	<i>MD (s)</i>	4.80 (0.92)	4.43 (0.82)	9.11 (13.16)
	<i>Distance (cm)</i>	164.42 (5.24)	164.23 (3.72)	0.1 (1.94)
	<i>Vmean (cm/s)</i>	32.43 (5.38)	35.25 (5.91)	7.38 (11.34)
	<i>Vmax (cm/s)</i>	73.44 (13.25)	81.25 (12.35)	9.39 (11.43)
	<i>NbPeaks</i>	4.60 (1.13)	3.87 (0.77)	18.62 (15.25)
<i>Ctrl</i>	<i>MD (s)</i>	4.87 (0.84)	4.67 (0.87)	4.85 (7.89)
	<i>Distance (cm)</i>	163.55 (4.34)	163.54 (4.44)	0.02 (1.49)
	<i>Vmean (cm/s)</i>	32.31 (5.94)	33.76 (6.74)	3.82 (6.53)
	<i>Vmax (cm/s)</i>	71.59 (14.27)	71.18 (15.56)	-1.03 (6.30)
	<i>NbPeaks</i>	6.22 (2.27)	5.75 (2.45)	11.48 (19.15)

4  
5 **Table 1.** Average values and standard deviation (SD) for the PreTest, PostTest, and gains of  
6 the five parameters and the three experimental groups. MD: Movement duration; Vmean:  
7 Mean velocity; Vmax: Maximal velocity; NbPeaks: Number of peaks, s: second, cm:  
8 centimeter.

9

### 10 *One sample t-tests*

1 Firstly, to check whether motor performances improved between PreTest and PostTest  
 2 after practices, we used unilateral one-sample t-tests compared to the reference value 100.  
 3 Table 2 reports the results and effect sizes for one-sample t-tests analysis.

		t (14)	p (adjusted)	Cohen's d
<i>PP</i>	<i>MD</i>	4.39	0.0009	1.13
	<i>Vmean</i>	4.36	0.001	1.12
	<i>Vmax</i>	3.9	0.002	1
	<i>NbPeaks</i>	4.89	0.0003	1.26
	<i>Distance</i>	-0.55	1	-0.14
<i>MP</i>	<i>MD</i>	2.68	0.027	0.69
	<i>Vmean</i>	2.52	0.037	0.65
	<i>Vmax</i>	3.26	0.008	0.84
	<i>NbPeaks</i>	4.84	0.0004	1.25
	<i>Distance</i>	0.21	1	0.05
<i>Ctrl</i>	<i>MD</i>	2.38	0.048	0.61
	<i>Vmean</i>	2.26	0.06	0.58
	<i>Vmax</i>	-0.63	0.8	-0.16
	<i>NbPeaks</i>	2.32	0.053	0.6
	<i>Distance</i>	0.05	1	0.01

4  
 5 **Table 2.** Summarized results and effect sizes for one-sample t-tests analysis. PP: Physical  
 6 practice group; MP: Mental practice group; Ctrl; Control group. MD: Movement duration;  
 7 Vmean: Mean velocity; Vmax: Maximal velocity; NbPeaks: Number of peaks.

8  
 9 PP and MP groups significantly improved their performances between PreTest and  
 10 PostTest sessions. Precisely, MD and NbPeaks decreased, while Vmax and Vmean increased

