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## ► To cite this version:

Ross Parry, Fabrice Sarlegna, Nathanael Jarrasse, Agnès Roby-Brami. Anticipation and compensation for somatosensory deficits in object handling: evidence from a patient with large fibre sensory neuropathy. *Journal of Neurophysiology*, 2021, 10.1152/jn.00517.2020 . hal-03289253

**HAL Id: hal-03289253**

**<https://hal.science/hal-03289253>**

Submitted on 24 Aug 2021

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1 **Anticipation and compensation for somatosensory deficits in object handling:**  
2 **evidence from a patient with large fibre sensory neuropathy**

3

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## ABSTRACT

20

21 The purpose of this study was to determine the contributions of feedforward and feedback  
22 processes on grip force regulation and object orientation during functional manipulation tasks.

23 One patient with massive somatosensory loss resulting from large fibre sensory neuropathy,  
24 and ten control participants were recruited. Three experiments were conducted:

25 1) perturbation to static holding; 2) discrete vertical movement; and 3) functional grasp and  
26 place. The availability of visual feedback was also manipulated to assess the nature of

27 compensatory mechanisms. Results from experiment 1 indicated that both the deafferented  
28 patient and controls used anticipatory grip force adjustments prior to self-induced perturbation

29 to static holding. The patient exhibited increased grip response time, but the magnitude of grip  
30 force adjustments remained correlated with perturbation forces in the self-induced and

31 external perturbation conditions. In experiment 2, the patient applied peak grip force  
32 substantially in advance of maximum load force. Unlike controls, the patient's ability to

33 regulate object orientation was impaired without visual feedback. In experiment 3, the  
34 duration of unloading, transport and release phases were longer for the patient, with increased

35 deviation of object orientation at phase transitions. These findings show that the deafferented  
36 patient uses distinct modes of anticipatory control according to task constraints, and that

37 responses to perturbations are mediated by alternative afferent information. The loss of  
38 somatosensory feedback thus appears to impair control of object orientation, while variation

39 in the temporal organization of functional tasks may reflect strategies to mitigate object  
40 instability associated with changes in movement dynamics.

41 Key words: manual dexterity, somatosensory feedback, grip force control, sensory neuropathy

42

43 **New and noteworthy:** This study evaluates the effects of sensory neuropathy on the scaling  
44 and timing of grip force adjustments across different object handling tasks (i.e. holding,  
45 vertical movement, grasping and placement). In particular, these results illustrate how novel  
46 anticipatory and online control processes emerge in order to compensate for the loss of  
47 somatosensory feedback. In addition, we provide new evidence on the role of somatosensory  
48 feedback for regulating object orientation during functional prehensile movement.

## 1. INTRODUCTION

49

50 Grasping and using everyday objects implies the ability to anticipate and respond to dynamic  
51 task constraints (1), assuring regulation of forces and object orientation. Somatosensory  
52 feedback supports prehensile and manipulative function as cutaneous mechanoreceptors  
53 provide information on skin deformation while intrafusal muscle fibres, tendon organs and  
54 joint capsules transmit information regarding dynamic properties relevant to object mass and  
55 limb kinematics (2–4). Integration of these tactile and proprioceptive afferents assists to guide  
56 arm movement and coordinate finger forces applied to handheld objects. Experimental studies  
57 using dorsal rhizotomy procedures on non-human primates (5, 6), local anaesthetics/nerve  
58 blocks on healthy humans (7–13), or investigations on patients suffering from somatosensory  
59 deficits (14–16) demonstrate that tactile and proprioceptive dysfunction is associated with  
60 deficits in the accuracy and coordination of arm movements (17–19), and diminished manual  
61 dexterity (20–24).

62

Experimental studies of motor control in humans with somatosensory deficits have  
63 provided specific insights into the role of feedforward and feedback control mechanisms  
64 underlying object handling (23, 25–28). Using a precision grip with an object held between  
65 the thumb and index finger, healthy adults regulate grip force according to the displacement  
66 of the handheld object, concurrent with the associated load force variation (a product of the  
67 mass and acceleration of the handheld object) (29). This behaviour has served as a model for  
68 studying feedforward sensorimotor control processes (30, 31). Under similar conditions,  
69 persons suffering from sensory deficits exhibit grip forces with increased magnitude and, in  
70 most cases, decreased temporal precision (25, 32). This has been interpreted as a breakdown  
71 in feedforward control whereby decreased afferent input precludes the ability to update  
72 internal models allowing to anticipate the effects of movement kinematics upon inertial loads  
73 (26).

74           Of course, sensory feedback also is essential for reacting to external perturbations, in  
75 that it informs the nervous system when generating an appropriate motor command with  
76 respect to changing task demands (33). For instance, when external forces are applied to a  
77 handheld object, somatosensory feedback enables a reflexive grip force increase (34, 35). This  
78 process is mediated by tactile afferents and long-latency stretch reflexes combined with fast  
79 volitional adjustments engaging transcortical pathways (36, 37). The ability to scale this  
80 “catch up” response to the magnitude of the perturbation is impaired when cutaneous  
81 feedback is compromised (34). Visual feedback has also been shown to contribute to the  
82 control of arm movements (38, 39) and dextrous manipulation (40, 41). But the extent to  
83 which this visual stream enables an individual to compensate for the loss of somatosensory  
84 afferents in object handling is less apparent (24). For instance, it remains to be determined  
85 how vision influences the ability to stabilize a handheld object through the course of  
86 movement, or respond to external perturbations in the absence of tactile or proprioceptive  
87 feedback.

88           Functional actions, such as grasping and moving an object, involve distinct phases  
89 characterized by changing task constraints (2). Feedforward control assures grip-load force  
90 coupling with variations in object acceleration, according to the specific constraints of each  
91 sub-goal of the task (42), while somatosensory signals continuously inform the nervous  
92 system of changes in mechanical events corresponding with phase transitions (i.e. object  
93 grasping to object unloading, unloading to lifting...) to ensure feedback control (2). Generally  
94 speaking, experiments on these types of naturalistic tasks are less common than those  
95 examining some functional primitive (i.e. reach, transport...) of a complex task (43, 44).  
96 Characterisation of a functional task which integrates grasp, transport and placement  
97 components may provide greater insight regarding the interplay of feedforward and feedback  
98 processes which underpin fine motor activities. In particular, further observation with

99 deafferented patients may help to illustrate the role of somatosensory afferents in regulating  
100 grip forces and maintaining object orientation across the component phases of the functional  
101 movement.

102 In the present study, our objective was to examine the strategies used to stabilise  
103 grasp, adjust grip forces and maintain object orientation in the absence of somatosensory  
104 feedback. To this end, we compared the object handling abilities of one patient with large  
105 fibre sensory neuropathy and age-matched controls in a series of experiments with different  
106 task constraints. Perturbation to static holding, discrete vertical movement, and functional  
107 grasp and place paradigms were used in order to distinguish specific feedforward and  
108 feedback mechanisms. Visual feedback and the source of perturbation were also manipulated  
109 to better elucidate how the deafferented patient compensates for the loss of touch and  
110 proprioception. Based upon previous studies (26), we expected that the deafferented patient  
111 would use increased grip forces as a means to ensure object stability during perturbations to  
112 static holding and vertical movements. We also hypothesised that the deafferented patient's  
113 performance in perturbation to static holding and vertical movement would be compromised  
114 by removing visual feedback. Given the known interactions between feedforward and  
115 feedback control mechanisms in the functional grasp and place task (2), we further predicted  
116 that loss of somatosensory feedback would impair movement kinematics as well as the grip-  
117 load force coupling and object orientation across the sequence of phases.

118

## 119 **2. MATERIALS AND METHODS**

### 120 **2.1 Participants**

121 Eleven participants were recruited: one deafferented patient (GL, a 67-year-old female) and  
122 ten adult controls (6 females/4 males, mean age  $63 \pm 6$  years) with no known neurological or

123 orthopaedic pathology affecting upper limb function. The deafferented patient suffered from a  
124 rare condition resulting in a massive yet specific, large-fibre sensory neuropathy (confirmed  
125 by sural nerve biopsy) (14). GL had thus lost somatosensory feedback from cutaneous  
126 receptors, muscle spindles and Golgi tendon organs (14). Consequently, this patient had  
127 chronic loss of proprioception and tactile sensation below the level of the nose.

128 All participants were tested for hand dominance using the Edinburg Handedness  
129 Inventory (45) prior to beginning the evaluation. Overall grip strength was evaluated using a  
130 hand dynamometer (LiteXpress GmbH, Germany). In addition, GL responded to the  
131 QuickDASH questionnaire in order to measure self-perceived upper limb disability in daily  
132 life tasks (46). This study was approved by the ethics committee of Paris Descartes University  
133 and conducted in accordance with the declaration of Helsinki. All participants provided  
134 written consent prior to engaging in this experiment.

