



HAL
open science

Development of EMG-based criteria to evaluate the difficulty of realization of sign language: A potential contribution for understanding the negative hand paintings

Laurent Vigouroux, Ricardo Etxepare, Hugo Lepine, Benjamin Goislard de Monsabert, Aritz Irurtzun

► To cite this version:

Laurent Vigouroux, Ricardo Etxepare, Hugo Lepine, Benjamin Goislard de Monsabert, Aritz Irurtzun. Development of EMG-based criteria to evaluate the difficulty of realization of sign language: A potential contribution for understanding the negative hand paintings. *Journal of Electromyography and Kinesiology*, 2024, 79, pp.102943. 10.1016/j.jelekin.2024.102943 . hal-04857109

HAL Id: hal-04857109

<https://cnrs.hal.science/hal-04857109v1>

Submitted on 7 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **DEVELOPMENT OF EMG-BASED CRITERIA TO EVALUATE THE DIFFICULTY**
2 **OF REALIZATION OF SIGN LANGUAGE: A POTENTIAL CONTRIBUTION FOR**
3 **UNDERSTANDING THE NEGATIVE HAND PAINTINGS**

4

5 Laurent **VIGOUROUX**^{1*}, Ricardo **ETXEPARE**², Hugo **LEPINE**¹, Benjamin
6 **GOISLARD de MONSABERT**¹, Aritz **IRURTZUN**²

7 ¹ Aix-Marseille Univ, ISM, CNRS, Marseille, France

8 ²CNRS, IKER UMR 5478, Aquitaine, France

9

10 ***Correspondence: laurent Vigouroux**

11 Institute of Movement Sciences

12 163 av de Luminy, CP910

13 13288 Marseille, cedex 09

14 laurent.vigouroux@univ-amu.fr

15 date of submission : 15th July 2024

16

17 **running head: “EMG-based criterion to evaluate sign language difficulties”**

18

19 **ABSTRACT**

20 The sign language uses a combination of complex finger and wrist configurations. The
21 frequency of use of a particular sign is highly dependent on its physiological difficulty.
22 However, no method allows to quantify accurately this difficulty. In the context of paleolithic
23 negative hand paintings this absence of methods is problematic since the hand signs which are
24 painted may be related to a primitive hand sign language. The objective of this study was to
25 develop and validate a method based on electromyography recordings for quantifying sign
26 language difficulty. Electromyography of the six main hand muscles were recorded and
27 analyzed to determine individual muscle activity, summed muscle activity and muscle
28 coactivation. Those results were correlated to subjective scales of difficulties to determine the
29 electromyographic variables and/or the combinations of them which are good candidates for
30 determining hand sign difficulties. Among all variables the summed muscle activities and the
31 thumb muscle coactivation presented the most promising criterion. On the top of that, those
32 criterion presented encouraging correlation with the frequency of occurrence of ten hand
33 paintings of the Gargas Cave which open further studies for analyzing the origin of negative
34 hand paintings.

35

36

37 INTRODUCTION

38 Negative hands are one of the most predominant images of paleolithic era art with for
39 example 619 images identified in Europe [Groenen, 2016]. Some negative hands sites exhibit
40 what has been called “mutilated fingers hands”. The traditional hypotheses are that those
41 “mutilated” hands either correspond to ritual mutilations, chilblains’ effects, or other
42 pathologies [Mc Cauley et al., 2018]. However, [Etxepare and Irurtzun, 2021] suggested an
43 alternative hypothesis, further called “negative hand writing” stating that the mutilated
44 images have a linguistic meaning. In this interpretation, the artist would deliberately project
45 hand configurations to represent a structured code similar to sign language. This hypothesis
46 would therefore mean that those negative hands represent the earliest form of writing, existing
47 almost 25.000 years prior to the invention of cuneiform in Babylon [Van de Mieroop, 2005].

48 Numerous scientific studies related to language and writing showed that the frequency of
49 appearance of a sign decreases when the cost to perform it increases [Mertz et al. 2022]. To
50 validate the “negative hand writing” hypothesis, the functional constraints imposed by this
51 hypothetical sign language should thus be evaluated and put in regard to the frequency of
52 occurrence. Ann [1993, 1996] proposed a method to describe the finger anatomical coupling in
53 sign language with the *Ease of Articulation Score* (EAS). EAS attributes a note from 0 to 4
54 depending on the execution difficulty of a given sign (from 0: articulable to 4: non
55 articulable). [Etxepare and Irurtzun, 2021] used EAS to classify negative hand paintings
56 which contributed to argue in favor of the negative hand writing hypothesis. These works
57 allow for a first approach in classifying hand signs but the limited 5-grade scale of EAS only
58 based on visual observation does not allow for a precise understanding of biomechanical cost:
59 the sign is either articulable or not and the reason behind this state remains unclear.

60 Nevertheless, the functional constraints associated to multi-finger movement such as sign
61 language are complex [Liang et al., 2021] and this complexity is mainly associated to finger

62 interdependency [Shieber 1999; Schieber and Santello 2004]. Interdependency can be defined
63 as the tendency of one finger to move concomitantly with the neighbor fingers. When a sign
64 language needs to dissociate the position of two fingers (e.g.: one finger is flexed while the
65 neighbor finger is extended) this generates difficulties that can be associated to two
66 predominant factors. The first is the neural control of fingers and the muscle coordination as
67 fingers share common neurons in the motor cortex [Schieber and Hibbard, 1993] and since
68 flexing one articulation while another is executing an extension is harder than flexing both
69 articulation at the same time [Kelso et al. 1981]. The second factor is associated to the
70 mechanical constraints due to the anatomical finger interdependency [Shieber et al., 2001;
71 Van den Noort et al., 2016]. For example, anatomical characteristics limit mechanically the
72 finger interdependency such as tendon interconnection or the flexibilities of
73 metacarpophalangeal joints (e.g. when one is fully flexed while the neighbor finger is fully
74 extended). To counteract these mechanical constraints, muscles must generate a given
75 intensity of force [Gracia-Ibanez et al., 2016] which represents a second level of difficulties
76 associated to a physiological cost. To this day the overall biomechanical cost, which includes
77 the neural and the physiological aspects, associated to the execution of hand sign remains
78 poorly understood. It is therefore essential to develop a methodology based on objective
79 measurements to assess those parameters to further understand how it can correlate with the
80 frequency of use within a whole language.

81 In human movement studies, the level of difficulty of a given movement can be achieved by
82 subjective evaluations and/or objective physiological measurements [Borg, 1982]. Subjective
83 evaluation of effort consists in asking the feeling of perceived effort and placing it on a scale
84 ranging from a level 0 (no perceived effort) to 10 (maximal perceived effort). Such subjective
85 scales are highly correlated to physiological measurements in aerobic sports for example
86 [Chen et al., 2002; Sherr et al., 2013]. Nevertheless, such approach relies on the participant's

87 subjective interpretation of the task or exercise difficulty which is interesting to punctually
88 evaluate difficulties and classify a few numbers of signs but would be insufficient to overall
89 conclude on the negative hand writing hypothesis given the number of signs that have to be
90 evaluated. Concerning the objective physiological measurements, among the overall potential
91 methods available in biomechanics and physiology, the electromyography (EMG) appears
92 particularly adapted for sign language. EMG allows to quantify muscle involvement in a task
93 either through the level of muscle activation [Chao et al., 1989] or the level of co-activation
94 [Olney and Winter 1985]. For the hand, the usual recorded muscles are the main flexors and
95 extensors of fingers and wrist [Vigouroux et al., 2015] as well as the thumb because they are
96 representative of the main muscle groups and they are accessible with surface EMG. EMG
97 measurements thus have the potential to be an objective physiological measure able to
98 evaluate and differentiate the difficulties of each sign from others. Nevertheless, as many
99 variables could be calculated from the combination of multiple EMG, such approach method
100 should be first tested to select the right muscles and the adapted variables that should be
101 analyzed to represent the sign difficulty.