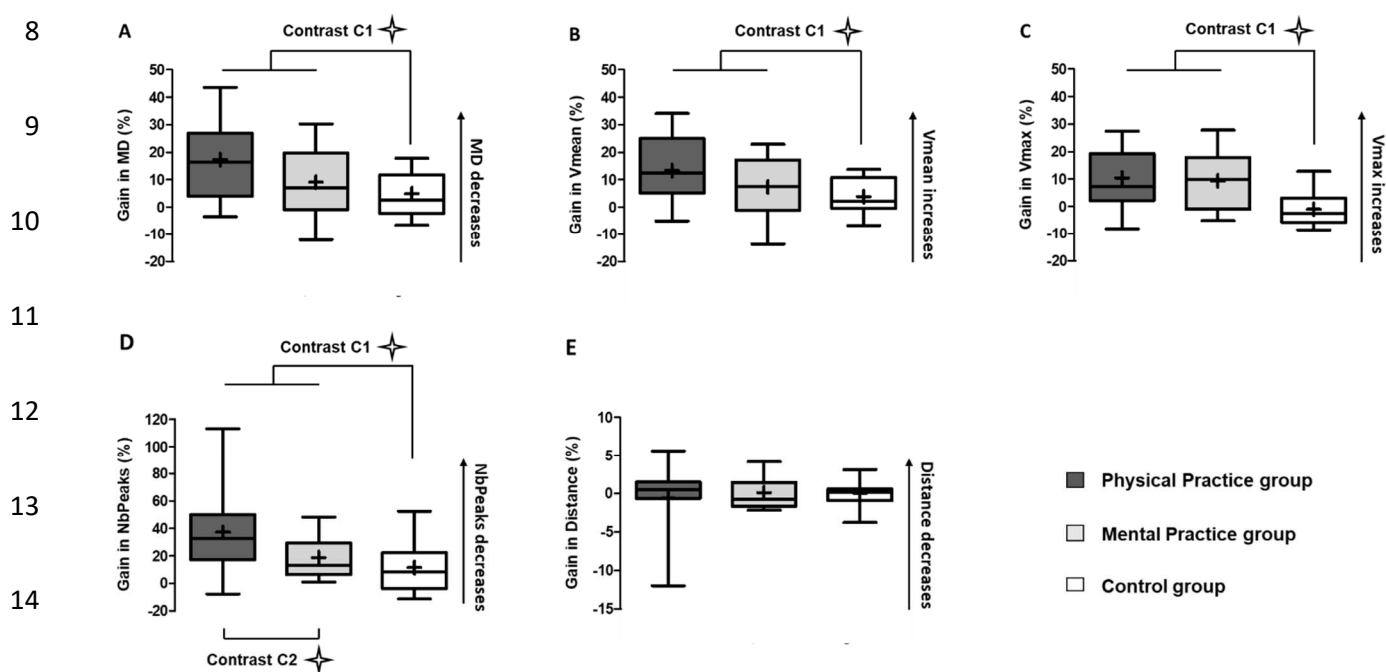
1 after practice. The Ctrl group improved movement duration. No significant effect of Distance  
 2 was observed (all  $p$ 's > 0.05).

3

4

### 5 *One factor ANOVA and contrast analysis*

6 Secondly, we compared gains between groups by means of one-factor ANOVAs and planned  
 7 comparisons. The results are depicted in Figure 2.



16 **Fig. 2.** Gains for MD (A. movement duration), Vmean (B. mean velocity), Vmax (C. maximal  
 17 velocity), NbPeaks (D. number of peaks) and Distance (E.) for each group. Cross and  
 18 horizontal bars within the boxplots represent mean and median, respectively. Boxplots  
 19 borders delimitate the first and third quartiles. Errors bars represents the 5th and the 95th  
 20 percentiles. Stars indicate significant effects of the contrasts (C1: Ctrl vs PP + MP and C2: PP  
 21 vs MP).

22

1           The ANOVA revealed a main effect of Group for MD ( $F_{2, 42} = 3.85, p = 0.03, \eta_p^2 =$   
2 0.15), Vmean ( $F_{2, 42} = 3.32, p = 0.045, \eta_p^2 = 0.14$ ), Vmax ( $F_{2, 42} = 6.64, p < 0.01, \eta_p^2 = 0.24$ ) and  
3 NbPeaks ( $F_{2, 42} = 5.37, p < 0.01, \eta_p^2 = 0.2$ ), but nor for Distance ( $F_{2, 42} = 0.29, p = 0.75$ ). The  
4 contrast analysis revealed significant effect of the contrast C1 (Ctrl vs MP + PP) for MD ( $t =$   
5 2.11,  $p = 0.04, \text{Cohen's } d = 0.69$ ), Vmean ( $t = 2.02, p = 0.049, \text{Cohen's } d = 0.66$ ), Vmax ( $t = 3.63,$   
6  $p < 0.01, \text{Cohen's } d = 1.18$ ) and NbPeaks ( $t = 2.36, p = 0.02, \text{Cohen's } d = 0.78$ ), without effect  
7 for Distance ( $t = -0.3, p = 0.76$ ). This confirms that, except for Distance, practice (MP & PP)  
8 improved motor performance when compared to the absence of practice (Ctrl). The contrast  
9 C2 (MP vs PP) revealed no statistically significant difference for MD, Vmean, Vmax or  
10 Distance (*all p's* > 0.12). However, there was a significant effect for the contrast C2 regarding  
11 NbPeaks ( $t = 2.27, p = 0.03, \text{Cohen's } d = 0.82$ ), suggesting better performance after PP than  
12 MP.