135

## 136 **2.2 Apparatus**

137 Object manipulation parameters were measured using an instrumented object (iBox),  
138 measuring 108x70x40mm with a mass of 0.370kg (see Figure 1A). The iBox is equipped with  
139 six load cells to measure the normal force applied to the six faces of the object, as well as an  
140 inertial measurement unit to record acceleration, rotational velocities and orientation (47).  
141 Each load cell has a range of 0N—50N with a precision of  $\pm 0.25\text{N}$ , measured by a set of 8Bit  
142 analogue to digital converters (ADC). This device is calibrated on a flat surface to offset the  
143 mass of the iBox so that the base load cell measures 0N when resting on a table and has a  
144 negative value when completely lifted from the table. Data was acquired at a sampling rate of  
145 100Hz and relayed to a personal computer via Bluetooth. All variables examined in this paper  
146 were extracted from the raw data obtained during the three experiments. A 10Hz low-pass



147 Butterworth filter was used to remove low resolution artifacts for the purposes of illustration  
148 in the present manuscript.

149 The experiment with GL was recorded in its entirety (with her signed consent) using a  
150 digital camera. The first author (RP) was responsible for conducting each experiment.

151 *Insert figure 1 about here*

152

### 153 **2.3 Experiment 1: Perturbation to static holding**

154 **2.3.1 Procedure.** Participants were instructed to hold the iBox in a comfortable posture in  
155 front of their body, approximately 30cm from the surface of the table with the elbow flexed  
156 and the shoulder in a neutral or slightly flexed position. From this position, load perturbations  
157 were introduced by striking the upper surface of the iBox by hand to produce a downward  
158 force pulse. Three conditions were evaluated: self-induced perturbation with visual feedback;  
159 external perturbation with visual feedback; and external perturbation without visual feedback  
160 (NB: previous tests indicated that self-induced perturbation without visual feedback was not  
161 feasible with the deafferented patient). For self-induced perturbation with visual feedback,  
162 participants used their free hand to strike the upper surface of the handheld iBox upon verbal  
163 command of the researcher. In the conditions involving an externally applied perturbation  
164 (with/without visual feedback), the researcher used their dominant hand to strike the iBox. For  
165 both the self-induced and external perturbation with vision conditions, participants were  
166 permitted to observe each action. A mask was applied over the participant's eyes for the  
167 external perturbation without visual feedback condition.

168 A demonstration for each condition was carried out prior to recording in order to  
169 illustrate the desired action when striking the iBox. A practice trial was used to ensure that  
170 instructions for each condition were understood. Force of the perturbation during each

171 condition was varied in a semi-randomised manner according to the verbal instructions of the  
172 researcher ('stronger', 'softer'). Intervals between each perturbation event were staggered to  
173 prevent priming effects. Desired range of force perturbations was 1.5N—16N (mean = 6N)  
174 with a force pulse duration of ~70ms. Magnitude of force signals was inspected during  
175 recordings to ensure consistency in the strength of perturbations. Where required, certain  
176 trials were repeated to ensure comparability across participants for a total of ten trials. Each  
177 condition was conducted first with the non-dominant hand and then with the dominant hand.

178 **2.3.2 Data extraction.** Perturbation events were identified from the load cell on the upper  
179 surface of the iBox. Onset was defined as the data sample immediately preceding a threshold  
180 value of 0.25N. Grip force was measured as the mean grip forces recorded on the front and  
181 back load cells of the iBox. The following variables were then extracted for analysis:

- 182 • Baseline grip force during holding: minimum value for grip force during a 1s time  
183 window prior to perturbation
- 184 • Grip response time: interval between perturbation onset and the time of maximum grip  
185 force
- 186 • Correlation for grip force scaling: Pearson correlation coefficient between the values  
187 of maximum grip force and maximum force applied to the upper load cell, across trials  
188 for a given condition

189 Ten perturbation trials for each condition on both dominant and non-dominant hands were  
190 selected for each participant. Trials for GL were selected to include a wide range of  
191 perturbation forces while trials with more variable acceleration during the static phase were  
192 eliminated. Trials in healthy participants were selected according to the maximum force on  
193 the upper load cell from the range of values observed with GL. In order to ensure the validity  
194 of comparisons, maximum force applied to the upper load cell, duration of the force pulse,

195 and load rate parameters were examined (see S1.1—S1.3 for data visualization of stimulus  
196 parameters: <https://figshare.com/s/840e0e8efb1e87e43157>).

197 <https://doi.org/10.6084/m9.figshare.12888311>

198 No significant differences were found between GL and control subjects (results of statistical  
199 analysis are provided in supplementary material S2.1:  
200 <https://figshare.com/s/840e0e8efb1e87e43157>)

201 <https://doi.org/10.6084/m9.figshare.12888311>

202

203

## 204 **2.4 Experiment 2: Vertical displacement of handheld object**

205 **2.4.1 Procedure.** In a seated position, participants held the iBox in a comfortable posture in  
206 front of their body as for experiment 1. Participants were instructed to move the iBox on the  
207 vertical axis for a distance of approximately 30cm. Each trial consisted of one upward and  
208 one downward movement. A pause of approximately 1s was imposed between movements to  
209 ensure that each trial involved two discrete gestures (upward and downward). A verbal  
210 command was provided to signal the time of commencement for each direction. A ruler was  
211 used to demonstrate the appropriate movement amplitude prior to each trial. In the condition  
212 without visual feedback (blinded), a mask was placed over the participants' eyes. This mask  
213 was removed following each trial so that participants could adjust the orientation of the iBox  
214 as necessary. A total of 6 trials for the dominant and non-dominant hands were recorded for  
215 both directions under each condition (with and without visual feedback).

216 **2.4.2 Data extraction.** The instant of movement onset was detected using an interactive  
217 graphic interface allowing the selection of the inflection point in the acceleration signal.  
218 Individual movement trials were identified with windows beginning 500ms prior to

219 movement onset and lasting 2000ms. Grip force was measured as the mean grip forces  
220 recorded on the front and back load cells of the iBox (per experiment 1). Load force was  
221 measured as the product of the object's acceleration with the object's mass, using the method  
222 described in (48). Object orientation was calculated from the inertial motion unit data and  
223 expressed as the alpha angle, indicating the deviation of the longitudinal axis of the iBox from  
224 the vertical axis. The following variables were then extracted for analysis:

- 225 • Baseline grip force during holding: minimum value for grip force during the 500ms  
226 prior to onset of movement
- 227 • Maximum acceleration: value for maximum acceleration during the movement  
228 window
- 229 • Maximum grip force: value for maximum grip force and the instant it occurred after  
230 movement onset
- 231 • Magnitude of grip force increase: difference between baseline and maximum grip  
232 force
- 233 • Time series correlation of grip force and load force: correlation coefficient for grip  
234 force and load force signals during the 1500ms window from movement onset
- 235 • Ratio of maximum grip to maximum load: calculated by dividing the maximum grip  
236 force value from each trial by the maximum load force value from each trial
- 237 • Grip-load time delay: interval between the time points for the maximum grip force and  
238 the maximum load force values
- 239 • Average object angle: mean alpha angle calculated across time points for the duration  
240 of each trial
- 241 • Variability of object angle: standard deviation of the alpha angle calculated across  
242 time points for the duration of each trial

243 Accelerometer data for GL could not be exploited for vertical movement without visual  
244 feedback due to large variations in iBox orientation during her movements.

245

## 246 **2.5 Experiment 3: Grasp, transport and placement of handheld object**

247 **2.5.1 Procedure.** Participants were in the seated position with their hand placed in the hand  
248 start area. The iBox was placed vertically before each participant, positioned in the  
249 parasagittal plane, 20cm in front of the hand used. For each trial, participants were asked to  
250 grasp the object and place it on an 8cm high platform located 15cm distal to the initial  
251 position. This layout is illustrated in figure 1B. Three repetitions were carried out for the  
252 dominant and non-dominant hands.

253 **2.5.2 Data extraction.** Grip force and load force parameters were calculated using the same  
254 methods described in experiments 1 and 2. Transitions between unloading, lifting and  
255 placement phases were identified in an automated manner with reference to iBox load cell  
256 data, following the process described in (43, 49). Grasp onset was defined as the moment  
257 when the force applied to each of the front and back load cells exceeded 0.15N. Lift onset was  
258 the moment when the base load cell value was inferior to a threshold of -3.4N (based upon  
259 offset from object's mass). Placement was the moment when the base load cell returned to the  
260 threshold value of -3.4N. Object release was defined as the moment when the mean of the  
261 forces applied to the two front and back load cells were inferior to 0.15N. Transport onset and  
262 transport end events were tagged manually from data in each trial using a graphic interface;  
263 these events corresponded with the end of the upward vertical acceleration and the beginning  
264 of the downward vertical acceleration respectively. From these events, five separate phases  
265 were identified: (1) unloading, between grasp onset and lifting onset; (2) lifting, between lift  
266 onset and transport onset; (3) transport, between transport onset and transport end; (4)

267 descent, between transport end and placement; and (5) release phase, between placement and  
268 release.