102 Consequently, the main objective of this study was to propose EMG-based criteria to assess
103 hand sign difficulty. The second objective was to primarily evaluate the potential correlation
104 of such criteria with signs occurrence frequency by using the signs appearing in a selected
105 site: Gargas [Leroi-Gourhan, 1967]. Ten hand signs chosen among the painting of negative
106 hands observed in cave of Gargas were tested. To develop the EMG-based criteria, EMG
107 signals of 6 main muscle groups of the hand were recorded. Signals were analyzed to evaluate
108 the muscle activity of each muscle and the muscle coactivation. From those recordings we
109 determine the criteria which represent at best the sign difficulty by first identifying the EMG
110 variables significantly modified according to the signs and then by testing how each of them
111 and/or combination of them correlated with subjective scales of sign difficulty. Our first

112 hypothesis is that EMG variables are significantly affected by hand sign. Our second
113 hypothesis is that at least one EMG variable or one combination of EMG variables are
114 correlated with subjective scales which would demonstrate the feasibility of using EMG-
115 based criteria for evaluating the difficulty of sign language. Our third hypothesis is that the
116 elaborated EMG-based criteria provide a better explanation for Gargas hand sign occurrence
117 than previously obtained with EAS method.

118

119

120

121 MATERIAL & METHODS

122 *Participants*











123 Eight female non-signers (age = 24.0 ± 2.5 , weight = 60.7 ± 4.9 kg, forearm length = $24.3 \pm$
124 1.5 cm, hand height = 17.1 ± 1.0 cm, hand width = 7.5 ± 0.5 cm) and eight male non-signers
125 (age = 26.7 ± 4.4 , weight = 77.8 ± 9.7 kg, forearm length = 27.0 ± 1.7 cm, hand height = 19.1
126 ± 0.9 cm, hand width = 8.8 ± 0.4 cm) were recruited. All participants reported no traumas to
127 right upper limb extremity. All volunteers did not present an expert level in manual activities
128 which required either a high level of dexterity, phalanx independence or finger force (e.g.
129 rock-climbers, musicians, or craftsmen). Prior to the experiments, volunteers were informed
130 about the testing procedure and signed an informed consent according to the university
131 guideline that was approved by ethics committee of CERSTAPS (*Comité d'Ethique pour la*
132 *Recherche en Sciences et Techniques des Activités Physiques et Sportives*) IRB00012476-
133 2022-24-06-192.

134 *Tested hand signs*

135 The participants were asked to perform static hand sign tasks consisting in maintaining
136 specific wrist and finger postures with no external forces. Ten hand signs were tested in total
137 (Table 1), including a control posture (five fingers extended with joint articulation close to
138 neutral position). For the nine other signs, one or more fingers were flexed. At this step of
139 knowledge, we chose to work on a subset of the observed negative hand paintings to develop
140 and validate our method rather than working on the overall repertoire of observed negative
141 hand paintings. This subset of ten hand postures were selected to be representative of five
142 hand sign families, depending on the number of flexed fingers (Table 1). The choice also
143 ensured to cover a large rank of difficulties according to the EAS classification.

144

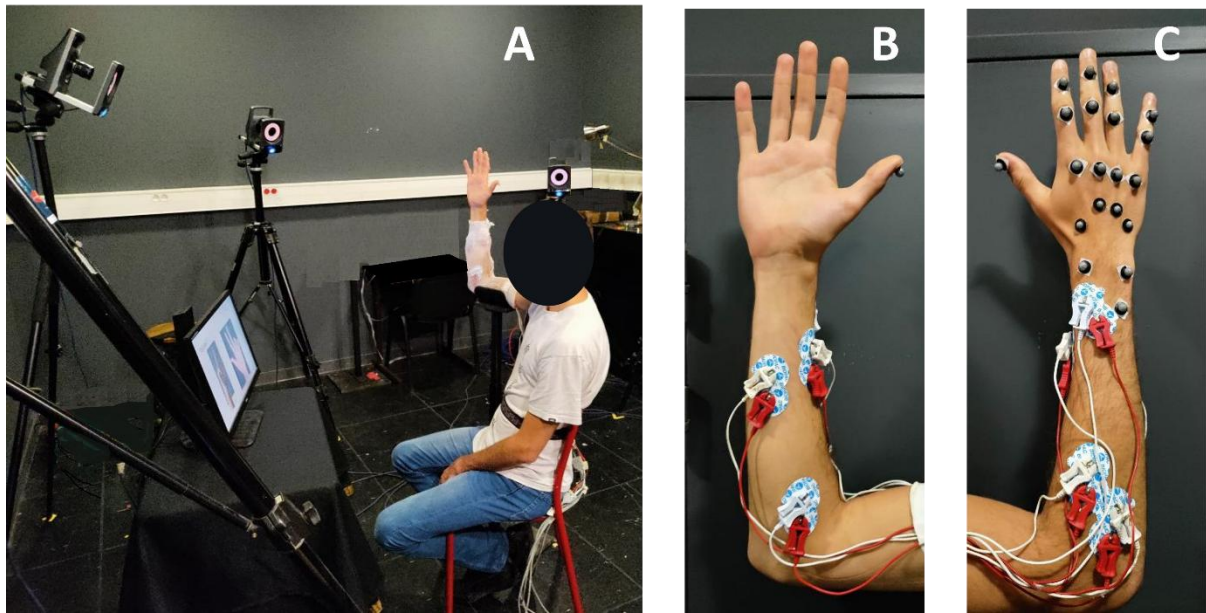
145 *Table 1: Hand signs tested in the current study and the associated name attributed to each.*
 146 *The name of each signs indicated the number of flexed fingers (F) and which finger is flexed*
 147 *(I: index finger; M: Middle finger; R: ring finger; L: little finger). Signs were chosen among*
 148 *all those appearing in the Gargas cave by both selecting a panel going from 1 to 4 involved*
 149 *fingers and ensuring a large range of identified difficulties based on EAS scores. Gargas*
 150 *frequency of occurrence are noted in brackets.*

Tested hand signs				
0 finger involved	1 finger involved	2 fingers involved	3 fingers involved	4 fingers involved
 0F; control (12)	 1F-I (3)	 2F-IM (1)	 3F-IMR (4)	 4F-IMRL (44)
	 1F-R (0)	 2F-MR (2)	 3F-MRL (5)	
	 1F-L (1)	 2F-RL (7)		

151
 152 The participants were seated and placed their right upper limb in a support device (Figure 1).
 153 The device held the arm while leaving the volunteers' elbow, forearm, and wrist constraint-
 154 free. The device could be adjusted in height and position to match participants' anthropometry
 155 and ensure a same upper limb posture. This posture was such that the hand palm was aligned
 156 with the thorax frontal plane, facing anteriorly and the fingers pointing upwardly. This

157 configuration required to place the shoulder was at 90° in flexion, and as close as 45° in
158 abduction, the elbow close to 90° in of flexion, the forearm in neutral pronation and the wrist
159 at 0° of both flexion-extension (F-E) and radial-ulnar deviation.