13

#### 14 ***Stepwise generalized linear discriminant analysis***

15           Finally, we performed a stepwise generalized linear discriminant analysis to identify  
16 the parameters that best discriminated the groups. The three groups (PP, MP, and Ctrl) were  
17 considered as the dependent variable and the gains for each parameter as the independent  
18 variable. The discriminant power of each variable was tested using a forward stepwise  
19 approach, revealing that Vmax and NbPeaks significantly contributed to group discrimination  
20 ( $F_2 = 5.19, p < 0.01$  and  $F_2 = 3.99, p = 0.025$ , respectively), whereas MD ( $F_2 = 1.41, p = 0.25$ ),  
21 distance ( $F_2 = 0.04, p = 0.96$ ), and Vmean ( $F_2 = 1.38, p = 0.26$ ) did not.

22

23           The discriminant analysis gave two canonical functions (*Wilks'  $\lambda = 0.64; \chi^2(4) = 18.62,$*   
24  *$p < .01$  for the first function; *Wilks'  $\lambda = 0.84; \chi^2(1) = 7.43, p < .01$  for the second one).* The first*

1 discriminant function accounted for 30.94% of total variance, while the second one for  
2 19.61%, for a total of 50.55%. The classification accuracy of the discriminant functions was  
3 62.2% with a significant Press Q score ( $\chi^2(1) = 16.9, p < .01$ ). This result ensures that the  
4 discriminant functions classified experimental observations in their respective groups better  
5 than chance (i.e., 50%). To conclude, the results of discriminant analysis and contrasts  
6 analysis suggest that Vmax discriminates practice from the absence of practice, whereas  
7 Nbpeaks also discriminates the performance improvement between PP and MP.

8

### 9 *Electromyographic analysis*

10 Participants did not activate their muscles during mental training in comparison to rest.  
11 Statistical comparison (Friedman's Anova) of EMG activity between each block of MP and  
12 rest revealed no significant difference neither for the BB muscle ( $X^2 = 5.47; p = 0.48$ ) nor for  
13 the TB muscle ( $X^2 = 10.39; p = 0.11$ ).

14

## 15 **Discussion**

16 In the current study, we identified the number of velocity peaks, an indicator of  
17 movement smoothness, as the most relevant parameter that differentiated PP from MP for an  
18 arm pointing task. While classical parameters as movement duration or maximal and mean  
19 velocity improved in a comparable extent following both practices, movement smoothness  
20 improved following MP but to a lower extent than that after PP. These findings provide  
21 relevant information about the specific influence of practice types on motor performance  
22 parameters.

23

### 24 *General motor performance improvement*



1 Motor performance improvement of arm reaching movement have been widely  
2 investigated, considering both PP and MP (Gentili et al. 2006; Gentili et al. 2010; Yàgüez et  
3 al. 1998; Ingram et al. 2019). Our findings corroborate previous results, showing an  
4 improvement of temporal parameters, such as movement duration, mean and maximal  
5 velocity after both practices, compared to the Control group.

6 The improvement of motor performance following MP could be explained by the  
7 concept of forward internal model (Gentili et al. 2006; Gentili et al. 2010; Dahm et Rieger  
8 2019; Kilteni et al. 2018). The internal model theory postulates the existence of predictive  
9 processes that simulate sensory prediction and the dynamic consequences of action (Wolpert  
10 and Flanagan, 2001; Friston, 2011; Kilteni et al., 2018). During the mental simulation of a  
11 movement, a motor command is generated by the controller based on the desired outcome. In  
12 parallel, an efferent copy is also generated and transmitted to the forward models, which  
13 produce a sensorimotor prediction about the future states of the arm (Wolpert and  
14 Ghahramani, 2000). If the motor command is inaccurate, then the forward models would  
15 predict an undesired final state for the arm (e.g., pointing next to the target instead of reaching  
16 it). It is hypothesized that, during mental practice, a comparator integrates the discrepancy  
17 (i.e., the error) between the desired outcome and this sensorimotor prediction. This  
18 information would be sent back from the comparator to the controller as a teaching signal,  
19 permitting an internal adjustment of the future motor command despite the absence of sensory  
20 feedbacks. However, due to the absence of such feedbacks, the training of the internal models  
21 would be more variable, that could be one explanation for the well-known difference between  
22 mental and physical practice when considering performance-related motor gains (Gentili et al.  
23 2006, 2010). Interestingly, PP and MP increased mean and maximal velocity to the same  
24 extent, but PP greater decreased the number of velocity peaks. These findings provide

