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1 Comparative efficacy of robotic and manual massage interventions on performance
2 and well-being: A randomized crossover trial

3
4 Yann Kerautret¹, Franck Di Rienzo¹, Carole Eyssautier² & Aymeric Guillot¹

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6 ¹Universite Lyon 1, UCB-Lyon 1, Laboratoire Interuniversitaire de Biologie de la
7 Motricité-UR 7424, F-69622, Villeurbanne Cedex, France; Allyane®, 84 quai Joseph Gillet,
8 69004 Lyon, France.

9 ²CAPSIX, Lyon, France

10

11 **Abstract**

12 **Background:** Manual massage (MM) interventions can improve psychophysiological
13 states of relaxation and well-being. In this context, robotic massage (RM) represents a
14 promising, but currently understudied, solution. **Purpose:** The present study aimed at
15 comparing the effects of MM and RM on psychometric, behavioral, and neurophysiological
16 indexes of motor/cognitive performances and well-being. **Level of evidence:** Level 2. **Study**
17 **design:** A single-blind randomized crossover trial. **Methods:** Twenty-one participants
18 experienced two massage intervention targeting back soft tissues. During a first condition, the
19 intervention was performed by a physiotherapist, whereas during a second condition the
20 intervention was performed by a robot. We collected a series objective and subjective indexes
21 of performances and well-being before and after each massage intervention. We also collected
22 physiotherapist's self-reports of perceived fatigue, tension, and ability to maintain the massage
23 routine. **Results:** Skin conductance decreased from the pretest to the posttest in both conditions
24 (partial R-squared = 0.44, 95% CI [0.30, 1.00], $p < 0.001$), although the decrease was more
25 pronounced after MM. While both interventions were associated with improved subjective
26 sensations, e.g. pain, warmth, well-being (partial R-squared = 0.08, 95% CI [0.06, 1.00], $p <$
27 0.001), MM yielded additional benefits compared to RM. The physiotherapist reported greater
28 fatigue and tension and reduced perceived massage efficiency along with repeated massage
29 interventions. MM outperformed RM to elicit a psychophysiological state of relaxation.

30 **Conclusion:** RM exhibited a comparable pattern of changes to that of MM, for both objective
31 and subjective indexes of relaxation and well-being. **Clinical relevance:** RM could represent a
32 prophylactic option to prevent the onset of counterproductive fatigability in physiotherapists.

33 Key Words: physiotherapy, manual massage, cobots, robotic, electrodermal activity.

34 1) Introduction

35 Manual massage (MM) has ancestral roots among human civilizations ²¹, and can be
36 used to address a variety of outcomes ranging from well-being to sports performance and
37 recovery ³³. MM also has beneficial therapeutic effects, e.g. growth and gastrointestinal
38 function disorders in premature infants, infants of depressed mothers or elderly patients with
39 severe dementia ^{15,22,54}. Pressures elicited during MM target the soft tissues, i.e. skin, muscles,
40 tendons and their fascia, hence affecting their biomechanical and/or neurophysiological
41 properties ^{27,28,60}. MM stimulates mechanoreceptors such as the Golgi tendon organ, Pacinian,
42 Meissner, Ruffini corpuscles and interstitial type III and IV receptors, hence yielding bottom-
43 up regulations of autonomic nervous system activities ^{48,49,61}. This is a possible mechanism
44 underlying MM uses to promote well-being through enhanced psychophysiological relaxation
45 states ¹.

46 MM requires a trained practitioner to perform manual manoeuvres such as effleurage,
47 kneading, or sliding pressures. MM is thus a difficult intervention to scale, which represents a
48 major obstacle to its democratization ²⁶. Furthermore, MM involves fine adjustments by the
49 practitioner, which prevents standardization of MM procedures in experimental research
50 designs ⁵³. MM practitioners may eventually adjust their gestures based on both direct and
51 indirect feedbacks provided in real-time by the massaged participant ³³. Moraska ⁴¹ provided
52 evidence that the physiotherapist' professional experience influenced MM outcomes. A
53 physiotherapist with > 950 h of didactic training achieved better results compared 450 or 700 h
54 trained physiotherapists to alleviate muscle soreness. While there is now abundant data
55 supporting the benefits of MM for a variety of outcomes in both healthy and patient populations
56 ^{33,47}, it remains an expensive and time-consuming intervention ^{12,59}.

57 During MM, the person receiving the massage lies on the massage table in prone or
58 supine position, and cannot regulate the massage gestures provided by the physiotherapist.

59 While the person can adjust muscle tone at his/her convenience, she remains in a primarily
60 retroactive mode of action control where pressures cannot be anticipated ³³. MM is getting
61 increasingly assisted by technological devices, such as the LPG endermologie[®], with recent
62 development of robotic devices ³³. The Waseda Asahi Oral-Rehabilitation Robot 1 (WAO-1),
63 specialized in the temporalis and masseter muscles treatment, was one of the pioneer robotic
64 massage (RM) solutions ^{55,56}. The WAO-1 robot showed promising results in oral hygiene such
65 as dry-mouth, temporomandibular joint disorders ^{2-5,32,36,44}. Despite its standardized
66 maneuvers and lack adaptation to individual morphology, patients suffering from
67 temporomandibular disorders reported beneficial results approaching those obtained by
68 experienced doctor after a single RM session ³⁶.

69 Although it seems difficult, not to say impossible, to implement a MM individualized
70 to the point of MM delivered by a trained therapist, start-up companies such as AiTreat,
71 Massage robotics, Adamo Robot[®] and Capsix[®] are currently developing RM solutions that
72 provide greater degrees of individualization ³³. The RM solution developed by Capsix[®] can
73 adjust the trajectories to the morphology of the user through preliminary scanning of their
74 anatomy. They also engineered a remote device that users can use to control the intensity of
75 the pressures applied by the robot. Such RM solution engages fundamentally distinct
76 sensorimotor control modalities compared to traditional MM, since users will be able to switch
77 from a retroactive to a proactive mode of action control during the massage routine. This
78 questions whether RM delivered by collaborative robot may reproduce some of the benefits of
79 MM performed by a trained physiotherapist.

80 In the present experiment, we compared in a single-blind randomized controlled design
81 the effects of a MM and RM intervention targeting the lumbopelvic muscles on psychometric,
82 behavioral and neurophysiological indexes of performance and well-being. We hypothesized
83 that both MM and RM would improve flexibility of the hamstrings and lumbopelvic muscles,

84 and promote a psychophysiological state of relaxation through decreased sympathetic activity.
85 We hypothesized that RM might increase alertness compared to MM, since such type of
86 intervention engages more proactive modes of action control. Overall, we aimed to disentangle
87 the selective effects of RM compared to MM, and provide new knowledge regarding the effects
88 of emerging RM solutions at the single-session level.