160



161

162 *Figure 1: Pictures of the experimental setup. A: participants seated with the right arm in the*
163 *support device. The participant looks at the screen where the tested sign is presented. B and*
164 *C: pictures of the marker placements and EMG electrode positionings.*

165

166 Volunteers were then instructed to perform one of the ten hand signs by reproducing a posture
167 illustrated by three images, one in the dorsal view, one in the palmar-radial view and another
168 on in the palmar-ulnar view. Signs were performed randomly, except the 0F which was
169 always executing first. The sign was held for a short duration (10s). At the end of each trial, a
170 break of 1mn was instructed, or more depending on the subject's feedback. After the fourth
171 posture, a longer break of 5mn was set to minimize any muscle fatigue effect. During the

172 breaks, the volunteers were asked to remove their arm from the support device and rest at
173 their convenience.

174 *Kinematic acquisition and processing*

175 For each sign, the experimenter visually checked the correct realization of the sign. To
176 provide an objective validation, the hand kinematics was recorded to post-check the postures.
177 It consisted in determining the joint angles in F-E of each finger and the wrist for a given
178 posture. The proposed kinematic recordings protocol is an adaptation of [Goislard De
179 Monsabert *et al.* 2012] and detailed in supplementary material. The calculated joint angles
180 showed that all analyzed trials were performed in agreement with the asked sign which means
181 that the corresponding joint were either flexed or extended posture when required.

182 *EMG acquisition and processing*

183 Before performing the signs, the volunteers were first equipped with surface EMG electrodes
184 on the forearm. Three functional blocks of the muscle hand were studied: the muscles acting
185 at the long fingers, those acting at the wrist, and those of the thumb. A pair of flexor-extensor
186 muscles for each block were recorded to assess the overall agonist-antagonist activation. The
187 muscles of the thumb and wrist were studied for their stabilizer role in maintaining the
188 gestures while the pair of long fingers muscles were recorded as principal actuators of the
189 signs. Six muscles were thus recorded in total: *Flexor Digitorum Superficialis* (FDS),
190 *Extensor Digitorum Communis* (EDC), *Flexor Pollicis Longus* (FPL), *Abductor Pollicis*
191 *Longus* (APL), *Flexor Carpi Radialis* (FCR) and *Extensor Carpi Radialis Longus* (ECRL).
192 Positioning of the electrodes was determined with the literature [Vigouroux *et al.*, 2015] and
193 by palpation. Electrode placement was determined with the wrist in neutral position in P-S, as
194 required during the trials. The skin was prepared before placing the electrodes by shaving and
195 cleaning with an alcohol solution. Thirteen electrodes (twelve for the muscles, one for

196 ground) Ag/AgCl (Ø11 mm, 15mm spacing) were used. A visual check of EMG signals
197 during functional movements was performed to confirm the adequate placement of the
198 electrodes.

199 After electrode placement participants were then asked to perform maximum voluntary
200 contraction (MVC) tasks. MVC tasks were performed to record the maximum activation level
201 of the observed muscles. Six MVC tasks were performed, with two trials per task: F-E of the
202 wrist, thumb, and fingers. All the trials were executed randomly as to not introduce muscle
203 fatigue between the tasks. During the trial, the volunteer was encouraged out loud.

204 EMG signals recording was performed using a Biopac MP 150 system (Biopac Systems, Inc.,
205 Santa Barbara, CA, USA) at a sampling rate of 1000 Hz. The muscles observed were
206 superficial muscles involved in the selected gestures.

207 EMG signals were processed to develop a criterion to evaluate the sign difficult. EMG signals
208 were first filtered (butterworth, 4th order, 20-450 Hz cut-off bandwidth). Two types of
209 variables were tested for this criterion: muscular activation, coactivation index.

210 For each of the 6 signal, muscular activation was calculated as the *Root Mean Square* (RMS)
211 over a 750 ms window of the filtered signal expressed as the percentage of MVC (%MVC).
212 %MVC allows to quantify the degree of the involvement for a given muscle (0%
213 corresponding to total rest, and 100% to the highest muscular activity possible). This way, a
214 significantly higher muscle activation indicated a more difficult sign to maintain while a
215 lower percentage indicated a less difficult sign. Individual muscle activation of each muscle
216 was considered. The sum of activation (SumAct) of all 6 muscles was also computed.

217 Then the coactivation index (CI) was defined as a ratio involving both flexor and extensor
218 muscle activations for a given muscle pair (thumb, finger or wrist) and time [Olney and
219 Winter, 1985]:

$$CI(\%) = \frac{2 * activation_{flexor}}{act_{flexor} + act_{extensor}} * 100$$

220 Three CI were computed: one for the finger flexors and extensors couple, one for the thumb
221 flexor and extensor couple and one for the wrist flexor and extensor couple. Coactivation was
222 computed as a function of the activation (%MVC) calculated above. The CI allowed for a
223 more global analysis of muscle effort at the joint level. A CI value of 1 would correspond to
224 maximal co-activation where both muscles are equally involved. A value between 0 and 1
225 would indicate that extensor muscles are more involved than flexor muscles. Finally, a value
226 between 1 and 2 would indicate that flexor muscles are more involved than extensors.

227 *Subjective scales acquisition and processing*

228 To assess the perceived effort associated to each sign, the participants were asked to rate the
229 signs using two subjective scales: one associated to the perception of physiological cost and
230 one to the coordination difficulty (see supplementary material). The participants were asked to
231 manually draw a cross on a scale going from 0 to 10 without graduations to indicate their
232 perceived feeling concerning coordination or cost.

233 Raw coordination level (Coord-R) and physiological cost (Phy-R) ratings were computed by
234 measuring the distance between the left side of the scale (0 score) and the center of the cross
235 and scaled by the actual total length of the bar. Distances were measured in millimeters
236 (resolution = 0.5mm). Then, for each participant, the normalized coordination (Coord-N) and
237 normalized physiological cost (Phy-N) ratings were obtained by normalizing raw ratings by
238 the highest score across all signs [Clin et al., 1992].

239 *Statistical analysis*

240 First, the influence of hand sign on EMG variables (muscle activation, sum of activations and
241 co-activation) and subjective ratings (Coord-N and Phy-N) were tested to verify our first

242 hypothesis. For each EMG variable and subjective rating, residuals normality and
243 homoscedasticity were verified for each condition with a Shapiro-Wilk and Bartlett tests,
244 respectively. If the prerequisites were met, repeated measures ANOVAs were performed to
245 test the influence of hand sign on each computed EMG variables (10 conditions). If not, this
246 influence was evaluated by a non-parametric Friedman test.

247 Correlation tests were then used to verify our second hypothesis and identify which EMG
248 variables or combinations of them were the most suitable to create an EMG-based criterion
249 assessing hand sign difficulty. A Pearson test was thus used to quantify the correlation of
250 individual variables (muscle activations, coactivations) to the Coord-N and Phy-N ratings.
251 The correlations of Coord-N and Phy-N with all unweighted linear combination of EMG
252 variables were also tested to identify either combinations of two, three, four, five and six
253 muscle activations or combinations of two and three coactivations allowing a good prediction
254 of those subjective ratings.