269 Further to this, the occurrence of push and touch errors (43) were identified. Touch  
270 errors were defined as events where the sum of forces on the exposed (front, back, top and  
271 lateral) load cells exceeded 0.7N before grasp onset or after release. A push error was detected  
272 as increased force (>0.4N) on the base load cell during the unloading or release phases.

273 Based upon this, the following variables were then extracted for analysis:

- 274 • Durations for the unloading, lifting, transport, descent and release phases of the task
- 275 • Average grip-load ratio through unloading, lifting, transport, descent and release  
276 phases: a mean value calculated from the grip-load ratios from all time points within  
277 each respective phase
- 278 • Ratio of maximum grip to maximum load: calculated by dividing the maximum grip  
279 force value by the maximal load force value from each task
- 280 • Time series correlation of grip force and base load cell: correlation coefficient for grip  
281 force and base load sensor signals, calculated across the duration of unloading and  
282 release phases
- 283 • Grip-load time delay: interval between the time point for the maximum grip force and  
284 time point for the maximum load force
- 285 • Object angle at phase transitions: alpha angle at the grasp onset, lifting onset,  
286 transport onset, transport end, placement, and release end time points
- 287 • Average object angle through each respective phase: the mean alpha angle calculated  
288 across the time points for each of the unloading, lifting, transport, descent and release  
289 phases

- 290 • Variability of object angle through each respective phase: the standard deviation  
291 calculated on the alpha angle across the time points within each respective phase of  
292 the task
- 293 • Occurrence of touch and push errors

## 294 **2.6 Statistical analysis**

295 Data was firstly analysed by examining each experimental task individually. Repeated  
296 measures analysis of variance (ANOVA) was performed on control data taking into account  
297 the different factors examined across the different experimental tasks (e.g. dominant / non-  
298 dominant hand; visual feedback / absence of visual feedback; self-generated / external  
299 perturbation). These tests indicated that across control participants, there were no significant  
300 effects for the hand used in experiment 1 and experiment 2, and only 1 difference for  
301 variables examined in experiment 3 (grip-load time delay in the downward direction). Results  
302 for these statistical tests are provided in S2.2—S2.4:  
303 <https://figshare.com/s/840e0e8efb1e87e43157>). Due to the absence of significant differences  
304 between dominant and non-dominant hands, all data was pooled for subsequent statistical  
305 analysis with the deafferented patient.

306 Fisher transformations were performed prior to statistical comparison of correlation  
307 coefficients and Chi-squared tests were used for testing statistical difference in frequency of  
308 touch/push contact errors. Direct comparisons between values for GL and the controls data  
309 were carried out using the method described by (50), specifically designed for testing the  
310 mean of single subject data against a normative sample.

311 Secondly, further testing for common variables across different tasks (e.g. baseline  
312 grip force for vertical displacement and perturbation tasks) was performed upon the ensemble  
313 of the deafferented patient's data using a two-way ANOVA (hand used and experimental task  
314 as independent factors). Equivalent tests upon control group averages were conducted using

315 repeated measures ANOVA with Greenhouse-Geisser adjustments where necessary.  
316 Statistical significance was set at  $p=0.05$  and Bonferroni corrections were applied for multiple  
317 comparisons on post-hoc testing. All statistical analyses were conducted using Matlab, JASP  
318 and the SINGLIMS toolbox. Summary statistics in the results are expressed in terms of the  
319 mean and standard deviation (i.e. the '±' indicates intraindividual variability for G.L and  
320 interindividual variability for control subjects). Where boxplots are used to represent data, the  
321 central line corresponds to the median with the boxes indicating quartile values and whiskers  
322 the extremities.

323

324

### 3. RESULTS

325 The deafferented patient was evaluated as being right hand dominant (laterality quotient 80).  
326 The control group comprised 9 right handed participants (laterality quotient  $90\pm 8$ ) and 1 left  
327 handed participant (laterality quotient -100). Maximum grip strength for GL was 17.2kg for  
328 the dominant hand and 18.1kg for the non-dominant hand. These values did not significantly  
329 differ to  $29.1\pm 6.5$ kg for the dominant hand ( $p=0.12$ ) and  $26.9\pm 7.1$ kg ( $p=0.27$ ) for the non-  
330 dominant hand in the control group (NB: control averages in the 6 females were  $24.8\pm 3.5$ kg  
331 and  $22.8\pm 1.7$ kg for dominant and non-dominant hands respectively). Differences between  
332 grip strength in the right and left hands of the control group were not statistically significant  
333 ( $p=0.14$ ). The deafferented patient scored 25/100 on a QuickDASH questionnaire, indicating  
334 functional upper limb deficits with daily living tasks compared to females of a similar age  
335 group (46, 51).

#### 3.1 Experiment 1: Perturbation to static holding

337 For the perturbation tasks, both the deafferented patient (GL) and the control group presented  
338 with increased grip forces in response to the iBox being struck. Figure 2 provides an example



339 for each perturbation condition for GL and one representative control participant (C7).  
340 Generally speaking, GL's baseline grip force appeared to fluctuate more than controls.  
341 Similar to controls, GL was observed to have an increase in grip force prior to the  
342 perturbation event in the self-induced condition. The timing of this grip force increase in the  
343 self-induced condition, however, did appear to commence earlier for GL than for control  
344 subjects (see figure 3).

345 *Insert figures 2 and 3 about here*

346 While GL appeared to have slightly greater baseline grip forces across perturbation  
347 conditions, these values were not statistically different from the control group (see figure 4A).  
348 Grip response time was significantly greater for GL than controls across the self-perturbation  
349 ( $p=0.049$ ), external perturbation with visual feedback ( $p=0.003$ ) and external perturbation  
350 without visual feedback ( $p=0.003$ ) conditions (see figure 4B). No significant difference was  
351 observed for grip force increase between GL and the control group in self perturbation  
352 ( $4.7\text{N}\pm 3.1\text{N}$  vs  $5.2\text{N}\pm 3.0\text{N}$ ;  $p=0.844$ ) or external perturbation ( $8.8\text{N}\pm 5.3\text{N}$  vs  $6.1\text{N}\pm 2.6\text{N}$ ;  
353  $p=0.332$ ). However, average grip force increase for GL in the external perturbation without  
354 visual feedback condition was  $7.9\text{N}$  ( $\pm 5.6\text{N}$ ), significantly greater than the control group at  
355  $4.3\text{N}$  ( $\pm 3.39\text{N}$ ;  $p=0.043$ ).

356 Figure 4C provides a boxplot summary for the correlation of grip force scaling, which  
357 did not significantly differ between GL and the control group. Further detail on results from  
358 experiment 1 are provided S2.1—S2.2 (<https://figshare.com/s/840e0e8efb1e87e43157>).

359 *Insert figure 4 about here*

### 360 **3.2 Experiment 2: Vertical displacement of handheld object**

361 Qualitative differences were observed in the grip force dynamics of the deafferented patient  
362 and controls. Overall, GL presented with higher grip forces than controls. Figure 5 provides

363 examples of an upward movement from the dominant hand for GL and one representative  
364 control participant (C5). While grip force variations appeared associated with variations in  
365 acceleration for controls, this was less evident for GL. In effect, relatively large grip forces  
366 were apparent even prior to movement initiation (see figure 5A). In the upward direction,  
367 GL's grip forces tended to decrease progressively during the duration of the movement (see  
368 figure 5A) but were more irregular in the downward direction (see examples of downward  
369 vertical movements in supplementary figure S1.4 and 1.5:  
370 <https://figshare.com/s/840e0e8efb1e87e43157>). In general, peak acceleration for GL ( $2.1\text{ms}^{-2}$   
371  $\pm 0.8\text{ms}^{-2}$  for upward direction,  $1.3\text{ms}^{-2} \pm 0.4\text{ms}^{-2}$  for downward direction) tended to be lower  
372 than controls ( $4.0\text{ms}^{-2} \pm 1.7\text{ms}^{-2}$  for upward direction,  $2.9\text{ms}^{-2} \pm 1.4\text{ms}^{-2}$  for downward  
373 direction), although this was not statistically significant ( $p=0.289$ ,  $p=0.271$ ).