89 **2) Materials and methods**

90 **a) Participants**

91 Twenty-one healthy adults volunteered to participate in the present blinded randomized
92 crossover trial (for a greater description of participant's characteristics, see Table 1).
93 Participants had no current or past medical history (including functional limitations) which
94 could have compromised the results. They were off medication and not allowed to consume
95 alcoholic and caffeinated beverages before the study. Participants were also instructed to not
96 engage in any strenuous form of exercise that could induce delayed-onset muscle soreness
97 during the experimental period. No information regarding the purpose of the experiment was
98 provided to the participants until completion of the design. The present experiment was
99 approved by CPP Ouest 6 ethical review board (IRB 2019-A01732-55) and previously
100 registered on [ClinicalTrial.gov](https://clinicaltrials.gov). All participants signed an informed consent form prior to
101 enrollment in the study, in accordance with the ethical standards laid down in the Declaration
102 of Helsinki and its later amendments ⁶³.

Characteristics	Age (years)	Height (m)	Mass (kg)	BMI (kg/m ²)	105
Hommes	33.2 ± 6.4 (range 24-45)	1.76 ± 8.8 (range 1.68-1.93)	77.4 ± 7.2 (range 69-92)	24.9 ± 1.00 (range 23.2-26.6)	
Femmes	30.8 ± 9.9 (range 20-54)	1.64 ± 5.2 (range 1.55-1.75)	61.1 ± 10.7 (range 46-89)	22.7 ± 2.6 (range 19.1-29.1)	
Group differences (1-way ANOVA)	F(1, 19) = 0.38, p = 0.054	F(1, 19) = 14.93, p < 0.01	F(1, 19) = 14.96, p < 0.01	F(1, 19) = 5.8, p < 0.05	

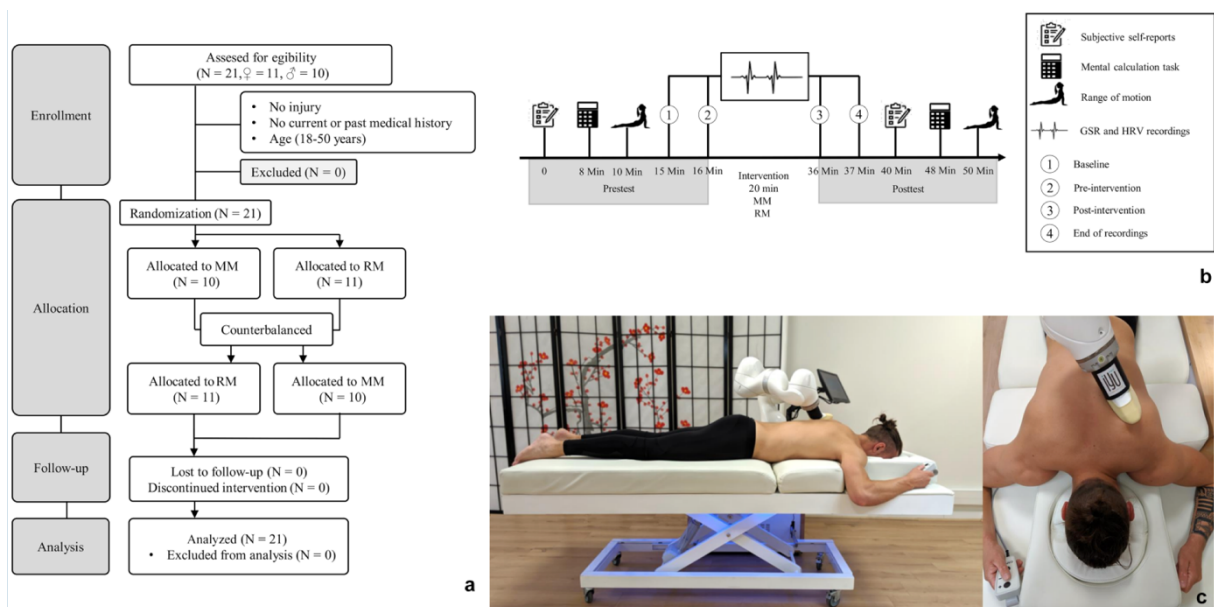
107 Table 1. Participants' characteristics (M ± SD).

108 There were no adverse events and no subjects withdrew during data collection. Statistical analysis of the descriptive data revealed no
 109 significant differences between the two groups for age, height, body mass, and BMI (all p > 0.05). BMI: Body Mass Index.

111

112 **b) Experimental design**

113 The present single-blind randomized crossover trial involved two experimental sessions
 114 separated by 7 days (Figure 1a). Experimental sessions were supervised by the same
 115 experimenter to ensure reproducibility, and the study took place over an inclusion period of 8
 116 weeks. Experimental sessions consisted in pretest and immediate posttest measures of
 117 psychometric, motor and cognitive performances, neurophysiological indexes of performance,
 118 and well-being, respectively before and after an experimental massage intervention (Figure 1b).
 119 Participants completed a form to collect demographic information before completing the first
 120 experimental session of the design. During a first experimental condition, they received MM
 121 by a trained physiotherapist (MANUAL MASSAGE, see below for further description). During a
 122 second experimental condition, they received RM by iYU[®] (ROBOTIC MASSAGE, see below for
 123 further description). For both experimental conditions, the room temperature was controlled
 124 between 24 and 27°C (Figure 1c).



125

126 **Figure 1. a.** Flowchart (inspired from CONSORT guidelines⁵⁰ describing participants’

127 inclusion and randomization procedure); **b.** Flowchart of the experimental procedures and

128 psychometric, motor and cognitive performances and neurophysiological indexes of
129 performance and well-being; **c.** Representative photographs of the iYU[®] device.

130 **c) Experimental sessions**

131 **i) Manual massage intervention**

132 Participants in the MANUAL MASSAGE condition underwent MM performed by a
133 qualified physiotherapist blinded to the purpose of the experiment (20 years of clinical
134 experience). Participants lied in the prone position on a massage table. The MM intervention
135 lasted 20 min and involved traditional bilateral effleurage (1 min) with the palmar aspect of the
136 hands over the entire back and paravertebral muscles, followed by deep bilateral sliding
137 pressures (1 min 30), and unilateral pressures (4 min 30) of the paravertebral, trapezius, and
138 rhomboid muscles. The protocol continued with deep kneading, unilateral sinusoids (4 min 30)
139 and bilateral rotational friction of the paravertebral muscles (7 min). Finally, the physiotherapist
140 applied again unilateral (1 min 30) and bilateral (1 min 30) deep sliding pressures on the
141 paravertebral, trapezius and rhomboid muscles before targeting the entire back by a simple light
142 touch. To facilitate maneuvers, massage cream was used. The physiotherapist was trained on
143 the protocol and did not play another role in the study.