1 evidence that PP and MP may improve specifically the parameters of performance for arm  
2 reaching tasks.

3

#### 4 ***Movement smoothness discriminates physical and mental practices***

5         The arm reaching movements can be decomposed in two distinct phases: i) an initial  
6 impulse phase, involving predictive loops and ii) a final phase, known as the corrective phase,  
7 implying online movement corrections (Elliott et al., 2001; Thompson et al., 2007). Kinematic  
8 analyses revealed that the first phase can be characterized by one or two high velocity peaks,  
9 permitting to quickly get closer to the target, while the second contains low secondary  
10 velocity peaks, which are likely to represent corrective sub-movements when approaching the  
11 target (Novak et al., 2002). The authors also suggested that PP leads to faster and precise  
12 initial movements in order to quickly approach the target and to reduce the number of  
13 corrective sub-movements, respectively. Here, we discuss the difference in number of  
14 velocity peaks between PP and MP groups, considering the insights of studies that  
15 investigated the absence of feedbacks during actual reaching movements (Khan et al., 2003;  
16 Franklin et al., 2017). These studies showed that the actual execution of fast and smooth  
17 movements during the initial phase is possible with or without feedbacks, whereas the  
18 reduction of the endpoint variability during the final phase is feedback-dependent. Because of  
19 the similar increase of  $V_{max}$  for both groups and the decrease of NbPeaks, even for MP, we  
20 suggest that both PP and MP may lead to the execution of faster and precise initial  
21 movements that minimize the corrective phase and thus reduce the number of sub-  
22 movements. The distinction between PP and MP could thus stand in the corrective phase,  
23 where sensory feedbacks are necessary. Indeed, the feedbacks of actual movements during PP  
24 may help to optimize the corrective phase when approaching the target, and therefore to  
25 greater reduce NbPeaks in comparison to MP. The absence of sensory feedbacks during

1 imagined movements would be an obstacle to reduce the number of sub-movements when  
2 actually approaching the target.

3

#### 4 *Limitations*

5         The chosen experimental paradigm limits some additional analyses. Indeed, the  
6 instruction given to the participants was to pass through a target to validate it, without  
7 necessarily stopping the movement in each target. Thus, it is difficult to decompose the  
8 movement into acceleration and deceleration phases to interpret how arm motor control  
9 acquired the various targets. Further investigations could allow confirming our hypothesis  
10 concerning the distinction between the initial and the corrective phase about the decrease of  
11 the number of peaks. For instance, an experimental paradigm using isolated pointing  
12 movements, would allow decomposing each movement in clear acceleration and deceleration  
13 phases, and therefore to quantify the evolution of the number of peaks in each phase, before  
14 and after physical or mental practices.

15         Likewise, further studies could analyze a broader range of movements, tasks (e.g., to  
16 perform and/or imagine the movement at different velocities) and smoothness metrics (e.g.  
17 dimensionless jerk or Spectral Arc Length; Balasubramanian et al., 2015; Gulde and  
18 Hermsdorfer 2018) to better characterize and understand the influence of MP on varied  
19 movements parameters.

20

#### 21 *Conclusion*

22         In conclusion, the present study provided the first evidence that MP increased  
23 smoothness of arm-reaching movement, and that this performance parameter discriminated  
24 between PP from MP. Although, no sensory feedbacks are present during imagined  
25 movements, the increase of movement velocity would lead to greater smoothness after MP.

- 1 Further studies could analyse a broader range of movements and tasks (e.g., to perform and/or
- 2 imagine the movement at different velocities) to better understand the influence of MP on
- 3 movements parameters.