255 Finally, the significantly correlated EMG variables and the results obtained by the identified
256 significant multiple correlation models were used as potential difficulty criteria and their
257 correlation with the ten hand signs occurrence frequency in Gargas was tested. This was done
258 by using the non-parametric Spearman test. These correlations were put in regard to those
259 performed with the AES scale which was previously used by [Etxepare and Irurtzun, 2021].

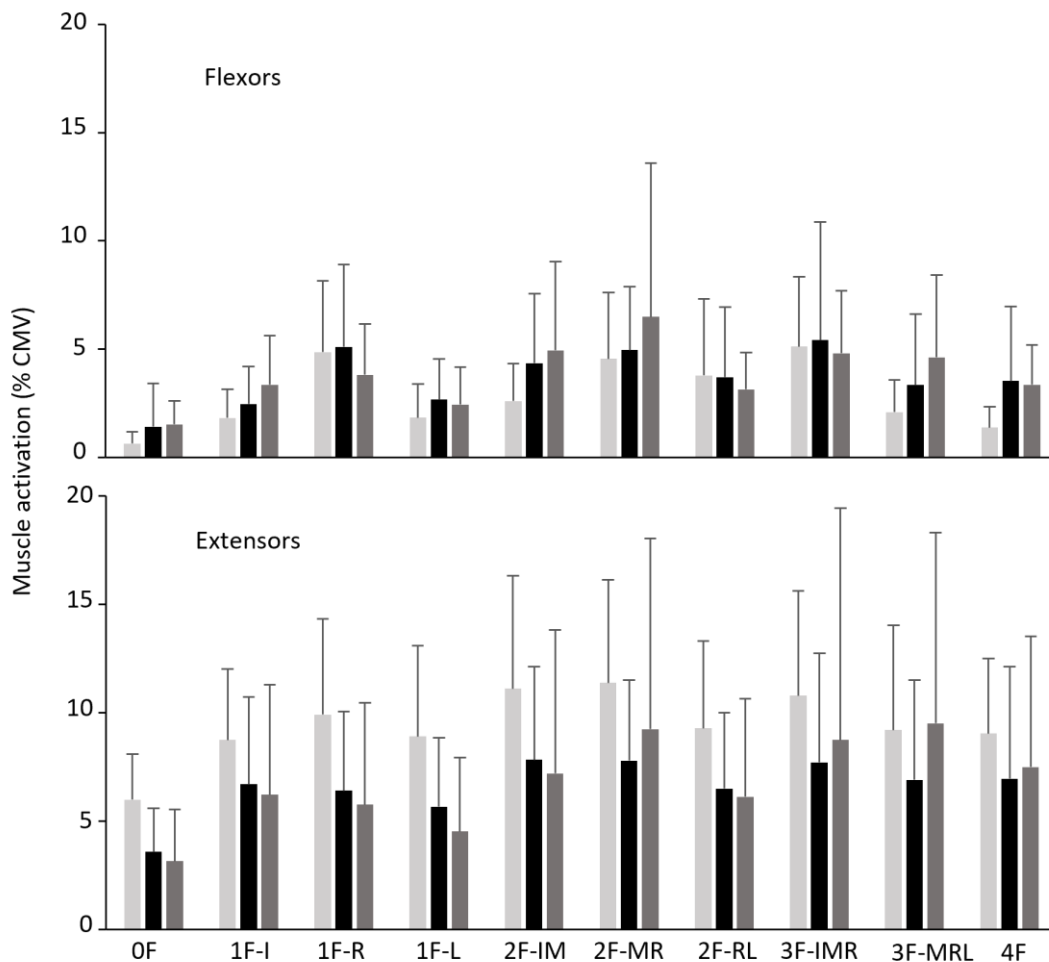
260

261 **RESULTS**

262 *EMG variables*

263 The figure 2 shows the mean activation (%MVC) of each muscle averaged for each tested
264 hand signs for each muscle. The results showed relatively large variabilities and low
265 activation values ranging from $2.0 \pm 3.1\%$ for the FCR to $9.4 \pm 4.1\%$ for the EDC when

266 averaged across all signs. The mean extensors muscles activations (EDC, ECRL, APL)
 267 reached up to $6.6 \pm 3.9\%$ and those of flexors (FDS, FCR, FPL) are below $3.9 \pm 1.4\%$. A
 268 significant effect of the Signs was found for all muscles (FDS: $F(9,135)=10.4$; $p < 10^{-6}$;
 269 $\text{Chi}^2(16,9)=84.9$; $p < 10^{-6}$; EDC: $F(9,135)=4.8$; $p < 10^{-5}$; $\text{Chi}^2(16,9)=37.9$; 2.10^{-5} ; FCR:
 270 $F(9,135)=4.6$; $p < 10^{-4}$; $\text{Chi}^2(16,9)=58.6$; $p < 10^{-6}$; ECR: $F(9,135)=5.0$; $p < 10^{-4}$; $\text{Chi}^2(16,9)=43.7$;
 271 $p < 10^{-6}$; FPL: $F(9,135)=5.3$; $p < 10^{-4}$; $\text{Chi}^2(16,9)=71.4$; $p < 10^{-6}$; APL: $F(9,135)=3.9$; $p < 10^{-4}$;
 272 $\text{Chi}^2(16,9)=53.0$; $p < 10^{-6}$). For flexor muscles, the 1F-R, 2F-IM, 2F-MR, 3F-IMR signs were
 273 the most soliciting signs. For extensors, the 2F-IM, 2F-MR, 3F-IMR were the more soliciting
 274 signs.



275

276

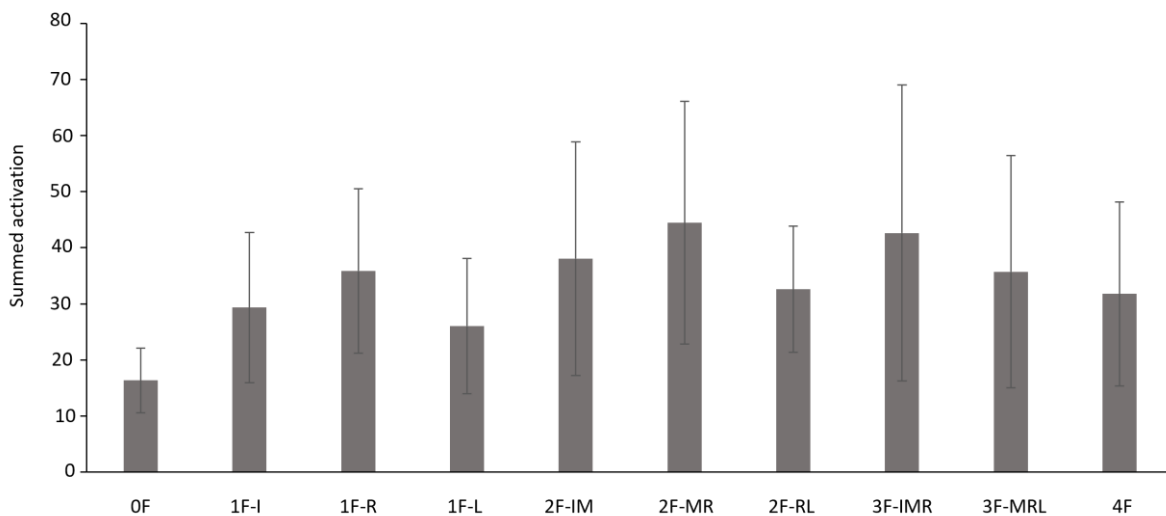
277 *Figure 2: mean results of muscle activation (%CMV) for flexors (upper pannel) and extensors*
 278 *(lower pannel). The finger muscles (FDS and EDC) are in light grey, the wrist muscles are in*
 279 *black (FCR, ECRL) and the thumb muscles are in dark grey (FPL and APL).*

280

281 The sum of muscles activities (Figure 3) also showed a significant effect of Signs (F(9,
 282 135)=7.8; $p < 10^{-8}$). The sum of activation showed that 2F-IM, 2F-MR and 3F-IMR were the
 283 three most soliciting signs. The sign 0F, 1F-L, 2F-RL and 4F-IMRL showed the smallest
 284 summed activation.