144 The MM routine was standardized for all participants (order of the target areas, type and
145 frequency of maneuvers), with only minor adjustments regarding the treatment time per muscle
146 and the total duration of the session based on the morphology of the participant. Each participant
147 received an identical number of massage gestures. For methodological reasons, we could not
148 control the pressures applied by the physiotherapist. To avoid interfering with the
149 physiotherapist's MM practice, he was free to apply a similar pressure to that used in his clinical
150 practice. This was deemed reliable to ensure homogeneity of pressures applied during the MM
151 routine throughout the design. The physiotherapist declared that he adjusted the massage

152 pressures according to the zones of perceived tension, and that he remained consistent across
153 participants.

154 **ii) Robotic massage intervention**

155 Under the ROBOTIC MASSAGE condition, participants underwent a massage performed
156 by a robotic device (iYU®, Capsix®, Lyon, France). The robotic device consisted of a
157 collaborative robot (LBR Med R820, Kuka Robotics, Augsburg, Germany), a homemade
158 remote control, a 3D vision camera (Azure Kinect DK, Microsoft, Washington, USA), and a
159 motorized massage table (electric massage table 003815, Medeo Kosmetic GmbH, Bornheim,
160 Germany). The RM protocol, defined by a physiotherapist, accounted for the morphology of
161 each participant through a preliminary scanning procedure using the 3D vision camera. Without
162 leaving complete autonomy to users, the device exploited the potential of interaction offered by
163 cobotics via a remote control available to users to increase or decrease the pressure at any time
164 according to their needs. Similarly, to the MANUAL MASSAGE condition, participants were lying
165 in a prone position on the massage table. The RM routine matched the criteria of MM routine
166 (maneuvers order and target areas, treatment time per muscle and total duration of the routine).
167 Unlike MANUAL MASSAGE condition, however, participants could adjust the pressure applied
168 by the robot using the remote control. An operator provided assistance to calibrate and initiate
169 the RM routine, and guaranteed the safety of the participants.

170 **d) Dependent variables**

171 We measured a variety of neurophysiological, behavioral and psychometric indexes as
172 outcome variables of the study (see Table 2 for a summary).

173 **i) Neurophysiological variables**

174 **(1) Electrodermal activity**

175 We indexed electrodermal activity from continuous skin conductance using two finger
176 electrodes (MLT116F, GSR Finger Electrodes, ADInstruments, Dunedin, New-Zealand) with
177 constant voltage (0.5 V), positioned in the second phalanx on the second and third digits of the
178 right hand. Signals were processed online using a Galvanic Skin Resistance amplifier (FE116
179 GSR Amp, ADInstruments, Dunedin, New-Zealand) connected to a PowerLab 16/35
180 acquisition system (PL3516, Power Lab 16/35, ADInstrument, Dunedin, New-Zealand). The
181 skin conductance software was LabChart Pro (ADInstrument, Dunedin, New-Zealand). Skin
182 conductance (SC) mirrors the activity of eccrine sweat glands, which are under the control of
183 the sympathetic branch of the autonomic nervous system. Tonic changes reflect variations in
184 physiological arousal, whereas phasic responses primarily reflect cognitive changes such as
185 increased vigilance during motor preparation ¹⁷. Here, we were interested in participants'
186 physiological arousal during the massage as well as during the pretest and posttest resting-state
187 measures. We used the first minute of recordings before the massage as the baseline SC. Then,
188 we continuously recorded SC over the massage, extended up to 1 min after the end of the
189 massage. We finally calculated a normalized SC index (SC_{NORM}) according to the following
190 formulae:

$$191 \quad SC_{Norm} = \frac{\text{mean}(\text{Resting State SC})}{\text{Baseline SC}}$$

192 (2) Cardiac activity

193 Heart rate variability (HRV) indexes were calculated from R-R intervals using a finger
194 pulse transducer (TN1012/ST, Finger Pulse Transducers, ADInstrument, Dunedin, New-
195 Zealand) attached to the first phalanx on the right hand. Data were co-registered with SC signals
196 using the LabChart Pro acquisition software. The root mean square of successive differences
197 (RMSSD) was calculated as an index of the time domain of HRV, reflecting cardiac
198 parasympathetic modulation ³⁸. The LF/HF ratio was also used as an index of the frequency

199 domain of HRV to quantify the sympathovagal balance, i.e. the relationship between
200 sympathetic and parasympathetic nervous system activities²⁵. An increase in HRV is explained
201 by an opposite reaction of the LF/HF ratio, i.e., a decrease in the sympathovagal balance
202 indicative of a predominance of parasympathetic activity.

203 **ii) Motor and cognitive performances**

204 **(1) Motor performances**

205 To evaluate flexibility of lumbopelvic and hamstrings muscles, participants completed
206 two tests. For the sit-and-reach test (SRT), they adopted a seated position with their feet, hip-
207 width apart, and knees extended^{6,39}. Then, to try to reach as far as possible with their hands on
208 the tape measure, they were instructed to lean forward slowly and gradually, without bouncing.
209 To complete this assessment, we used the toes touch (TT) test^{6,39}. Conversely to SRT,
210 participants started from the stance on a wooden box with outstretched legs and feet hip-width
211 apart before to tilt the chest forward using only gravity. For both flexibility tests, they were
212 instructed to hold their maximal stretching position for 2 s for each trial attempt. The best score
213 of three trials was recorded to the nearest 0.1 cm¹⁶.

214 **(2) Cognitive performances**

215 To index cognitive performances, we used a mental calculation task. Performance in
216 mental calculation paradigms has been shown to be positively impacted by MM interventions
217^{23,24,34}. The task consisted in iterated subtractions (-7) from a starting number randomly selected
218 between 500 and 1 000. The participants had 120 s to execute the maximal number of correct
219 subtractions (total number of correct answers). To avoid contamination effects on other
220 dependent variables, including skin conductance and heart rate variability recordings, this
221 stressful task was performed at the end of the PRETEST and POSTTEST¹³.

222 **iii) Self-report ratings from visual analogue scales**

223 Participants were requested to provide self-report ratings of their physical sensations on
224 visual analogue scales (VAS, 0-100mm; 0: “*Not at all*”, 10: “*Strongly*”). They were asked to
225 rate their subjective sensations of warmth, muscle pain, perceived SRT flexibility, perceived
226 TT test flexibility, and their sensations of well-being, relaxation and anxiety.

227 **(1) Mood profile**

228 Participants’ mood profiles were evaluated using the BRUMS questionnaire ¹¹. The
229 BRUMS involves 24 items divided into six subscales: fatigue, tension, vigor, mental confusion,
230 depression and anger. For each item, participants respond to the question “*How do you feel*
231 *now?*” on a 5-point Likert-type scale (0: “*None*”, 4: “*Extremely*”). The total score of each
232 subscale was obtained by sum of the corresponding items and ranged between 0 and 16. The
233 highest scores indicated greater subjective experience of corresponding mood parameter.