374 *Insert figure 5 about here*

375 Figure 6 provides boxplot summaries for baseline grip force, maximum grip force and  
376 grip-load time delay during visually-guided vertical movements. In the upward direction,  
377 GL's baseline grip force was significantly higher than controls ( $p=0.007$ ; see figure 6A).  
378 Maximum grip force was greater for GL than controls ( $p=0.003$ ; see figure 6B). GL applied  
379 maximum grip force prior to maximum load force, significantly earlier than controls  
380 ( $p=0.004$ ; see grip-load time delay figure 6C). The time series correlation between grip and  
381 load force for GL was  $0.33 (\pm 0.24)$ , lower than controls at  $0.57 (\pm 0.25)$ , but not statistically  
382 different after Fisher transformation ( $p=0.35$ ). Statistical analysis of the variability of the  
383 different variables for each participant (i.e. measures of intra-individual variability) revealed  
384 that standard deviation in the baseline grip force signals ( $p<0.001$ ), maximum grip force  
385 across trials ( $p=0.001$ ) and grip-load time delay across trials ( $p<0.001$ ) were greater for GL  
386 than for individuals of the control group.

387 For visually-guided downward movements, no significant difference in baseline grip  
388 force was observed between GL and controls ( $p=0.061$ ; see figure 6A). The patient's  
389 maximum grip force however, was significantly greater than that of controls ( $p=0.004$ ; see  
390 figure 6B). Time series correlation between grip and load force for GL was  $-0.08 (\pm 0.37)$   
391 compared to  $0.42 (\pm 0.38)$  in controls, although this was not statistically significant ( $p=0.241$ ).  
392 Statistical analysis of the variability of the different variables for each participant (i.e. intra-  
393 individual variability) revealed that standard deviation in the baseline grip force signals  
394 ( $p=0.001$ ), maximum grip force across trials ( $p<0.001$ ) and ratio of maximum grip to  
395 maximum load across trials ( $p<0.001$ ) were all greater for GL than the control group. Grip-  
396 load time delay was abnormal and particularly variable for the deafferented patient. In effect,  
397 average grip-load time delay for GL was significantly earlier at  $-621\text{ms} (\pm 537\text{ms})$  compared  
398 to  $90\text{ms} (\pm 125\text{ms})$  in controls ( $p<0.001$ ) with variability between trials for GL ( $537\text{ms}$ ) being  
399 greater than for controls (range  $21\text{ms}$ — $390\text{ms}$ ;  $p=0.001$ ).

400 *Insert figure 6 about here*

401 Figure 7A shows that for vertical movement without visual feedback, GL exhibited  
402 irregular object orientation compared to controls (figure 7B). Mean object angle was  
403 significantly greater for GL in both upward and downward movement compared to controls  
404 ( $p<0.001$ ; see figure 7C). Object orientation also tended to be more variable for GL than  
405 controls during vertical movement without visual feedback. In the downward direction,  
406 variability of the continuous object angle signals for GL was  $7.8^\circ (\pm 5.4^\circ)$ , significantly greater  
407 than for individuals in the control group at  $3.0^\circ (\pm 1.7^\circ)$ ;  $p=.015$ ). When visual feedback was  
408 available, no significant differences in object orientation were observed between GL and  
409 controls. Further statistical details on results from experiment 2 are provided in supplementary  
410 materials S2.3 (<https://figshare.com/s/840e0e8efb1e87e43157>).

411

*Insert figure 7 about here*

### 412 **3.3 Experimental task 3: Grasp, transport and placement of the object**

413 Grip force profiles for the deafferented patient appeared distinct from controls in the grasp,  
414 transport and place task. Controls exhibited maximum grip force during the lifting phase,  
415 corresponding with maximum vertical acceleration. GL tended to have a progressive increase  
416 in grip force through the transport and preparation for deposit phase. This contrast can be  
417 observed in figure 8. In addition, the duration of the transport phase appeared longer for GL.  
418 Variations in GL's object acceleration were observed late in the transport phase and followed  
419 by a strong mechanical impact at the base load sensor upon object placement (see figure 8C).  
420 Touch errors involving force signal variations prior to grasp onset and following object  
421 release, as well as push errors involving variations in the base load sensor during unloading  
422 and release phases were more flagrant for GL than controls (see figure 8E).

423

*Insert figure 8 about here*

424 Durations of the component phases are indicated in the example trials provided in  
425 figure 8 while figure 9A provides a boxplot summary of phase durations in the grasp and  
426 place task. Overall, average duration for the functional grasp, transport and place task was  
427 1.98s ( $\pm 0.15$ s) for GL, longer than for controls ( $1.29 \pm 0.28$ s;  $p=0.017$ ). More specifically, GL  
428 exhibited longer unloading ( $p=0.044$ ), transport ( $p<0.001$ ) and release phases ( $p=0.038$ ) than  
429 controls. Figure 9B shows that average grip-load force ratios were higher for GL through the  
430 unloading ( $p=0.012$ ) and descent ( $p=0.012$ ) phases compared to controls.

431

*Insert figure 9 about here*

432 Figure 9C shows that object angle was increased for GL at several phase transitions  
433 during the grasp and place task compared to controls. Statistically significant differences in  
434 object angle were seen at grasp onset ( $p<0.001$ ; c.f. touch errors below), lift onset ( $p=0.019$ ),

435 transport end ( $p=0.035$ ) and placement ( $p=0.033$ ) time points. In addition to this, average  
436 object angle across the duration of the unloading phase was greater for GL than controls  
437 ( $2.2^\circ \pm 1.3^\circ$  v.  $0.8^\circ \pm 0.5^\circ$ ;  $p=0.029$ ), and variability of alpha angle was greater during the  
438 release phase ( $1.9^\circ \pm 0.9^\circ$  v.  $0.6^\circ \pm 0.3^\circ$ ;  $p<0.001$ ).

439 A greater frequency of touch errors on grasp initiation ( $p=0.022$ ) and for push errors  
440 ( $p=0.027$ ) were recorded for GL than for controls (see figure 10A). Time series correlation of  
441 grip force and base load cell during the unloading phase was lower for GL than for controls  
442 ( $p<0.001$ ), while no significant difference was observed during the release phase (see figure  
443 10B). Further statistical details on results from experiment 3 are provided in supplementary  
444 materials S2.4 (<https://figshare.com/s/840e0e8efb1e87e43157>).

445 *Insert figure 10 about here*

### 446 **3.4 Grip force control in the deafferented patient across experimental tasks**

447 Baseline grip force for GL was found to vary across all conditions of experiment 1  
448 (perturbations of static holding) and experiment 2 (vertical upward and downward  
449 movements, with or without vision) combined ( $p<0.001$ ;  $F=15.333$ ;  $df=6$ ). Figure 11 provides  
450 a boxplot summary of the ensemble of GL's baseline grip force when holding the object  
451 across experiments 1 and 2. Baseline grip force during external perturbation without vision  
452 was greatest, with post-hoc testing indicating that it was greater than in all other conditions. In  
453 addition to this, baseline grip force was smallest in self-perturbation to static holding (with  
454 vision), with post-hoc testing indicating differences compared to external perturbation of  
455 static holding with vision ( $p<0.001$ ) and upward movements with vision ( $p<0.001$ ). No  
456 significant effect of hand was observed.

457 *Insert figure 11 about here*

458 For the deafferented patient, the ratio of maximum grip to maximum load force in vertical  
459 movements (experiment 2) with vision and the grasp and place task (experiment 3) were  
460 found to vary according to condition ( $p=0.045$ ;  $F=3.529$ ;  $df=2$ ). This ratio was greatest in  
461 downward movement and lowest in the grasp and place task, although post-hoc testing did not  
462 find any significant differences in pairwise comparisons. Comparison of grip-load time delay  
463 across vertical movements with vision and the grasp and place task yielded no significant  
464 differences. Further statistical details and tables for comparisons across experimental tasks are  
465 provided in supplementary materials S2.5 and 2.6  
466 (<https://figshare.com/s/840e0e8efb1e87e43157>).  
467 <https://doi.org/10.6084/m9.figshare.12888311>

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#### 4. DISCUSSION

472 This study assessed the influence of somatosensory feedback on object manipulation by  
473 comparing the performance of a person with chronic large fibre sensory neuropathy to that of  
474 age-matched controls. As hypothesized, grip force analysis demonstrated that the deafferented  
475 patient (GL) generally used greater grip forces than the control group during object  
476 manipulation (vertical displacement, functional grasp and place). Moreover, GL had impaired  
477 temporal coupling of grip force adjustments with respect to voluntary movement dynamics  
478 (acceleration/load force) and perturbations to static holding (self-induced and externally  
479 induced). Without visual feedback, patient ability to maintain object orientation during  
480 discrete vertical movement was significantly impaired, which confirmed the second  
481 hypothesis of this study. This impairment appeared only partially compensated by visual  
482 feedback in the functional grasp and place task, as deviations in object angle were found to be  
483 superior to that of controls at several phase transitions. Increases in the duration and average  
484 grip-force ratios for certain phases further underscored kinematic and kinetic differences in  
485 the grasp and place task for the deafferented patient.