285

286



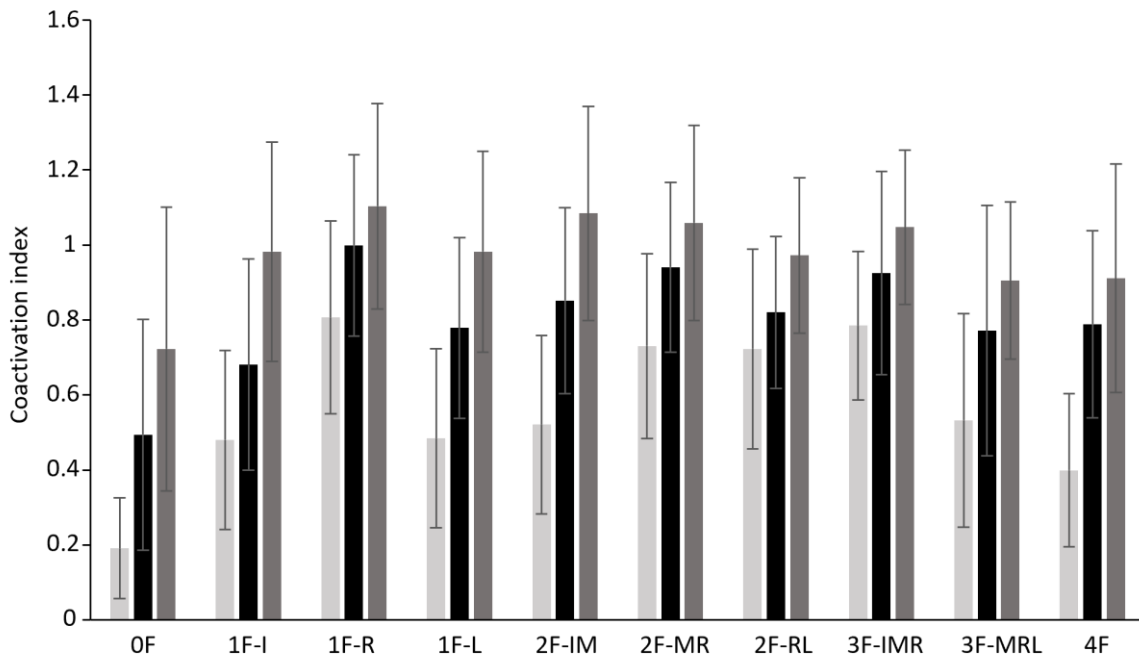
287

288 *Figure 3: Results of summed activations for the ten tested signs.*

289

290 The results of coactivation (Figure 4) showed a significant effect of Signs at the level of
 291 fingers muscles (F(9,135)=19.6; $p < 10^{-6}$; $\text{Chi}^2(16,9)=75.5$; $p < 10^{-6}$), the wrist (F(9,135)=8.0;
 292 $p < 10^{-6}$; $\text{Chi}^2(16,9)=45.9$; $p < 10^{-6}$) and the thumb (F(9,135)=8.9; $p < 10^{-6}$; $\text{Chi}^2(16,9)=36.8$;

293 $p=3.10^{-5}$). Highest values of coactivation are observed on the thumb muscles followed by the
 294 wrist muscles and then the finger muscles. For the fingers and the wrist muscles, the signs
 295 which generated the highest coactivation were the 1F-R, E, 2F-RL and 3F-IMR. The thumb
 296 muscles were highly coactivated for all signs, especially the 1F-R, 2F-IM, 2F-MR and 3F-
 297 IMR signs.

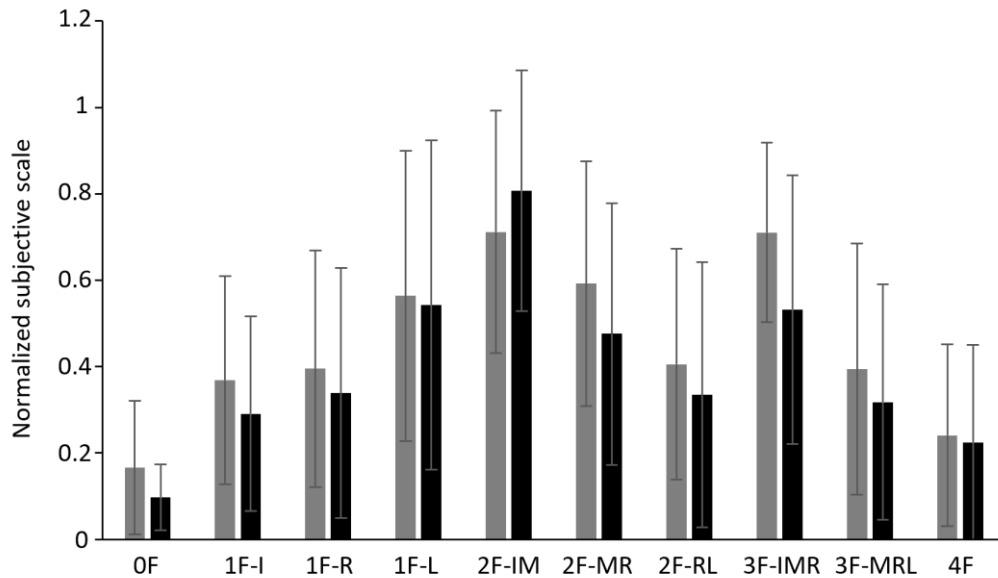


298
 299 *Figure 4: Mean (SD) results of coactivation indexes for the finger (light grey), the wrist*
 300 *(black) and the thumb (dark grey).*

301
 302 *Subjective ratings*

303 The results of perceived difficulty (Coord-N and Phy-N) are presented in Figure 5. The values
 304 of Coord-N ranged from $9.7\pm 7.6\%$ for the 0F sign to $80.7\pm 27.8\%$ for the 3F-IMR sign. The
 305 Friedman test showed a significant effect of the signs ($\text{Chi}^2(16,9)=60.6$; $p<10^{-5}$). The values
 306 of Phy-N ranged from $16.6\pm 15.4\%$ for sign the 0F sign to $71.2\pm 28.1\%$ and $71.1\pm 20.8\%$ with

307 signs 2F-IM and 3F-IMR respectively. The Friedman test showed a significant effect
 308 ($\text{Chi}^2(16,9)=59.8; p<10^{-5}$) of the signs.