234 **(2) Mental and physical workload**

235 Mental workload was evaluated using the NASA-TLX based on the weighted average
236 of ratings obtained from six subscales: mental demands, physical demands, temporal (time)
237 demands, performance, effort, and frustration ²⁹, on a 20-point Likert-type scale.

238 **(3) Physiotherapist’s self-report ratings**

239 The physiotherapist was requested to provide self-report ratings on three subjective
240 indicators using a 10-point VAS (0-100mm: 0 = “*Not at all*” to 100 = “*Strongly*”). Practically,
241 he was asked to rate his subjective sensations (fatigue and tension), as well as his ability to
242 maintain massage parameters (massage pressure, amplitude and frequency). Finally, he
243 assessed the overall effectiveness of his intervention after each massage.

Category	Outcome	Assessment method	Index	Measurement points
Psychometric	Perceived sensations	VAS	Self-report ratings	Pretest, Posttest
	Mood	BRUMS	Self-report ratings	Pretest, Posttest
	Physical and mental load	NASA-TLX	Self-report ratings	Pretest, Posttest
Behavioral	Flexibility	SRT, TT	Distance (cm) indicative of ROM	Pretest, Posttest
	Cognitive performance	Mental calculation	Number of correct calculations	Pretest, Posttest
Neurophysiological	Sympathetic activity	Electrodermal activity	Skin conductance	Pretest, During the intervention, Posttest
	Sympathovagal balance	Electrocardiogram	RMSSD, LF/HF ratio	Pretest, During the intervention, Posttest

245

246 Table 2. Outcome variables of the study.

247

248

249

250 3) Statistical analysis

251 We used R ⁵⁷ and the package *blockrand* ⁵² to allocate participants' to one of the two
252 experimental conditions order (i.e., ROBOTIC MESSAGE FIRST or MANUAL MESSAGE FIRST).
253 *blockrand* allows block randomization with random block size selection, which controls for
254 randomization bias ¹⁹. We used *a posteriori* power ($p_{1-\beta}$) calculations using the *pwr* package for
255 statistically significant main and interaction effects ¹⁴. The dependent variables were analyzed
256 using and the package *nlme* ⁴⁶. We built random-coefficient regression models with by-subjects
257 random intercepts, using the fixed effects of CONDITION (MANUAL MESSAGE, ROBOTIC
258 MESSAGE) and TEST (PRETEST, POSTTEST), with interaction term. For flexibility tests, the
259 additional fixed effects of TEST TYPE (TOE TOUCH, SIT-AND-REACH) were included in the
260 model. For mental calculation task measure and psychometric measures, we included the fixed
261 effect of TEST (PRETEST, POSTTEST) and VAS DIMENSION (i.e., WELL-BEING, RELAXATION,
262 WARMTH, MUSCLE PAIN, PERCEIVED SIT-AND-REACH TEST, PERCEIVED TOE TOUCH TEST,
263 ANXIETY) or BRUMS/NASA-TLX dimensions (cf. Methods, Section iii, (2), (3)). For the GSR
264 and HRV analysis, we included the fixed effect of TIME (PRETEST, DURING MESSAGE,
265 POSTTEST). Visual inspection of residual plots did not reveal any obvious deviations from
266 homoscedasticity or normality ⁶². The statistical threshold was set up for a type 1 error rate of
267 $\alpha = 5\%$. As measures of partial effect sizes, we reported the proportion of explained variation,
268 i.e., partial coefficients of determination (R_p^2) using the *effectsize* package ⁸. Main and
269 interaction effects were investigated post-hoc using general linear hypotheses testing of planned
270 contrasts from the *multcomp* package ³¹. We applied Holm's sequential corrections to control
271 the false discovery rate ³⁰.