486 Our findings appear to illustrate the important role of somatosensory signals for  
487 effective movement execution, supporting and extending previous reports of impaired fine  
488 motor skills in deafferented individuals (20, 23, 24, 26). In addition, this study presents novel  
489 findings through comparison of motor performance across different task constraints. Firstly,  
490 grip force adjustments appeared earlier for (self-initiated) discrete movement and later for  
491 perturbations to static holding in the deafferented patient. Secondly, variations in the duration  
492 of phases and average grip-load force ratios showed that the patient organises the different  
493 components of functional object handling tasks differently to people with efficient  
494 sensorimotor feedback. Finally, impairment with managing object orientation during vertical  
495 movements and the grasp and place task conveys the strengths and limits of the use of visual  
496 feedback to compensate for the loss of somatosensory feedback. Overall, these findings  
497 provide insight into the integrity of anticipatory control mechanisms and the use of  
498 compensatory control strategies of individuals deprived of limb somatosensory feedback  
499 during object handling.

500

#### 501 **4.1 Feedforward modelling and pre-emptive regulation of grip force control**

502 The motor behaviour observed across the three experiments highlights different aspects of  
503 anticipatory control in the deafferented patient. In certain circumstances, GL demonstrated  
504 anticipatory finger force adjustments indicative of feedforward control processes. This was  
505 most evident in self-induced perturbation to static holding (experiment 1). Here the patient's  
506 grip force increased prior to impact, in preparation for the self-induced perturbation (figure 3).  
507 Also, in the functional grasp and place task, GL increased grip forces in parallel to the load  
508 variation during the unloading phase (figure 8E), albeit with reduced sensitivity to load forces  
509 than controls (figures 9B, 10B). Increasing grip force in anticipation of load perturbation  
510 during holding (35, 52), and in parallel to load force increase during lifting (9, 43) is

511 indicative of feedforward modelling where the consequences of one's intended action upon  
512 the configuration of the body, object and environment are thought to be inferred based on an  
513 efferent copy of the descending motor command (53).

514         The deafferented patient's ability for feedforward grip force control was less evident  
515 during discrete vertical movement (experiment 2). While grip forces of control participants  
516 tended to vary in parallel with object acceleration, the deafferented patient exhibited a more  
517 progressive change. For example, during upward vertical movements, GL's grip forces tended  
518 to start high and decrease gradually (figure 5). GL's peak grip force occurred well in advance  
519 (~400ms) of peak acceleration (figure 6C). The increased baseline was not only seen in  
520 upward movements (experiment 2, figure 6A) but also seemed somewhat apparent in the  
521 externally-induced perturbation conditions (experiment 1, figures 2,4A) and might be  
522 interpreted as grip force adjustments in anticipation of the initiation of movement. In effect,  
523 the deafferented patient seems to pre-emptively set high baseline grip forces for impending  
524 load variations.

525         We venture that specific task constraints influenced the mode of anticipatory control  
526 employed by the deafferented patient. In conditions when the hand was relatively still (self-  
527 imposed perturbation, unloading phase of grasp and place), feedforward control for  
528 synchronous grip-load force adjustment was a viable strategy for the patient (experiment 1,  
529 figures 3, 4C; experiment 3 figure 10B). In tasks involving object displacement however (e.g.  
530 vertical movement), the patient seemed to apply an increased grip force safety margin prior to  
531 movement onset (experiment 2, figures 5A, 6C). In the case of external perturbation to  
532 holding, healthy participants may exhibit preparatory actions (~200ms before event) (35).  
533 Here again though, the deafferented patient still appeared to pre-set grip forces. Anticipatory  
534 control for the deafferented patient may thus involve distinct cognitive strategies to



535 compensate for situations where dynamic postural configuration or external loads are difficult  
536 to determine.

537

#### 538 **4.2 Compensation for somatosensory deficits in reactive grip force scaling**

539 The experimental conditions examining externally induced perturbation of static holding, with  
540 vision and without vision, provide some insight into feedback mechanisms involved in  
541 reactive grip force scaling. In these conditions, the deafferented patient was found to have an  
542 increased grip response time when compared to the control group. Despite these temporal  
543 discrepancies, differences in the scaling of the grip force response with respect to the force  
544 applied to the handheld object were less pronounced than may have been expected (figure  
545 4C). In the absence of tactile information pertaining to the state of the hand-object interface or  
546 proprioceptive stimulus pertaining to variations in joint position, the deafferented patient had  
547 limited direct access to mechanical features of the perturbation. From the observations  
548 presented here, it may thus be inferred that a deafferented patient uses other sensory  
549 modalities (albeit with greater latencies) to gauge the required grip force response.

550 For external perturbation with visual feedback, the deafferented patient may have  
551 adjusted grip forces based upon either her own arm movement or that of the person striking  
552 the object. Several studies (39, 54) have indicated that people are capable of identifying a  
553 change in their own arm trajectory and generate a corrective response within ~150ms. Further,  
554 healthy adults prove highly receptive to the motion of other individuals (55). Using visual  
555 information of another person's body movements, adult participants can be highly accurate at  
556 determining the effects of that person's arm movement (56). Significant information may  
557 even be extrapolated from the other person's preparatory actions (57, 58). It is thus plausible

558 that a deafferented patient can use visual perceptual capacities of human movement (40, 59,  
559 60) for determining the magnitude of the perturbation and thus the appropriate response.

560 The deafferented patient's ability to scale grip force during external perturbation in the  
561 blinded condition is more perplexing. Johansson et al (34) reported that certain participants  
562 managed to exhibit grip force adjustments in response to a pulling load despite having  
563 temporarily anaesthetised digits and their vision obscured. These participants may have relied  
564 on more proximal mechanoreceptors to mediate the grip force response. Similarly, Miall et al  
565 (60) found that deafferented patients detected unseen perturbations to reaching movements in  
566 a dynamically-perturbed environment (albeit with a higher threshold than controls). Several  
567 authors have also suggested that deafferented individuals may use vestibular feedback as a  
568 trigger for motion detection (61–63). In principle, the effects of arm oscillations upon the  
569 trunk and neck may provide the vestibular organs some crude information regarding load  
570 variations (25). In catching tasks, muscular cocontraction through the upper limb is  
571 commonly seen in anticipation of contact (64). It could be envisaged that in the case of static  
572 holding, an exaggerated pattern of cocontraction may assist in leveraging the effects of the  
573 distal perturbation and improve transmission of the mechanical stimulus to vestibular  
574 apparatus (59). The use of EMG and additional kinematic data would assist to verify this  
575 hypothesis.

576 The auditory stimulus associated with the impact represents another potential mode for  
577 the grip force adjustments observed during external perturbation without visual feedback.  
578 Using an experimental study on upper limb gestures, Danna & Velay (65) illustrated that task  
579 sonification had a greater impact upon motor learning in deafferented patients (including GL)  
580 than controls. These authors advanced that these patients may indeed develop a supranormal  
581 capacity to process auditory information through cross-modal compensation as observed

582 between sight and audition (66). Again, future studies manipulating auditory feedback with  
583 deafferented individuals would be required to further examine this question.

584

### 585 **4.3 Object handling across sequential phases in functional grasp and place**

586 The differences in the duration of the phases of the grasp and place experiment provide  
587 insight into how the deafferented patient manages a functional object manipulation task. The  
588 unloading, transport and release phases were notably longer for the deafferented patient  
589 (figure 9A). Importantly, (vertical) object acceleration increased late in the transport phase  
590 and tended to spike upon placement (e.g. figure 8C, see also discussion of “micro-errors” in  
591 (43)). These changes in movement dynamics were associated with a corresponding grip force  
592 increase. Our findings thus suggest that the deafferented patient “restructures” the grasp and  
593 place task to overcome the somatosensory deficit. Increased grip force during unloading may  
594 ensure that grasp is indeed established prior to object displacement (10), while the greater  
595 duration in the transport phase may be associated with the use of a visuomotor control  
596 strategy (67). Vertical acceleration late in the transport phase may represent a kinematic  
597 strategy whereby a late vertical movement serves to ensure that the object arrives completely  
598 above the deposit platform. Finally, as upper limb proprioception is essential for controlling  
599 hand velocity (68), increased grip force during descent may serve to ensure object stability  
600 when considering the expected shock upon placement. Despite the reorganization in  
601 movement strategy, the deafferented patient was more irregular in the sequence of sub-goals  
602 as evidenced by a greater rate of “touch” and “push” errors. Changes in the grip force,  
603 acceleration profiles and temporal organisation of grasp and reach might thus be seen as both  
604 consequence of, and compensation for, the loss of tactile and proprioceptive feedback.