309
 310 *Figure 5: Mean (SD) results of normalized subjective ratings (Coord-N and Phy-N) for the 10*
 311 *tested signs. Phy-N is in grey, Coord-N is in black.*

312

313 *Correlation between difficulty scales and EMG parameters*

314 The correlations between EMG variables (activations, sum of activations and co-activations)
 315 significantly affected by hand sign and subjective ratings were presented in Table 2 and 3.

316 Only 6 variables were significantly correlated to Phy-N rate: EDC ($r=0.82; t(10)=4.09;$
 317 $p=0.003$), FCR ($r=0.66; t(10)= 2.46; p=0.04$), ECRL ($r=0.68; t(10)=2.66; p=0.03$), FPL
 318 ($r=0.65; t(10)= 2.44; p=0.04$), sum of activation ($r=0.7; t(10)=2.83; p=0.02$), wrist
 319 coactivation ($r=0.63; t(10)=2.31; p=0.05$), thumb coactivation ($r=0.75; t(10)=3.28; p=0.01$).

320 When testing correlations between unweighted linear combination of several muscle
 321 activations and Phy-N, the combination of three muscles gave significant results and the

322 highest correlation was found for the ECR+FCR+ECRL model (r=0.89; p=0.04). The models
 323 combining two, four, five and six muscles were not significant.

324 When correlating the Coord-N subjective rating to EMG variables (Table 3), only EDC
 325 (r=0.76; t(10)=3.33; p=0.01), the sum of activation (r=0.79; t(10)=3.62; p=0.007) and the
 326 Thumb Coactivation (r=0.73; t(10)=2.99; p=0.02) were significant. When testing correlations
 327 between unweighted linear combination of several muscle activations and Coord-N, the
 328 models combining two, four and five variables were significantly correlated. The models
 329 combining three or six muscles were not significantly correlated. The highest correlations for
 330 combinations of two, four and five muscles were found for were EDC+APL;
 331 FDS+EDC+ECRL+FPL and FDS+EDC+FCR+ECRL+FPL, respectively.

332 When testing correlations between unweighted linear combinations of coactivations and
 333 Coord-N, only the combination of Finger-Coactivation and Thumb-coactivation was
 334 significant.

335 *Table 2: Significant correlation results with Phy-N subjective scale (r of Pearson and p-*
 336 *values) obtained for Individual muscles, Combined EMG variables and multiple correlation.*
 337 *The linear regression model coefficients are presented such as $Phy = a * 1^{st} \text{ correlated}$*
 338 *variable + $b * 2^{nd} \text{ correlated variable} + c * 3^{th} \text{ correlated variable} + d * 4^{th} \text{ correlated}$*
 339 *variable + $e * 5^{th} \text{ correlated variable} + f$*

	Correlated variables to Phy-N	r	p	a	b	c	d	e	f
Individual muscles	EDC	0.82	0.003	0.05	/	/	/	/	0.06
	FCR	0.66	0.04	0.03	/	/	/	/	0.02
	ECRL	0.69	0.03	0.03	/	/	/	/	0.04
	FPL	0.65	0.04	0.04	/	/		/	0.02
Combined	SumAct	0.70	0.02	0.21	/	/	/	/	-0.61

variables	Wrist CI	0.63	0.05	0.35	/	/	/	/	0.58
	Thumb CI	0.76	0.01	0.32	/	/	/	/	0.77
Multiple correlation	EDC+FCR+ECRL	0.89	0.04	2.06	-0.56	-0.8	/	/	-1.13

340

341 *Table 3: Significant correlation results with Coord-N subjective scale (r of Pearson and p-*
342 *values) obtained for Individual muscles, Combined EMG variables and multiple correlation.*

343 *The linear regression model coefficients are presented such as Coord-N=a*1st correlated*

344 *variable+ b*2nd correlated variable+c*3th correlated variable+d*4th correlated*

345 *variable+e*5th correlated variable+f*

	Correlated variables to Coord-N	r	p	a	b	c	d	e	f
Individual muscles	EDC	0.76	0.01	0.05	/	/	/	/	0.07
Combined variables	SumAct	0.78	0.006	0.25	/	/	/	/	-0.60
	Thumb CI	0.73	0.02	0.33	/	/	/	/	0.81
Multiple correlation	EDC+APL	0.83	0.04	1.13	-0.5	/	/	/	-0.79
	FDS+EDC+ECRL+FPL	0.92	0.01	-0.68	2.65	-1.0	-0.47	/	-1.54
	FDS+EDC+FCR+ECRL+FPL	0.93	0.02	-0.4	2.8	-0.43	-0.97	-0.48	-1.65
	Finger CI+ Thumb CI	0.80	0.03	-0.58	1.21	/	/	/	-1.68

346

347

348 *Correlation between EMG difficulty scales to Gargas frequency*

349 The correlation of the frequency occurrence of the signs observed in Gargas with the best
350 EMG-based criteria based on individual variables of activation or co-activation or
351 combinations of them identified above are presented in Table 4 as along with the correlation
352 with the EAS scale previously used in the literature. The EAS score significantly correlated
353 with hand sign occurrence in Gargas site with $R=-0.64$ and $p=0.045$. Among the EMG
354 variables, no individual muscle was significantly correlated with the hand sign occurrence in
355 Gargas. Among co-activation variables, only the thumb coactivation ($R=-0.83$; $p=0.003$) were
356 significantly correlated with Gargas hand sign occurrence. Among the combination of EMG
357 variables, the sum of activations (SumAct) ($R=-0.67$; $p=0.03$), the EDC+APL, the
358 EDC+FCR+ECRL and the FDS+EDC+FCR+ECRL+FPL were significantly correlated with
359 Gargas hand sign occurrence. Other models only showed tendency for significance
360 ($0.053 < p < 0.1$).

361 *Table 4: Correlation results with Coord-N subjective scale (R of Spearman, t and p-values)*
362 *obtained for Individual muscles, Combined EMG variables and multiple correlation models.*

	Correlated variables to Gargas	R	t	p
	Frequency	(spearman)		
<i>EAS scale</i>	<i>EAS</i>	-0.64	-2.36	0.045
Individual muscles	EDC	-0.43	-1.35	0.21
	FCR	-0.38	-1.17	0.27
	ECRL	-0.09	-0.25	0.80
	FPL	-0.35	-1.07	0.32
Combined variables	SumAct	-0.67	-2.54	0.03
	Thumb CI	-0.83	-4.26	0.003
Multiple	EDC+FCR+ECRL	-0.70	-2.81	0.02

correlation	EDC+APL	-0.8	-3.89	0.004
model	FDS+EDC+ECRL+FPL	-0.62	-2.27	0.053
	FDS+EDC+FCR+ECRL+ FPL	-0.65	-2.42	0.042
	Finger CI+ Thumb CI	-0.55	-1.88	0.1

363

364

365 **DISCUSSION**

366 The main goal of this study was to propose EMG-based criteria for quantifying the difficulty
367 of sign language. To this aim, surface EMG of six extrinsic hand muscles representing the
368 main muscle groups were recorded while executing ten hand signs selected among those
369 appearing in Gargas cave. EMG variables computed from these recordings were correlated to
370 the scores obtained by two subjective ratings of sign difficulty to identify the EMG-based
371 criteria significantly correlated with perceived effort. Then the EMG-based criteria were
372 correlated to Gargas hand sign occurrence to identify the potential benefits of using EMG
373 compared to the previously used EAS score.