4

1 **Authors contributions**

2 CR, CP, and FL designed the experiment; CR and DRM recorded the data; DRM and JG  
3 analysed the data; CR and DRM developed figures; CR, DRM, CP and FL wrote the  
4 manuscript; CP, JG, PMH and FL provided feedback on the manuscript; all co-authors read  
5 and approved the submitted version.

6

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10

11 **Conflict of Interest Statement**

12 The authors declare that the research was conducted in the absence of any commercial or  
13 financial relationship that could be construed as a potential conflict of interest.

14

15

## 1 **References**

- 2 Allami N, Paulignan Y, Brovelli A, Boussaoud D (2008) Visuo-motor learning with  
3 combination of different rates of motor imagery and physical practice. *Exp Brain Res*  
4 184:105–113.
- 5 Avanzino L, Gueugneau N, Bisio A, Ruggeri P, Papaxanthis C, Bove M (2015) Motor cortical  
6 plasticity induced by motor learning through mental practice. *Front Behav Neurosci* 9.
- 7 Balasubramanian S, Melendez-Calderon A, Roby-Brami A, Burdet E (2015) On the analysis  
8 of movement smoothness. *J Neuroeng Rehabil* 12:1–11.
- 9 Bonassi G, Biggio M, Bisio A, Ruggeri A, Bove M, Avanzino L (2017) Provision of  
10 somatosensory inputs during motor imagery enhances learning-induced plasticity in  
11 human motor cortex. *Sci Rep* 7:9300.
- 12 Brooks VB, Cooke JD, Thomas JS (1973) The Continuity of Movements. *Control of Posture*  
13 *and Locomotion* 257–272.
- 14 Criscimagna-Hemminger SE, Bastian AJ, Shadmehr R (2010) Size of error affects cerebellar  
15 contributions to motor learning. *J Neurophysiol* 103:2275–2284.
- 16 Dahm SF, Rieger M (2019) Is imagery better than reality? Performance in imagined dart  
17 throwing. *Hum Mov Sci* 66:38–52.
- 18 Elliott D, Chua R, Helsen WF (2001) A century later: Woodworth's (1899) two-component  
19 model of goal-directed aiming. *Psychol Bull* 127:342–357.
- 20 Fethers L, Todd J (1987) Quantitative assessment of infant reaching movements. *J Mot Behav*  
21 19:147–166.
- 22 Franklin S, Wolpert DM, Franklin DW (2017) Rapid visuomotor feedback gains are tuned to

- 1 the task dynamics. *J Neurophysiol* 118:2711–2726.
- 2 Friston K (2011) What is optimal about motor control? *Neuron* 72:488–498.
- 3 Gentili R, Han CE, Schweighofer N, Papaxanthis C (2010) Motor learning without doing:  
4 trial-by-trial improvement in motor performance during mental training. *J Neurophysiol*  
5 104:774–7830
- 6 Gentili R, Papaxanthis C, Pozzo T (2006) Improvement and generalization of arm motor  
7 performance through motor imagery practice. *Neuroscience* 137:761–772.
- 8 Grosprêtre S, Jacquet T, Lebon F, Papaxanthis C, Martin A (2018) Neural mechanisms of  
9 strength increase after one-week motor imagery training. *Eur J Sport Sci* 18:209–218.
- 10 Grosprêtre S, Lebon F, Papaxanthis C, Martin A (2019) Spinal plasticity with motor imagery  
11 practice. *J Physiol* 597:921–934.
- 12 Grush R (2004) The emulation theory of representation: Motor control, imagery, and  
13 perception. *Behav Brain Sci* 27:377–396.
- 14 Gulde P and Hermsdörfer (2018) Smoothness metrics in complex movement tasks. *Front*  
15 *Neurol*.
- 16 Hair JF, Anderson RE, Tatham RL, BW (1998) *Multivariate data analysis*. In: 5th ed. Upper  
17 Saddle River. New Jersey: Prentice-Hall, Inc.
- 18 Howell DC (2012) *Statistical Methods for Psychology* (8th edition). Belmont, CA :  
19 Wadsworth Publishing.
- 20 Ingram TGJ, Solomon JP, Westwood DA, Boe SG (2019) Movement related sensory  
21 feedback is not necessary for learning to execute a motor skill. *Behav Brain Res*  
22 359:135–142.