605           The effect of somatosensory dysfunction on the ability to regulate orientation of the  
606 handheld object represents one of the more novel findings of this study. Healthy participants  
607 are particularly skilled at maintaining vertical object orientation across tasks (43). In contrast,  
608 the deafferented patient exhibited marked difficulties to stabilize the object. This was most  
609 apparent at moments which coincided with changes in task dynamics in the functional  
610 prehensile task, those being grasp onset, lift onset, transport end and object placement. Again,  
611 it is likely that deafferented patients' impairments in intersegmental coordination (68) at these  
612 instants make phase transitions particularly vulnerable to instability of the handheld object.  
613 Given the deafferented patient's impaired ability to maintain object orientation during vertical  
614 movement in the absence of visual feedback (experiment 2), it appears that peripheral  
615 somatosensory feedback is critical for maintaining object orientation as the task constraints  
616 change with each sub-goal. Recent experimental findings (69) have suggested that  
617 proprioception is necessary for body schema plasticity which underlies tool use. As a  
618 consequence, a deafferented patient may tend to use more external reference frames than  
619 healthy participants, which is consistent with what (70) reported for GL in a perceptual task.  
620 However, in an object manipulation task, as in the present study, visual feedback control of  
621 the hand-object system with respect to the external environment likely requires greater  
622 processing time than proprioceptive feedback control (71), and may thus be more vulnerable  
623 to difficulty with maintaining the vertical orientation of the handheld object at dynamic phase  
624 transitions. Furthermore, GL was recently found to have altered patterns of finger enslaving  
625 (resulting in greater individuation) (23), and this may render the task of managing the torque  
626 generated between thumb and fingers, more complex than for a healthy participant.

#### 627 **4.4 Limitations of the study**

628 Several limitations should be recognized in the current study. Most importantly, perturbation  
629 stimulus from experiment 1 was not precisely controlled via an automated process.  
630 Nonetheless, the methods used here sought to limit the consequences through selection of

631 comparable stimulus based upon the magnitude, duration and loading rate of the force pulses  
632 (per <https://figshare.com/s/840e0e8efb1e87e43157>).  
633 <https://doi.org/10.6084/m9.figshare.12888311>

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635

636 In addition to this, further experimental apparatus including EMG and kinematic analysis  
637 would have provided further insight into the coordination of muscular activity and movement  
638 of the upper limb more generally. Finally, the present study included a modest number of  
639 trials for each experimental condition and only one deafferented patient. The results observed  
640 with GL in the current study may not necessarily generalize to other deafferented patients. In  
641 effect, differences in dexterous motor control was observed across deafferented patients in  
642 prior studies (25, 60). Accordingly, we would anticipate that other individuals may potentially  
643 employ alternative perceptual strategies for informing fast volitional responses to  
644 perturbations, or motor planning strategies in restructuring functional prehensile tasks.

645

## 5. CONCLUSION

646 A patient with chronic large fibre sensory neuropathy used different motor control strategies  
647 with respect to controls, highlighting the role of somatosensory feedback for object  
648 manipulation. Feedforward strategies were used for anticipatory grip force adjustment during  
649 self-induced perturbation and the unloading phase of a grasp and lift task in the deafferented  
650 and control participants, although increased grip-load ratios and increased response times  
651 illustrated that the integrity of this system was less effective when deprived of somatosensory  
652 feedback (26). Also, pre-emptive changes in baseline grip forces suggested that the  
653 deafferented patient used a cognitive strategy to estimate impending task dynamics and set  
654 grip force safety margins accordingly.

655

Despite temporal delays, the correlation of reactive grip force scaling suggests that  
656 alternative afferent signals (vision, not excluding audition and vestibular system) partially

657 compensated for the loss of tactile and proprioceptive signals. Recognising an individual  
658 aptitude with remaining sensory modalities may explain differences in motor performance  
659 between deafferented patients (25), or be harnessed using assistive devices involving sensory  
660 substitution (72). In a functional grasp and place task, certain phases were found to be  
661 prolonged in the deafferented patient, while other phases were characterized by increased  
662 grip-load force ratios. In addition, orientation of the object angle at several phase transitions  
663 deviated more greatly for the deafferented patient than for control participants. This illustrates  
664 the functional consequences of peripheral lesions to the somatosensory system and  
665 underscores the use of novel strategies used by the deafferented patient to mitigate deficits in  
666 everyday tasks such as object handling.

667

668 **Acknowledgments:** We would like to acknowledge the important contributions of the  
669 reviewers and the associate editor during the revision of the present manuscript. We also wish  
670 to thank those who gave their time to participate in this study. In particular, we are very  
671 grateful to the patient, GL, who sadly passed away (due to an unrelated medical condition)  
672 during revision of this article. We extend our heartfelt condolences to those who knew her,  
673 and dedicate this paper to her memory.

674 **Funding:** This work was supported by funding from the Labex SMART project (ANR-11-  
675 LABX-65), Investissements d'Avenir programme (ANR-11-DEX-0004-02) as well as the  
676 CNRS AUTON initiative (project SUBLIMA).

677

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880 Figure 1. Illustration of the iBox device and the experimental setup. (A) The iBox  
881 instrumented object. (B) Layout of the tabletop for the grasp, transport and place task. Initial  
882 positions of the iBox and hand start area are indicated by the dotted lines. The gray shaded  
883 rectangle indicates the deposit platform.

884 Figure 2. Experiment 1: Representative examples of grip force profiles for perturbation to  
885 static holding for the deafferented patient (GL, red) and one control subject (C7, blue). The  
886 perturbation is indicated by the signal from the upper load cell, in black. (A/B) Grip force  
887 during self-induced perturbation. (C/D) Grip force during external perturbation with visual  
888 feedback. (E/F) Grip force during external perturbation without visual feedback. Vertical lines  
889 indicate the moment of the strike to the upper surface of the iBox. Examples have been  
890 specifically chosen with comparable force perturbation ( $9N \pm 0.7N$ ).

891 Figure 3. Experiment 1: Preparatory grip force increase in self-induced perturbation. Grip  
892 force profiles for the deafferented patient (GL, red, left panel) and one representative control  
893 subject (C7, blue, right panel) during the 500ms preceding the strike to the upper surface of  
894 the iBox. Vertical line at 0ms indicates the moment of strike to the upper surface of the iBox.  
895 Arrows indicate approximate onset of grip force increase.

896 Figure 4. Experiment 1: Boxplot summary of results for perturbation of static holding in self-  
897 induced (Self), externally induced with visual feedback (External), and externally induced  
898 without visual feedback (Ext-Blinded) conditions. (A) Baseline grip force prior to  
899 perturbation. (B) Grip response time between peak force upon the upper surface of iBox and  
900 maximal grip force. (C) Pearson correlation between maximum force of strike to upper load  
901 cell and the maximum grip forces (calculated on  $n=20$  trials per subject). Blue boxplot data  
902 indicates mean values for the control group, red lines indicate mean values for the  
903 deafferented patient. Blue asterisks indicate significant results for post-hoc tests between  
904 conditions in the control group. Red asterisks indicate significant differences between the  
905 deafferented patient and the control group using the method described by (50). \* =  $p < 0.05$ , \*\*  
906 =  $p < 0.01$  \*\*\* =  $p < 0.001$ .

907 Figure 5. Experiment 2: Examples of upward vertical movements with the iBox for the  
908 deafferented patient (GL, red) and one representative control subject (C5, blue). (A/B) Grip  
909 force profiles. (C/D) Vertical (along the Y axis) acceleration of the object. (E/F) Alpha angle  
910 of the object, indicating deviation from the vertical. Vertical lines indicate onset of vertical  
911 movement.

912 Figure 6. Experiment 2: Boxplot summary of results for upward vertical movements. (A)  
913 Baseline grip force in visually guided movements. (B) Maximum grip force in visually guided  
914 movements. (C) Grip-load time delay for visually guided movements. Blue boxplot data  
915 indicates values for control group data, red lines indicate mean values for deafferented patient.  
916 Red asterisks indicate significant differences between the deafferented patient and the control  
917 group using the method described in (50). \*\* =  $p < 0.01$ , \*\*\* =  $p < 0.001$ .

918 Figure 7. Experiment 2: Object orientation during vertical movement. (A/B) Object  
919 orientation profiles during upward movement without visual feedback for the deafferented  
920 patient (GL, red) and one representative control subject (C1, blue). (C) Boxplot summary of  
921 average object orientation during vertical movement. Blue boxplot data indicates values for  
922 control group data, red lines indicate mean values for deafferented patient. Red asterisks  
923 indicate significant differences between the deafferented patient and the control group using  
924 the method described in (50). \*\*\* =  $p < 0.001$ . Lightning symbol indicates a break in the  
925 vertical axis for figure 7C.