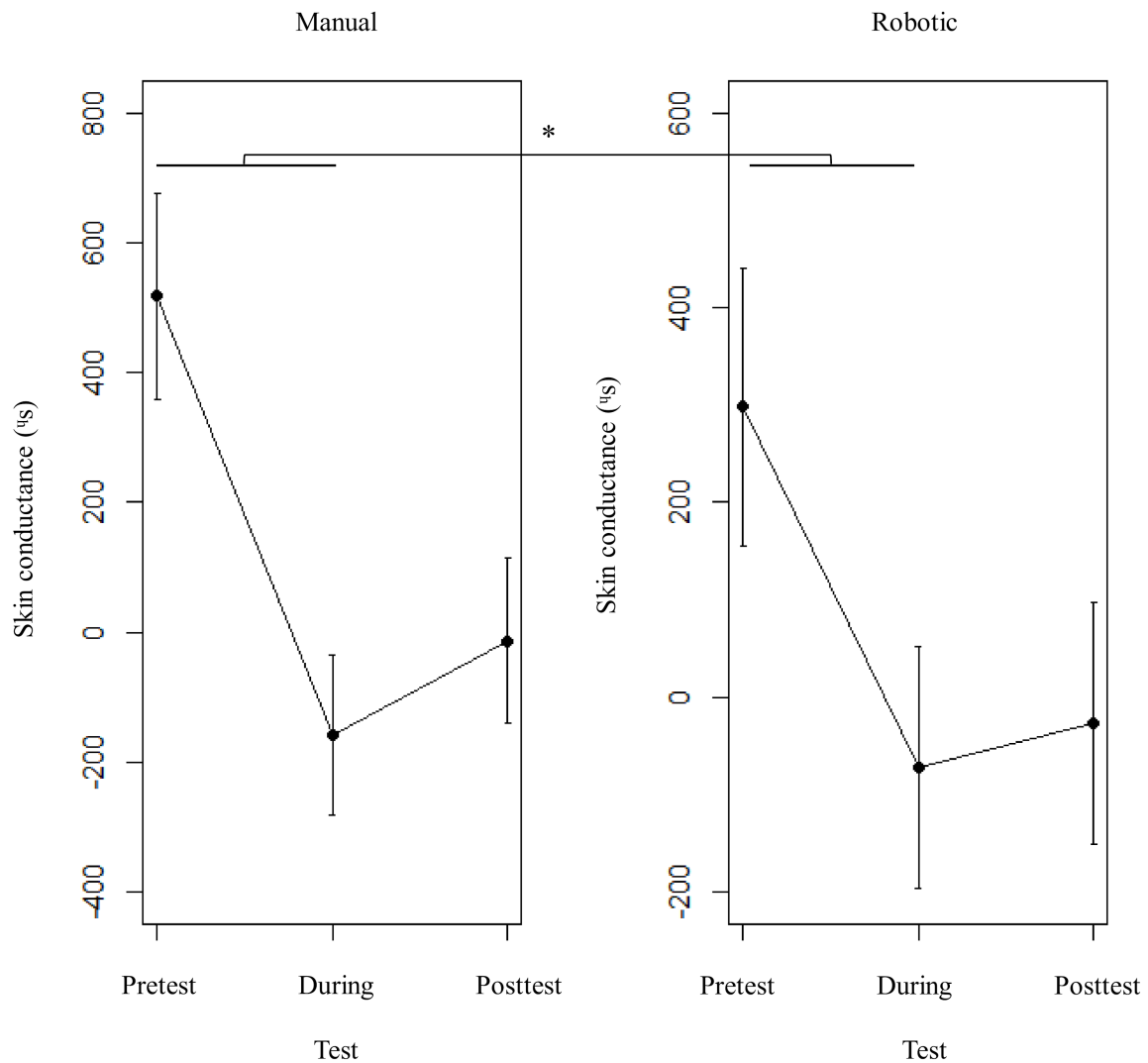
272

273 **4) Results**

274 **a) Neurophysiological data**

275 **i) Skin conductance**

276 The linear mixed effects analysis revealed that the TEST \times CONDITION interaction
277 affected SC_{NORM} ($F(2, 80) = 2.63, p < 0.05, R_p^2 = 0.06, p_{1-\beta} = 0.45$). Post-hoc analyses revealed
278 that the difference in SC_{NORM} BEFORE vs. DURING in the MANUAL MASSAGE condition (BEFORE:
279 517.40 %, 95% CI [358.88, 675.93]; DURING: -159.01 %, 95% CI [-282.44, 35.58]) was greater
280 than that recorded in the ROBOTIC MASSAGE condition (BEFORE: 298.00, 95% CI [155.93,
281 440.07]; DURING: -72.17%, 95% CI [-195.61, 51.27]) ($p < 0.05$). There was also a main effect
282 of TEST for the SC_{NORM} ($F(2, 80) = 31.46, p < 0.001, R_p^2 = 0.44, p_{1-\beta} = 0.45$). Post-hoc analyses
283 revealed a decrease from BEFORE (403.56%, 95% CI [294.65,512.48]) to DURING recording
284 part (-113.95%, 95% CI [-204.87, -23.03]) ($p < 0.001$) and increase from DURING (-113.95%,
285 95% CI [-204.87, -23.03]) to FINAL recording part (-19.94%, 95% CI [-111.84, 71.96]) ($p <$
286 0.001)) (Figure 2).



287

288 **Figure 2.** Fitted values revealed by the linear mixed effects analysis for the
 289 TEST*CONDITION interaction on skin conductance, represented with their 95% confidence
 290 intervals (error bars). * $p < 0.05$.

291 **ii) Heart rate variability**

292 We found no CONDITION \times TEST interaction effect on RMSSD and LF/HF ratio
 293 measures (all $p > 0.05$). There was no main effect of TEST and CONDITION for RMSSD data
 294 ($p > 0.05$). However, there was a main effect of TEST for the LF/HF ratio ($F(2, 87) = 4.40, p <$
 295 $0.05, R_p^2 = 0.09, p_{1-\beta} = 0.56$). Post-hoc analyses revealed a LF/HF ratio increase from the
 296 PRETEST (0.59, 95% CI [0.39, 0.78]) to the POSTTEST (0.86, 95% CI [0.66, 1.05]) ($p < 0.01$).

297 **b) Motor and cognitive performances**

298 **i) Flexibility data**

299 No main or interaction effects emerged for the linear mixed effects analysis of
300 performance on the SRT and TT tests (i.e. all $p > 0.05$). This indicate an absence of influence
301 of CONDITION, TEST TYPE and TEST factors accounted for in the model.

302 **ii) Mental calculation**

303 We found no CONDITION by TEST interaction effect on total scores ($p > 0.05$).
304 However, total scores were affected by the main effect of TEST ($F(1,57) = 12.37$, $p < 0.001$,
305 $R_p^2 = 0.18$, $p_{1-\beta} = 0.19$). Post-hoc analyses revealed that the total scores were reduced from the
306 PRETEST (23.43, 95% CI [18.73, 28.12]) to the POSTTEST (26.45, 95% CI [21.76, 31.14]) ($p <$
307 0.001).

308 **c) Participant's self-report ratings**

Subjective self-reports on VAS scales							
	Numerator degrees of freedom	Denominator Degrees of freedom	F-value	p-value	R _p ²	p _{1-β}	
TEST	1	512	45.67	<.0001	0.08	> 0.99	
CONDITION	1	512	3.41	0.06	0.01	0.65	
VAS DIMENSION	6	512	0	1	> 0.001		
TEST:CONDITION	1	512	4.07	0.04	0.01	0.64	
BRUMS questionnaire							
	Num. degrees of freedom	Den. Degrees of freedom	F-value	p-value	R _p ²	p _{1-β}	
TEST	1	448	17.22	<.0001	0.04	0.98	
BRUMS DIMENSION	5	448	119.96	<.0001	0.57	> 0.99	
TEST:BRUMS DIMENSION	5	448	3.09	< 0.01	0.03	0.82	
NASA-TLX questionnaire							
	Num. degrees of freedom	Den. Degrees of freedom	F-value	p-value	R _p ²	p _{1-β}	
TEST	1	451	18.33	<.0001	0.04	0.98	
CONDITION	1	451	0.01	0.94	< 0.001		
NASA-TLX DIMENSION	5	451	20.89	<.0001	0.19	> 0.99	
TEST_NASA:COND_NASA	1	451	3.71	0.05	< 0.01	0.56	

309

310 Table 3. ANOVA tables of the variation within the linear mixed effects models calculated for the subjective measures of participants' sensations

311 on the VAS scales, BRUMS and NASA-TLX ratings.