- 1 Izawa J, Shadmehr R (2011) Learning from sensory and reward prediction errors during  
2 motor adaptation. *PLoS Comput Biol* 7:1002012.
- 3 Karni A, Meyer G, Rey-Hipolito C, Jezzard P, Adams MM, Turner R, Ungerleider LG (1998)  
4 The acquisition of skilled motor performance: Fast and slow experience-driven changes  
5 in primary motor cortex. *Proc Natl Acad Sci U S A* 95:861–868.
- 6 Kawato M, Kuroda T, Imamizu H, Nakano E, Miyauchi S, Yoshioka T (2003) Internal  
7 forward models in the cerebellum: fMRI study on grip force and load force coupling.  
8 *Prog Brain Res* 142.
- 9 Kelso JAS, Southard DL, Goodman D (1979) On the nature of human interlimb coordination.  
10 *Science* (80- ) 203:1029–1031.
- 11 Ketcham CJ, Seidler RD, Van Gemmert AWA, Stelmach GE (2002) Age-Related Kinematic  
12 Differences as Influenced by Task Difficulty, Target Size, and Movement Amplitude.  
13 *Journals Gerontol Ser B Psychol Sci Soc Sci* 57:P54–P64.
- 14 Ketcham CJ, Stelmach GE (2004) Movement Control in the Older Adult. *Technology for*  
15 *adaptive aging*.
- 16 Khan MA, Lawrence G, Fourkas A, Franks IM, Elliott D, Pembroke S (2003) Online versus  
17 offline processing of visual feedback in the control of movement amplitude. *Acta*  
18 *Psychol (Amst)* 113:83–97.
- 19 Kilteni K, Andersson BJ, Houborg C, Ehrsson HH (2018) Motor imagery involves predicting  
20 the sensory consequences of the imagined movement. *Nat Commun* 9:1617.
- 21 Kitago T, Krakauer JW (2013) Motor learning principles for neurorehabilitation. *Handb Clin*  
22 *Neurol* 110:93–103.
- 23 Lebon F, Collet C, Guillot A (2010) Benefits of motor imagery training on muscle strength. *J*



- 1           Strength Cond Res 24:1680–1687.
- 2   Lorant J, Nicolas A (2004) Validation de la traduction française du Movement Imagery  
3           Questionnaire-Revised (MIQ-R). *Sci Mot*:57–68.
- 4   Novak K, Miller L, Houk J (2002) The use of overlapping submovements in the control of  
5           rapid hand movements. *Exp Brain Res* 144:351–364.
- 6   Ranganathan VK, Siemionow V, Liu JZ, Sahgal V, Yue GH (2004) From mental power to  
7           muscle power - Gaining strength by using the mind. *Neuropsychologia* 42:944–956.
- 8   Robertson EM, Pascual-Leone A, Miall RC (2004) Current concepts in procedural  
9           consolidation. *Nat Rev Neurosci* 5:576–582.
- 10   Rozand V, Lebon F, Stapley PJ, Papaxanthis C, Lepers R (2016) A prolonged motor imagery  
11           session alter imagined and actual movement durations: Potential implications for  
12           neurorehabilitation. *Behav Brain Res* 297:67–75.
- 13   Ruffino C, Gaveau J, Papaxanthis C, Lebon F (2019) An acute session of motor imagery  
14           training induces use-dependent plasticity. *Sci Rep* 9:20002.
- 15   Ruffino C, Truong C, Dupont W, Bouguila F, Michel C, Lebon F, Papaxanthis C (2021)  
16           Acquisition and consolidation processes following motor imagery practice. *Sci Rep*  
17           11:2295.
- 18   Shadmehr R, Krakauer JW (2008) A computational neuroanatomy for motor control. *Exp*  
19           *Brain Res* 185:359–381.
- 20   Shadmehr R, Smith M a, Krakauer JW (2010) Error correction, sensory prediction, and  
21           adaptation in motor control. *Annu Rev Neurosci* 33:89–108.
- 22   Spampinato D, Celnik P (2017) Temporal dynamics of cerebellar and motor cortex