374 The first main result of this study was that all the individual EMG activations and coactivation
375 evaluated in this study are significantly influenced by the sign executed by the hand. The
376 levels of activation of extensors remained relatively stable across hand signs compared to
377 flexors, which showed larger variations according to the performed sign. The signs that
378 required the highest muscle efforts, as seen through the high levels of sum of activations
379 (Figure 2) required flexing the ring finger and/or middle finger while the little finger remains
380 extended, i.e., 2F-MR, 3F-IMR and 1F-R, while the signs which required least efforts were
381 those where the fingers flexed together (4F-IMRL) or extend together (0F). The influence of
382 the performed hand sign on the muscle activity can be explained by anatomical and neural
383 constraints. As previously described (Schieber 1999), the little and ring fingers share a
384 common innervation. It is thus logical that performing a hand posture where these two fingers
385 act separately, e.g., the 1F-R sign where the ring finger is flexed and the little finger is
386 extended, puts higher strain on the central nervous system than a sign where the two fingers
387 act together, as with the 1F-I sign. Other previous studies on finger enslaving [Ann 1996;
388 Zatsiorsky, Li and Latash 1998] described various mechanical constraints for finger
389 interdependence associated to anatomical specificities, such as tendon interconnection, and

390 showed that the ring finger has the lowest level of independence while the index finger has
391 the highest. A sign that will go against those mechanical and anatomical constraints thus will
392 require a higher involvement of finger muscles to position the fingers. Our results
393 corroborated those works since different levels of EMG activations were observed according
394 to the combination of fingers involved in the sign, implying thus different physiological cost.
395 This can especially be observed for the 3F-IMR sign which implied a flexed ring finger with
396 an extended little finger in a same time. Conversely the 0F sign implied all finger extended
397 which is related to a low activity level. Those results show that the use of EMG is pertinent to
398 evaluate the hand sign difficulty and pertinent to understand the occurrence of specific gesture
399 in language, as with the negative hands observed in Gargas.

400 The current study also showed that the hand signs associated to higher muscle activations
401 were also associated with higher coactivation levels. Higher coactivation levels are generally
402 associated to the improvement of posture stability as it is a mean for the central nervous
403 system to increase the joint stiffness. Those variables thus are also pertinent to describe the
404 hand sign difficulty since it means that the posture is instable and requires higher stability to
405 execute the correct combination of finger flexion/extension. This idea is especially well
406 demonstrated by the high level of co-activation of the thumb (FPL/APL) and wrist
407 (FCR/ECR) muscles. Those muscle groups are indeed not directly required in the flexion or
408 extension of the fingers but necessary to ensure a stabilization of the entire musculoskeletal
409 chain during the hand sign. The activation of extrinsic fingers, such as the FDS, indeed results
410 in both mechanical action at the finger and the wrist because they originate in the forearm and
411 their tendon cross the wrist to reach their termination at the finger phalanx. As a result,
412 maintaining the wrist posture while flexing the fingers requires additional action of hand
413 muscles (Snijders et al., 1987; Charissou et al., 2017). Those biomechanical phenomena were
414 observed in previous studies focused on hang grip and multi-finger force production

415 illustrating that the central role of the wrist mechanical equilibrium influences both grip
416 performance and muscle coordination. For example, [Li et al., 1998] showed that during a
417 four-finger pressing tasks, the force sharing in between the four implicated fingers is mainly
418 dependant on the wrist moment equilibrium. As another example, [Goislard de Monsabert et
419 al. 2012] showed that the muscle coordination, especially the force in wrist extensors when
420 squeezing a handle, are dependent on the muscle force equilibration around the wrist degrees
421 of freedom. Our results corroborate those works since the co-activation levels suggest that the
422 thumb muscles are probably necessary in the stabilisation of the wrist concomitantly with
423 wrist muscles while the finger muscles are necessary to flex/extend the fingers to perform the
424 hand sign. Interestingly, the different signs required different coactivation which is a clue of
425 various coordination/equilibrium difficulties and by way of consequences different
426 physiological demand. Again, those results confirm that EMG is a valuable tool to understand
427 the reason explaining the difficulty of specific hand signs and the consequent occurrence
428 within a language. Outside of the current context of negative hand painting, these results open
429 a larger possibility for hand sign language analysis. As an example, such measurements may
430 be used to evaluate expertise or pathologies in sign language speakers.

431 Our results showed a strong correlation between EMG variables and subjective ratings of
432 perceived difficulty. Two different subjective scales were used to evaluate the “physiological
433 difficulty” on one side and the “coordination difficulty” on the other. Concerning the
434 physiological cost aspect (Phy-N) several individual muscle activations (EDC, FCR, ECRL,
435 FPL), several combinations of muscle EMG (Sum of activation, Wrist coactivation, Thumb
436 coactivation) and one multiple correlation model (EDC+FCR+ECRL) were correlated.
437 Concerning the coordination difficulty (Coord-N), only EDC individual muscle activation was
438 correlated to this criterion as well as the Sum of activity and the thumb coactivation. In
439 addition, linear combinations implying two, four or five muscles with EDC, FDS, ECRL,

440 FCR and FPL muscles were significantly correlated to this subjective rating. Several EMG
441 criteria thus are good candidate and could be useful to evaluate physiological and
442 coordination difficulties. In those possible criteria, it is interesting to identify that the EDC
443 muscles, involved in maintaining finger extended, the thumb coactivation, probably
444 participating to hand posture stability and the sum of activation were significantly correlated
445 to both subjective ratings which tend to establish them as relatively robust to evaluate hand
446 sign difficulty. Nevertheless, one limitation of EMG measurements should be considered
447 when evaluating the pertinence of these EMG criteria: FDS and EDC muscles are common
448 flexor/extensors of the fingers which include a common origin and muscle belly but split into
449 individual bellies and tendons each corresponding to one of the four long fingers. The level of
450 activation of FDS muscles and EDC muscles determined from EMG are thus highly
451 dependent on the electrode placement. Consequently, the used placement may correspond to
452 the activation of one finger muscle belly more than the others. This means that the recording
453 of FDS or EDC muscles could be more dependent on the finger implicated in the sign and the
454 electrode placement than the physiological cost or the muscle coordination intensity.
455 Consequently, the use of an EMG criterion relying on other muscles than the common
456 extrinsic finger muscles appeared more pertinent. Keeping this idea in mind together with our
457 correlation results, the thumb coactivation could thus be an interesting candidate for an EMG-
458 base criterion. It could also be concluded that EMG-based criteria that are based on a
459 consequent number of EMG muscles such as the sum of activation or the linear combinations
460 of four or five muscles could provide a more global index and thus limit the dependence on
461 finger extrinsic electrode placement. Nevertheless, it should be reminded that a criterion such
462 as the Sum of activation is necessarily harder to implement and longer to process as it
463 necessitates the acquisition and processing of 6 muscles electrodes, requiring for instance 6
464 maximal voluntary contraction tasks to establish the reference levels for each muscle. On the

465 contrary, the thumb coactivation is relatively easy to implement as it necessitates only two
466 EMG muscles (FPL and APL).