312

313 **i) Subjective sensations**

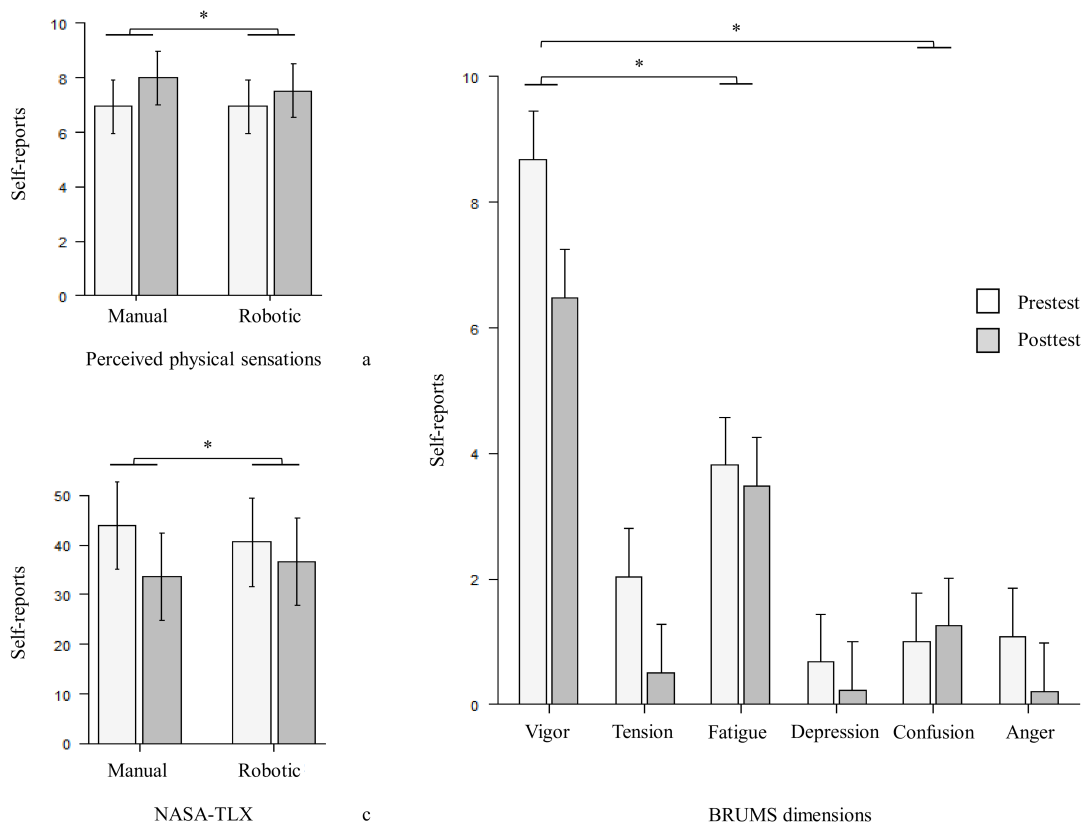
314 The TEST × CONDITION interaction influenced VAS scores (Table 3). Post-hoc
315 analyses revealed that the PRETEST vs. POSTTEST difference in the MANUAL MASSAGE condition
316 (PRETEST: 6.94, 95% CI [5.95, 7.92]; POSTTEST: 7.99, 95% CI [7.01, 8.98]) was greater than
317 that recorded under the ROBOTIC MASSAGE condition (PRETEST: 6.95, 95% CI [5.97, 7.94];
318 POSTTEST: 7.52, 95% CI [6.54 to 8.51]) ($p < 0.05$). The main effect of TEST reported in Table
319 2 corresponded to an increase in VAS scores from the PRETEST (6.95, 95% CI [5.98, 7.92]) to
320 the POSTTEST (7.76, 95% CI [6.79, 8.73]) ($p < 0.001$, Figure 3a).

321 **ii) Mood profile**

322 The TEST × BRUMS DIMENSION interaction affected BRUMS ratings (Table 3). The
323 difference in perceived VIGOR between the PRETEST and the POSTTEST (PRETEST: 8.68, 95% CI
324 [7.92, 9.44]; POSTTEST: 6.49, 95% CI [5.72, 7.25]) was greater than the corresponding
325 difference for CONFUSION (PRETEST: 1.01, 95% CI [0.25, 1.77]; POSTTEST: 1.26, 95% CI [0.50,
326 2.02]) ($p < 0.01$) and FATIGUE (PRETEST: 3.81, 95% [CI 3.05, 4.57]; POSTTEST: 3.49, 95% CI
327 [2.72, 4.25]) ($p < 0.05$) (Figure 3b).

328 **iii) Mental and physical workload**

329 The TEST × CONDITION interaction affected the NASA-TLX scores (Table 3). Post-
330 hoc analyses revealed that the difference in PRETEST vs. POSTTEST scores under the MANUAL
331 MASSAGE condition (PRETEST: 43.87, 95% CI [52.71, 35.03]; POSTTEST: 33.66, 95% CI [42.50,
332 24.82]) was greater than that recorded during the ROBOTIC MASSAGE condition (PRETEST: 40.58,
333 95% CI [49.42, 31.74]; POSTTEST: 36.71, 95% CI [45.54, 27.87]) ($p < 0.05$) (Figure 3c). A main
334 effect of NASA-TLX DIMENSION was also present (Table 2), due to reduced PHYSICAL
335 DIFFICULTY scores compared to the other NASA-TLX dimensions (all $p < 0.05$)



336

337 **Figure 3. a.** Barplot of the TEST*CONDITION interaction effects obtained for

338 subjective scores. **b.** Barplot of the TEST*DIMENSION interaction effects obtained for mood

339 profile. Average fitted values by the linear mixed-effects analysis are presented with 95%

340 confidence intervals (dotted bars). * $p < 0,05$. **C.** Barplot of the TEST*CONDITION interaction

341 effects obtained for mental and physical workload.

342 **d) Physiotherapist self-report**

VAS self-reports of perceived fatigue and tension					
	Degrees of freedom	F-value	p-value	R _p ²	p _{1-β}
TEST	1	18.25	> 0.001	0.22	0.96
VAS DIMENSION	1	1.12	0.29	0.02	
DAY	1	131.61	> 0.001	0.67	> 0.99
ORDER	1	156	> 0.001	0.71	> 0.99
TEST:VAS DIMENSION	1	0	0.97	> 0.001	
DAY:ORDER	1	9.21	> 0.01	0.12	0.79
Residuals	65				
VAS self-reports of perceived massage pressure, amplitude and frequency					
	Degrees of freedom	F-value	p-value	R _p ²	p _{1-β}
VAS DIMENSION	2	0.67	0.52	0.03	
DAY	1	27.54	> 0.001	0.38	0.98
ORDER	1	15.98	> 0.001	0.27	0.93
DAY:VAS DIMENSION	2	0.25	0.78	0.01	
ORDER:VAS DIMENSION	2	0.25	0.78	0.01	
DAY:ORDER	1	1.3	0.26	0.03	
Residuals	44				
VAS self-reports of perceived massage efficiency					
	Degrees of freedom	F-value	p-value	R _p ²	p _{1-β}
DAY	1	7.71	0.01	0.36	0.61
ORDER	1	2.25	0.16	0.14	
DAY:ORDER	1	0.29	0.6	0.02	
Residuals	14				