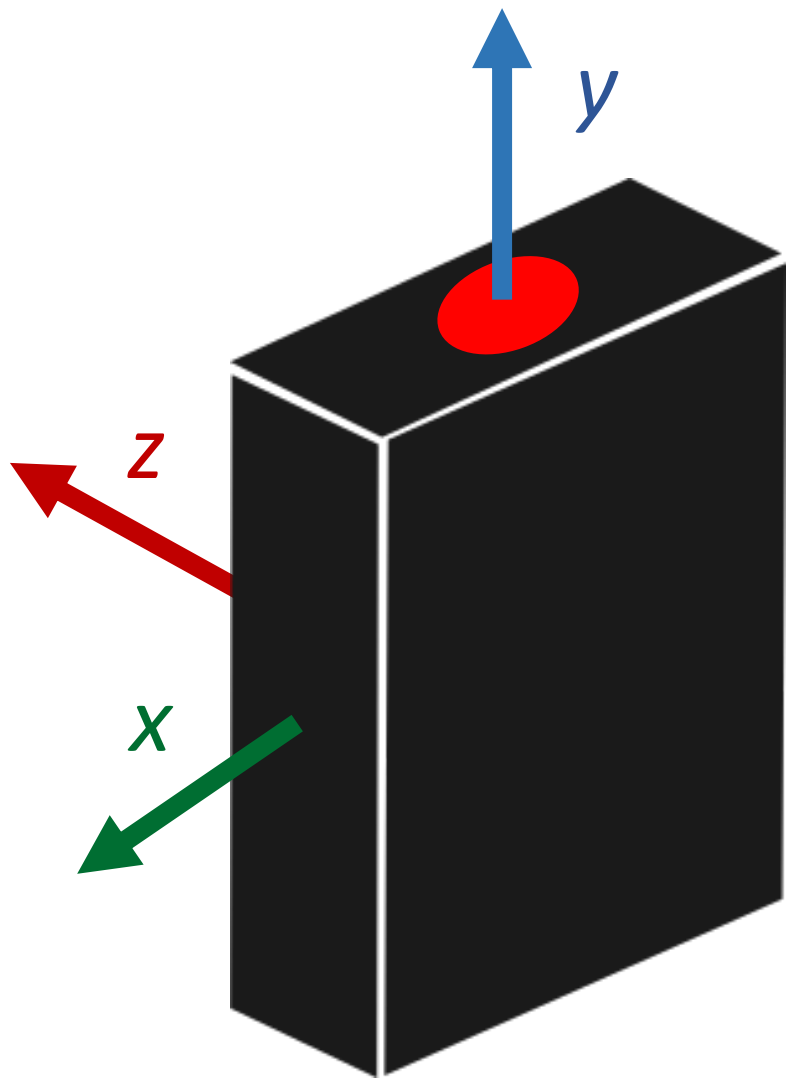
926 Figure 8. Experiment 3: Examples of signals from grasp, transport and place task for  
927 deafferented patient (GL, red) and one control subject (C1, blue). (A/B) Angle measuring the  
928 deviation of the iBox from the vertical. (C/D) Vertical (along the Y axis) acceleration of the  
929 iBox. (E/F) Grip force (plain line) during grasp, transport and place task. Object loading  
930 (dashed lines) is indicated using force data from load cell on the base of the iBox. Vertical  
931 lines indicate the times of transitions between phases  $gr$  = grasp onset;  $li$  = lift onset,  $tr$  =  
932 transport onset;  $te$  = transport end;  $pl$  = placement;  $re$  = release end. Time = 0 at  $tg$ . Arrows  
933 indicate instance of touch errors prior to establishing grasp and push errors during the  
934 unloading and release phases.

935 Figure 9. Boxplot summary of results for grasp, transport and place task. (A) Duration of  
936 component phases during the task. (B) Average grip-load force ratio during the different  
937 phases. (C) Object angle at transitions between phases of the task. Blue boxplot data indicates  
938 values for control group data (crosses indicate outliers), red lines indicate mean values for  
939 deafferented patient. Red asterisks indicate significant results for comparisons between the  
940 deafferented patient and the control group using the method described by (50). \* =  $p < 0.05$ , \*\*  
941 =  $p < 0.01$ , \*\*\* =  $p < 0.001$ .

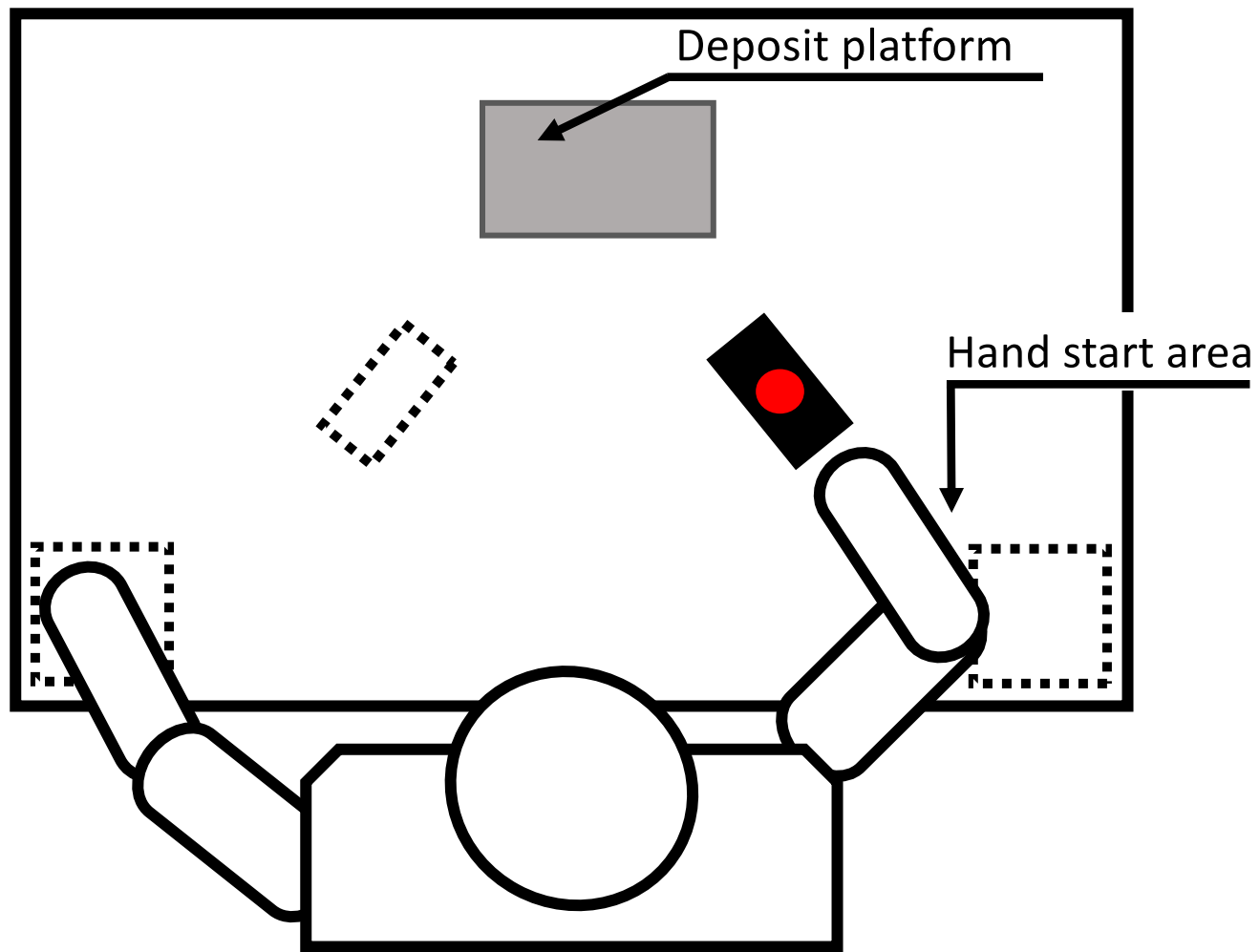
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943 Figure 10. (A) Frequency of touch errors prior to onset of grasp, and push errors through the  
944 unloading phase. NB: Absence of variation precluded establishing quartile values for touch  
945 error boxplot, for this reason, individual values are projected on the median bar line for  
946 clarity. Crosses indicate outliers. \* = Chi-squared test  $p < 0.05$ . (B) Correlation between grip  
947 force and force of the base load sensor of instrumented object during unloading and release  
948 (loading) phase. Correlation data is presented as an absolute value. Deafferented patient data  
949 is indicated in red while control subject data is indicated in blue. Statistical differences for  
950 correlation values have been calculated after Fisher transformation. \*\*\* =  $p < 0.001$  using  
951 method described in (50).