467 To evaluate the benefits of using EMG to assess hand sign difficulty, the correlation between
468 the aforementioned EMG-criteria and the Gargas frequency of occurrence. First, the initial
469 EAS method showed a significant correlation ($p=0.045$) with occurrence of hand signs in
470 Gargas for the ten tested signs. This result is encouraging for the negative hand writing
471 hypothesis and corroborate [Etxepare and Irurtzun, 2021] previous study but as mentioned
472 previously EMG could provide a more powerful tool to understand the rationale behind this
473 hypothesis. As a matter of fact, several EMG-based criteria (Sum of activation, thumb
474 coactivation, linear combination of 4 and 5 muscles) are strongly correlated to Gargas
475 frequency occurrence. Interestingly, the Thumb coactivation showed the strongest correlation
476 ($R=-0.83$; $p=0.003$) and the sum of activation was above the highest ones ($R=-0.67$; $p=0.03$)
477 which tends to corroborate the above hypothesis that those criteria are the best candidate to
478 evaluate hand sign difficulty. The fact that those correlation are negative indicated that when
479 thumb co-activation or global muscle effort are increasing, the occurrence of the hand sign is
480 decreasing. Again, this tends to confirm the negative hand writing hypothesis, as the signs that
481 are harder to perform would be less frequent in the repertoire, thus suggesting it was a form of
482 language and not mutilated hands. These results showed that our EMG-based criteria seemed
483 pertinent and could provide more precise explanation behind the difficulty and the consequent
484 occurrence of hand signs. The study is thus encouraging toward the use of EMG to better
485 understand physiological constraints behind hand sign language but needs more data to be
486 fully validated. Further works should thus focus on testing the negative hand writing
487 hypothesis with the frequency occurrence of all observed negative hand paintings in various
488 archaeological sites. Despite a limited dataset, the current study illustrated that the use of
489 EMG could significantly contribute to both evaluate the hand sign difficulties, more precisely

490 than with the purely visual EAS method and at the same time provide explanation as to why
491 certain signs are more difficult to perform.

492

493

494 **BIBLIOGRAPHIE**

- 495 Ann J. A linguistic investigation of the relationship between physiology and handshape. The
496 University of Arizona, 1993
- 497 Ann J. On the relation between ease of articulation and frequency of occurrence of
498 handshapes in two sign languages. *Lingua* 1996; 98(1-3): 19-41
- 499 Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc* 1982; **14**: 377-
500 81.
- 501 Chao EY. *Biomechanics of the Hand: A Basic Research Study*. ed. Singapore ; Teaneck, N.J:
502 World Scientific, 1989
- 503 Charissou C, Amarantini D, Baures R, Berton E, Vigouroux L. Effects of hand configuration
504 on muscle force coordination, co-contraction and concomitant intermuscular coupling during
505 maximal isometric flexion of the fingers. *European Journal of Applied Physiology* 2017; 117:
506 2309-2320
- 507 Chen MJ, Fan X, Moe ST. Criterion-related validity of the Borg ratings of perceived exertion
508 scale in healthy individuals: a meta-analysis. *Journal of Sports Sciences* 2002; 20(11) : 873-
509 899
- 510 Etxepare R, Irurtzun A. Gravettian hand stencils as sign language formatives. *Philosophical*
511 *Transactions of the Royal Society B* 2021; 376(1824): 20200205.
- 512 Goislard De Monsabert B, Rossi J, Berton E, Vigouroux L. Quantification of Hand and
513 Forearm Muscle Forces during a Maximal Power Grip Task. *Medicine & Science in Sports &*
514 *Exercise* 2012; 44: 1906-16

515 Gracia-Ibáñez V, Vergara M, Sancho-Bru JL. Interdependency of the maximum range of
516 flexion–extension of hand metacarpophalangeal joints. *Computer methods in biomechanics*
517 *and biomedical engineering* 2016 ; 19(16) : 1800-1807

518 Groenen, M. *L'art des grottes ornées du Paléolithique supérieur*. Bruxelles: Academie
519 Royale des Sciences, des Lettres et des Beaux-Arts de Belgique, 2016

520 Kelso JAS, Holt KG, Rubin P, Kugler PN. Patterns of Human Interlimb Coordination Emerge
521 from the Properties of Non-Linear, Limit Cycle Oscillatory Processes. *Journal of Motor*
522 *Behavior* 1981; 13: 226-261

523 Leroi-Gourhan A. Les mains de Gargas. Essai pour une étude d'ensemble. *bspf* 1967; 64:107–
524 22.

525 Li ZM, Latash ML, Newell KM, Zatsiorsky VM. Motor redundancy during
526 maximal voluntary contraction in four-finger tasks. *Exp. Brain Res* 1998; 122: 71-78.

527 Liang D., Yarossi M., Jacobs-Skolik S L, Furmanek M P, Brooks D, Erdogmus D, Tunik E.
528 Synergistic activation patterns of hand muscles in left-And right-hand dominant individuals.
529 *Journal of Human Kinetics* 2021; 76(1): 89-100.

530 Mertz J, Annucci C, Aristodemo V, Giustolisi B, Gras D, Turco G, Geraci C, Donati C.
531 Measuring sign complexity: Comparing a model- driven and an error-driven approach.
532 *Laboratory Phonology: Journal of the Association for Laboratory Phonology* 2022; 13, 1 (4):
533 1-33

534 McCauley B, Maxwell D, Collard M. A crosscultural perspective on Upper Palæolithic hand
535 images with missing phalanges. *J. Paleolithic Archaeol.* 2018; 1: 314-333.

536 Olney SJ, Winter DA. Predictions of knee and ankle moments of force in walking from EMG
537 and kinematic data. *Journal of Biomechanics* 1985; 18: 9–20

538 Schieber MH. Somatotopic gradients in the distributed organization of the human primary
539 motor cortex hand area: evidence from small infarcts. *Experimental Brain Research* 1999;
540 128:139-48

541 Shieber MH, Gardinier J, Liu J. Tension distribution to the five digits of the
542 hand by neuromuscular compartments in the macaque flexor digitorum profundus,
543 *J. Neurosci* 2011 ; 15 : 2150-2158

544 Schieber MH, Hibbard LS. How somatotopic is the motor cortex hand area? *Science* 1993;
545 261(5120): 489-492

546 Schieber MH, Santello M. Hand function: peripheral and central constraints on performance.
547 *Journal of Applied Physiology* 2004; 96:2293-300

548 Scherr J, Wolfarth B, Christle JW, Pressler A, Wagenpfeil S, Halle M. Associations between
549 Borg's rating of perceived exertion and physiological measures of exercise intensity. *Eur J*
550 *Appl Physiol* 2013; 113: 147-55

551 Snijders CJ, Volkers A C, Mechelse K, Vleeming A. Provocation of epicondylalgia
552 lateralis (tennis elbow) by power grip or pinching. *Medicine and Science in Sports and*
553 *Exercise* 1987; 19: 18-23.

554 Van Den Noort JC, Van Beek N, Van Der Kraan T, Veeger DH, Stegeman DF, Veltink PH
555 Maas H. Variable and asymmetric range of enslaving: fingers can act independently over
556 small range of flexion. *Plos one* 2016; 11(12) : e0168636

557 Van de Mierop M. *Cuneiform texts and the writing of history*. Routledge, 2005

558 Vigouroux L, Goislard de Monsabert B, Berton E. Estimation of hand and wrist muscle
559 capacities in rock climbers. *Eur J Appl Physiol* 2015; 115: 947-57.

- 560 Zatsiorsky VM, Li Z-M, Latash ML. Enslaving effects in multi-finger force production.
561 Experimental Brain Research 2000; 131: 187–95.