- 1       physiological processes during motor skill learning. *Sci Rep* 7:40715.
- 2       Thompson SG, McConnell DS, Slocum JS, Bohan M (2007) Kinematic analysis of multiple  
3       constraints on a pointing task. *Hum Mov Sci* 26:11–26.].
- 4       Walker MP, Brakefield T, Seidman J, Morgan A, Hobson JA, Stickgold R (2003) Sleep and  
5       the time course of motor skill learning. *Learn Mem* 10:275–284.
- 6       Willingham DB (1998) A neuropsychological theory of motor skill learning. *Psychol Rev*  
7       105:558–584.
- 8       Wolpert D, Diedrichsen J, Flanagan (2011) Principles of sensorimotor learning. *Nat Rev*  
9       Neurosci 12:739-751.
- 10      Wolpert D, Flanagan J (2001) Motor prediction. *Curr Biol* R729-732.
- 11      Wolpert D and Ghahramani (2000). Computational principles of movement neuroscience. *Nat*  
12      Neurosci 3:1212-1217.
- 13      Yáguez L, Nagel D, Hoffman H, Canavan A (1998) A mental route to motor learning:  
14      improving trajectorial kinematics through imagery training. *Behav brain* 90:95–106.
- 15      Yue G, Cole KJ (1992) Strength increases from the motor program: comparison of training  
16      with maximal voluntary and imagined muscle contractions. *J Neurophysiol* 67:1114–  
17      1123.
- 18

		PreTest	PostTest	Gain (%)
		Mean (SD)	Mean (SD)	Mean (SD)
<b>PP</b>	<i>MD (s)</i>	4.87 (0.97)	4.17 (0.78)	17.31 (15.26)
	<i>Distance (cm)</i>	162.01 (5.35)	163.19 (6.61)	-0.61 (4.23)
	<i>Vmean (cm/s)</i>	32.61 (8.07)	37.79 (8.42)	13.31 (11.81)
	<i>Vmax (cm/s)</i>	71.98 (22.12)	81.37 (26.18)	10.39 (10.34)
	<i>NbPeaks</i>	5.63 (2.14)	4.18 (1.47)	37.07 (29.37)
<b>MP</b>	<i>MD (s)</i>	4.80 (0.92)	4.43 (0.82)	9.11 (13.16)
	<i>Distance (cm)</i>	164.42 (5.24)	164.23 (3.72)	0.1 (1.94)
	<i>Vmean (cm/s)</i>	32.43 (5.38)	35.25 (5.91)	7.38 (11.34)
	<i>Vmax (cm/s)</i>	73.44 (13.25)	81.25 (12.35)	9.39 (11.43)
	<i>NbPeaks</i>	4.60 (1.13)	3.87 (0.77)	18.62 (15.25)
<b>Ctrl</b>	<i>MD (s)</i>	4.87 (0.84)	4.67 (0.87)	4.85 (7.89)
	<i>Distance (cm)</i>	163.55 (4.34)	163.54 (4.44)	0.02 (1.49)
	<i>Vmean (cm/s)</i>	32.31 (5.94)	33.76 (6.74)	3.82 (6.53)
	<i>Vmax (cm/s)</i>	71.59 (14.27)	71.18 (15.56)	-1.03 (6.30)
	<i>NbPeaks</i>	6.22 (2.27)	5.75 (2.45)	11.48 (19.15)

		<b>t (14)</b>	<b>p (adjusted)</b>	<b>Cohen's d</b>
<b>PP</b>	<b>MD</b>	4.39	0.0009	1.13
	<b>Distance</b>	-0.55	1	-0.14
	<b>Vmean</b>	4.36	0.001	1.12
	<b>Vmax</b>	3.9	0.002	1
	<b>NbPeaks</b>	4.89	0.0003	1.26
<b>MP</b>	<b>MD</b>	2.68	0.027	0.69
	<b>Distance</b>	0.21	1	0.05
	<b>Vmean</b>	2.52	0.037	0.65
	<b>Vmax</b>	3.26	0.008	0.84
	<b>NbPeaks</b>	4.84	0.0004	1.25
<b>Ctrl</b>	<b>MD</b>	2.38	0.048	0.61
	<b>Distance</b>	0.05	1	0.01
	<b>Vmean</b>	2.26	0.06	0.58
	<b>Vmax</b>	-0.63	0.8	-0.16
	<b>NbPeaks</b>	2.32	0.053	0.6