343

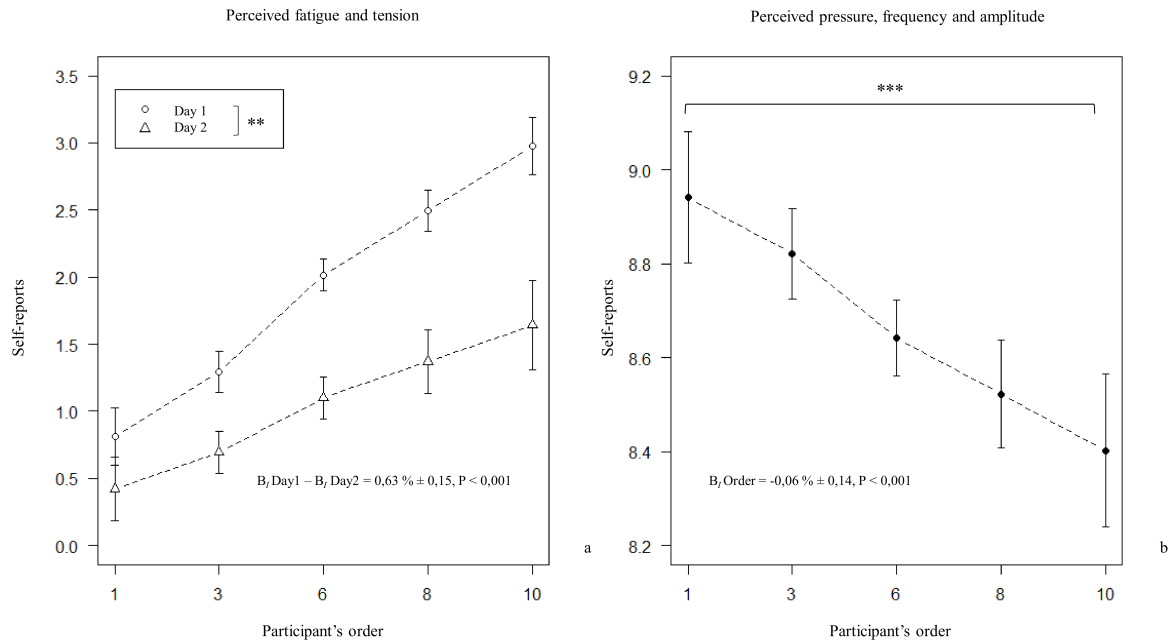
344 Table 4. ANOVA tables obtained from the linear regression models of the physiotherapist's subjective reports on VAS scales.

345 **i) Fatigue and tension self-reports**

346 The ORDER \times DAY interaction affected physiotherapist's self-reports of FATIGUE and
347 TENSION on the VAS (Table 4). Post-hoc analyses revealed that the increase in FATIGUE and
348 TENSION across participant observed during FIRST DAY (+0.24, 95% CI [0.20, 0.28]) was greater
349 than that recorded in the SECOND DAY (+0.13, 95% CI [0.08, 0.19]) (+0.11, 95% CI [0.17, 0.05],
350 $p < 0.01$). TEST and ORDER also affected physiotherapists' VAS ratings (Table 4). PRETEST
351 self-reports were higher than POSTTEST self-reports (PRETEST: 1.24, 95% CI [1.11, 1.36];
352 POSTTEST: 1.61, 95% CI [1.49, 1.73]) ($p < 0.001$). Self-report ratings of fatigue and tension
353 increased along with the number of massaged participants (+0.19, 95% CI [0.16, 0.23], $p <$
354 0.001). Further, the physiotherapist experienced greater fatigue and tension during the FIRST
355 compared to the SECOND day (FIRST: 1.77, 95% CI [1.67, 1.90]; SECOND: 0.97, 95% CI [0.84,
356 1.10]) (Figure 4a).

357 **ii) Massage parameters**

358 Two-way and three-way interactions did not affect self-reports of perceived massage
359 pressure, amplitude and frequency (all $p > 0.05$). However, there was a main ORDER effect
360 (Table 2), corresponding to a decrease in perceived massage pressure, frequency and amplitude
361 along with the number of massaged participants (-0.06, 95% CI [-0.08, -0.02], $p < 0.001$). There
362 was also a main effect of DAY (Table 2), indicating reduced perceived pressure, frequency and
363 amplitude during FIRST (8.54, 95% CI [8.44, 8.64]) compared to the SECOND day (8.90, 95% CI
364 [8.78, 9.01]) ($p < 0.001$) (Figure 4b).



365

366 **Figure 4. a.** Plot display illustrating the ORDER by DAY interaction of massages on
 367 physiotherapists' fatigue and tension, represented with 95% confidence intervals (error bars).

368 **b.** Plot display the main ORDER effect of massages on physiotherapists' pressure,
 369 frequency and amplitude, represented with 95% confidence intervals (error bars). *** $p < 0,001$.

370 ** $p < 0,01$.

371 **iii) Self-reports of perceived efficiency**

372 The ORDER by DAY interaction effect did not affect the physiotherapist's perceived
 373 massage efficiency ($p > 0.05$, Table 2). However, there was a main effect of DAY. Post-hoc
 374 analyses also revealed that EFFICIENCY reports during the SECOND day (8.96, 95% CI [8.67,
 375 9.24]) were higher compared to the FIRST (8.53, 95% CI [8.29, 8.79]).

376

377 **5) Discussion**

378 The primary aim of this study was to investigate the efficacy of RM compared to MM
 379 administered by a trained physiotherapist on psychometric, behavioral and neurophysiological

380 measures of performance and well-being. RM and MM both improved the psychophysiological
381 state of relaxation, with comparable effects on sympathetic activity and sympathovagal balance.
382 This suggests overlapping neurophysiological mechanisms between the two types of
383 interventions. In the framework laid down by Lehrer et al. ³⁷, RM and MM belong to the
384 category of “autonomically oriented” relaxation methods where the relaxation state is elicited
385 through bottom-up regulations. This is contrary to “cognitively oriented” relaxation
386 interventions where the relax is mediated by top-down processes, e.g. autogenic relaxation
387 ^{10,37,40}. During both RM and MM, mechanical pressures exerted by the hand of a physiotherapist
388 or the robot’s prosthesis on the soft tissues stimulate interstitial receptors type III, IV, and
389 Ruffini corpuscles. This prompt downregulations of muscle tone ^{7,33}. RM and MM
390 interventions, however, differ in terms motor control strategies involved for the passaged
391 participants ³³. During MM, the user remains passive and motionless, which emphasizes
392 retroactive modes of motor control and puts a specific emphasis on parietal networks mediating
393 the sensory integration of peripheral feedback ^{33,34}. On the contrary, during RM users were able
394 to control the pressure applied by the robot proactively using a remote. RM thus reproduced
395 some of the proactive component of a self-massage routine with a foam roller or a roller
396 massager ³³⁻³⁵. Contrary to our hypothesis, this did improve physical and cognitive performance
397 compared to the MM interventions. Both interventions downregulated physiological arousal, as
398 attested by decreased skin conductance and increased LF/HF. Although the relevance of the
399 LF/HF ratio to index sympathovagal balance remains debated ⁹, this is typically indicative of a
400 shift from sympathetic to parasympathetic dominance that characterizes relaxation states ^{45,58}.

401 Importantly, the MM interventions resulted in additional benefits compared to RM, for
402 several outcome variables. First, the skin conductance decrease during the massage intervention
403 was more pronounced during MM compared to RM. Likewise, improvements in mood and
404 perceived mental/physical workload were created after MM compared to RM for well-being,

405 relaxation, warmth, muscle pain and anxiety. While we found no flexibility improvements from
406 the SRT and TT measures after both MM and RM, the perceived efficacy during both tests was,
407 again, greater after MM. This contradicts past results supporting increased flexibility after
408 massage interventions^{18,34,60}. Despite our standardization precautions, the time delay between
409 the end of the massage interventions and the posttest could have mitigated the effects of the
410 intervention²⁰. Possibly, participants' lack of familiarity with human-robots interactions and
411 robotic solutions could have been a source of anxiety hindering its effects on relaxation^{42,43,51},
412 hence accounting for the additional benefits of MM compared to RM. Mental states of robot
413 users should be investigated to control for internal factors susceptible to confound the results
414 of RM interventions, e.g. increased apprehension, anxiety and negatives attitudes towards the
415 robot^{42,43,51}. The Robot Anxiety Scale^{42,43}, for instance, provides standardized measurements
416 of psychological dimensions of specific interest for RM interventions, e.g. “*Anxiety toward*
417 *Behavioral Characteristics of Robots*”. Implementing these measures may be critical in the
418 future to control for their influence on the outcome variables of RM interventions. Contrary to
419 flexibility measures, performances on the mental calculation task improved from the pretest to
420 the posttest after both MM and RM. Due to the lack of a no-intervention control condition, we
421 cannot establish that MM and RM improved cognitive performances. Progress could reflect
422 sheer task habituation. Nevertheless, the RM interventions was not associated with adverse
423 effects for any of the dependent variables, which represents an important finding due to the
424 novelty of human-robot interactions in massage practice.

425 The physiotherapist reported reduced perceived MM efficacy over the course of the
426 design. He also reported reduced amplitude, pressure and frequency of massage gestures. This
427 was particularly at the onset of the experiment, where baseline fatigability was absent. The
428 physiotherapist also reported increased fatigue and tension along with the repetition of massage
429 interventions. Here, the repeated MM interventions reproduced the conditions of a working

430 environment. It is well-established that MM requires repetitive and intense gestures from the
431 physiotherapist ³³, as well as exposure to uncomfortable postures and manipulations ³³. It is
432 therefore plausible that the fatigability elicited by the repetition of MM interventions produced
433 counterproductive changes in massage quality. The robot, however, is not susceptible to
434 fatigability. This enables the repetition of massage gestures without risk of reduced massage
435 quality. RM solutions thus represent an exciting tool to assist physiotherapists in the
436 management of their daily workload. Indeed, for the most simple, repetitive and reproducible
437 routines, administering a RM solution presents many advantages ³³. In addition to its
438 prophylaxis benefits, the physiotherapist's time could be invested in more complex and
439 demanding manipulations that cannot be effectively performed by a robot. This also applies to
440 sports. For instance, implementing RM recovery routines could incentivize optimal allocation
441 of human resources to the most critical aspects of athletes' recovery.

442 As with the majority of studies, the design of the current work is subjected to limitations,
443 specifically a small sample size and the absence of a non-intervention group. While present
444 findings provide valuable insights, both the generalization and reliability of the results may first
445 be limited due to the small number of participants included in the experimental design, hence
446 preventing from drawing firm conclusions. The present study should therefore be considered a
447 preliminary study awaiting further research with larger sample sizes to confirm and extend the
448 robustness of these results. Future research dealing with this issue should also ideally include a
449 non-intervention group to control for potential learning effects on motor and cognitive
450 performance.

451

452 **6) Conclusion**

453 This prospective investigation compared RM and MM interventions. RM reproduced
454 with reduced magnitude some of the benefits of the MM interventions ³⁶, although MM
455 remained the most efficient intervention to promote a psychophysiological state of relaxation.
456 MM intervention yielded greater results pattern regarding parasympathetic activity, while both
457 interventions had comparable effects on cognitive performances, mood profile and flexibility.
458 Nonetheless, participants reported a lower mental and physical workload in the MM condition.
459 Also, due to the massages repetition, the physiotherapist was subjected to fatigability. RM
460 appears to be a promising alternative for practitioners to alleviate part of the workload in the
461 context of currently limited paramedical resources.

462

463 [TABLE CAPTION AND FIGURES 2, 3, & 4 ONLINE ONLY]

464 **7) Declarations**

465 Ethics approval and consent to participate

466 The study was approved by the Committees of Protection of Persons Ouest 6. All
467 participants provide informed consent prior to study enrolment.

468 Availability of data and materials

469 The datasets used and/or analysed during the current study are available from the
470 corresponding author on reasonable request.

471 Competing interests

472 The authors declare they have no competing interests.

473 Author contributions

474 YK, FDR, AG and CE conceptualized the study. YK completed the data curation, while
475 YK and FDR conducted the formal analysis. AG, YK and CE performed the funding
476 acquisition. YK completed the investigations. AG, FDR and CE were involved in the project
477 administration, while AG and FDR performed the supervision. YK wrote the original draft,
478 while FDR, AG and CE achieved the review and editing.

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483

Characteristics	Age (years)	Height (m)	Mass (kg)	BMI (kg/m²)
Male (<i>n</i> = 10, 48%)	33.2 ± 6.4 (range 24-45)	1.76 ± 8.8 (range 1.68-1.93)	77.4 ± 7.2 (range 69-92)	24.9 ± 1.00 (range 23.2-26.6)
Female (<i>n</i> = 11, 52%)	30.8 ± 9.9 (range 20-54)	1.64 ± 5.2 (range 1.55-1.75)	61.1 ± 10.7 (range 46-89)	22.7 ± 2.6 (range 19.1-29.1)
Group differences (1-way ANOVA)	F(1, 19) = 0.38, <i>p</i> = 0.054	F(1, 19) = 14.93, <i>p</i> < 0.01	F(1, 19) = 14.96, <i>p</i> < 0.01	F(1, 19) = 5.8, <i>p</i> < 0.05

485

Table 1. Participants' characteristics (M ± SD).

486

There were no adverse events and no subjects withdrew during data collection. Statistical analysis of the descriptive data revealed no

487

significant differences between the two groups for age, height, body mass, and BMI (all *p* > 0.05). BMI: Body Mass Index.

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