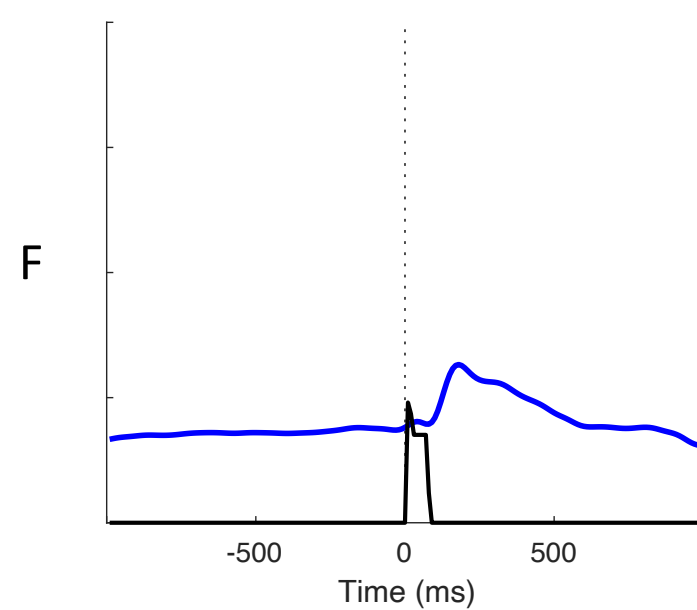
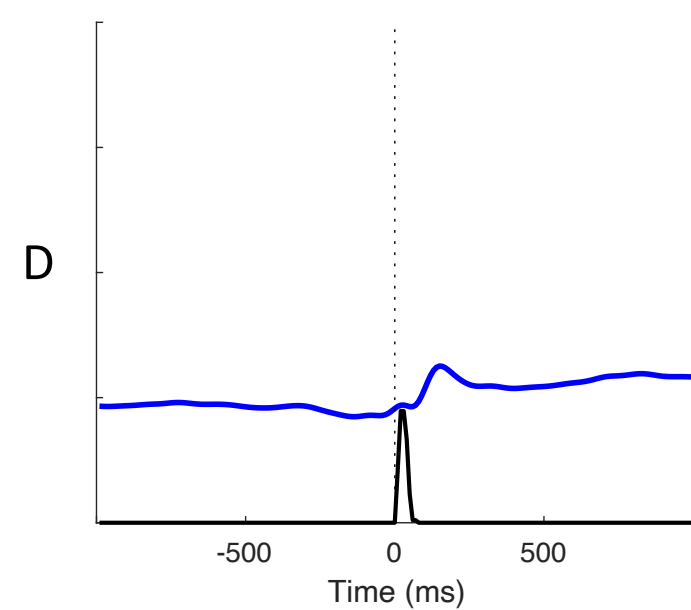
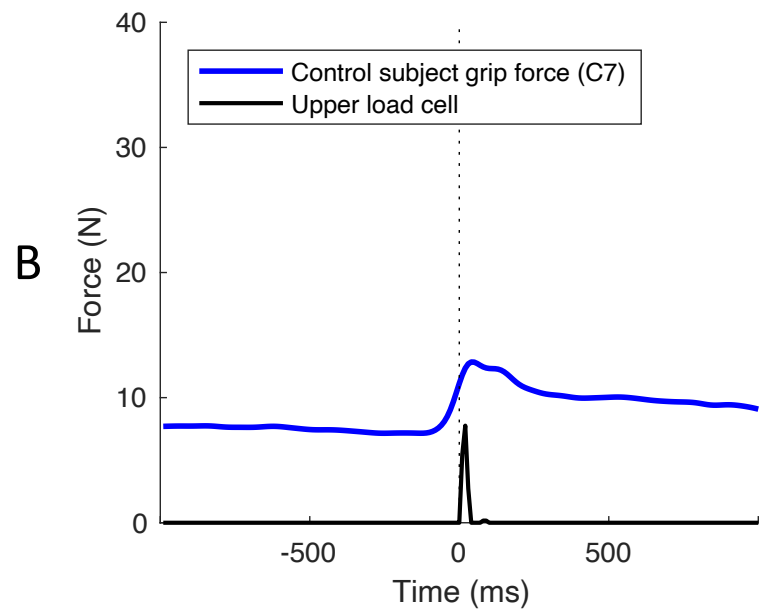
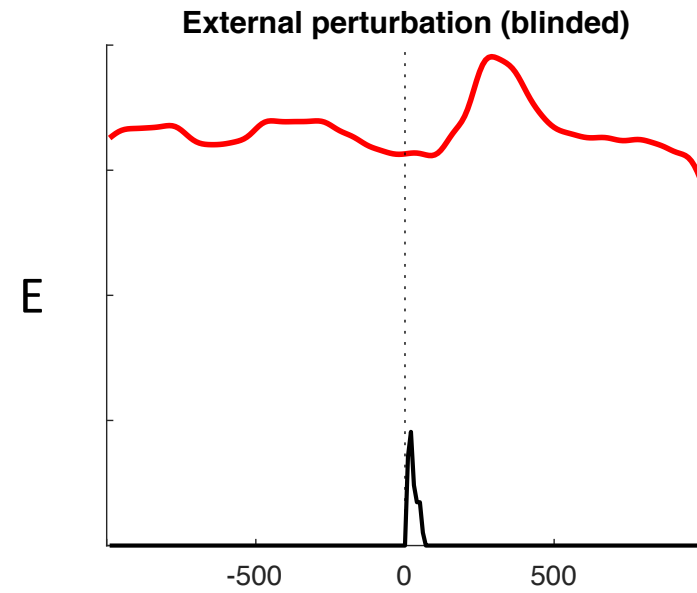
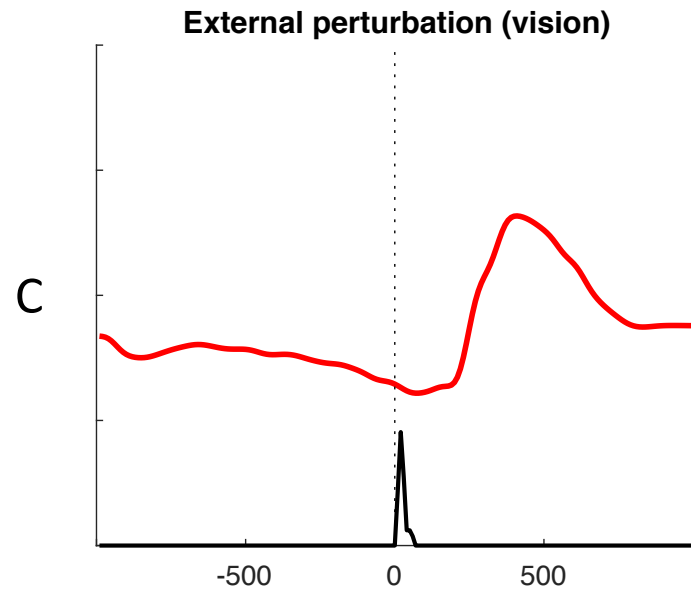
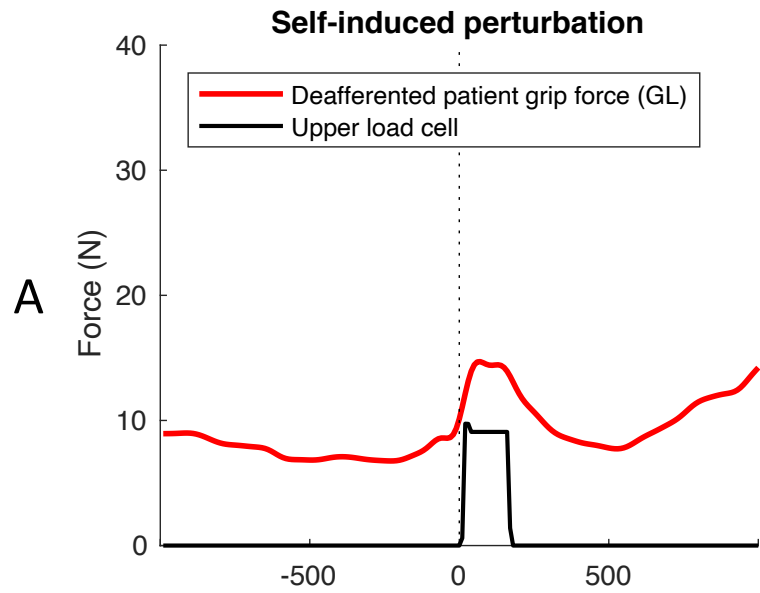
952 Figure 11. Baseline grip force for the deafferented patient across tasks with static holding  
953 phases. Black asterisks indicate results from post-hoc testing. \* =  $p < 0.05$ , \*\* =  $p < 0.01$ , \*\*\* =  
954  $p < 0.001$ .



A

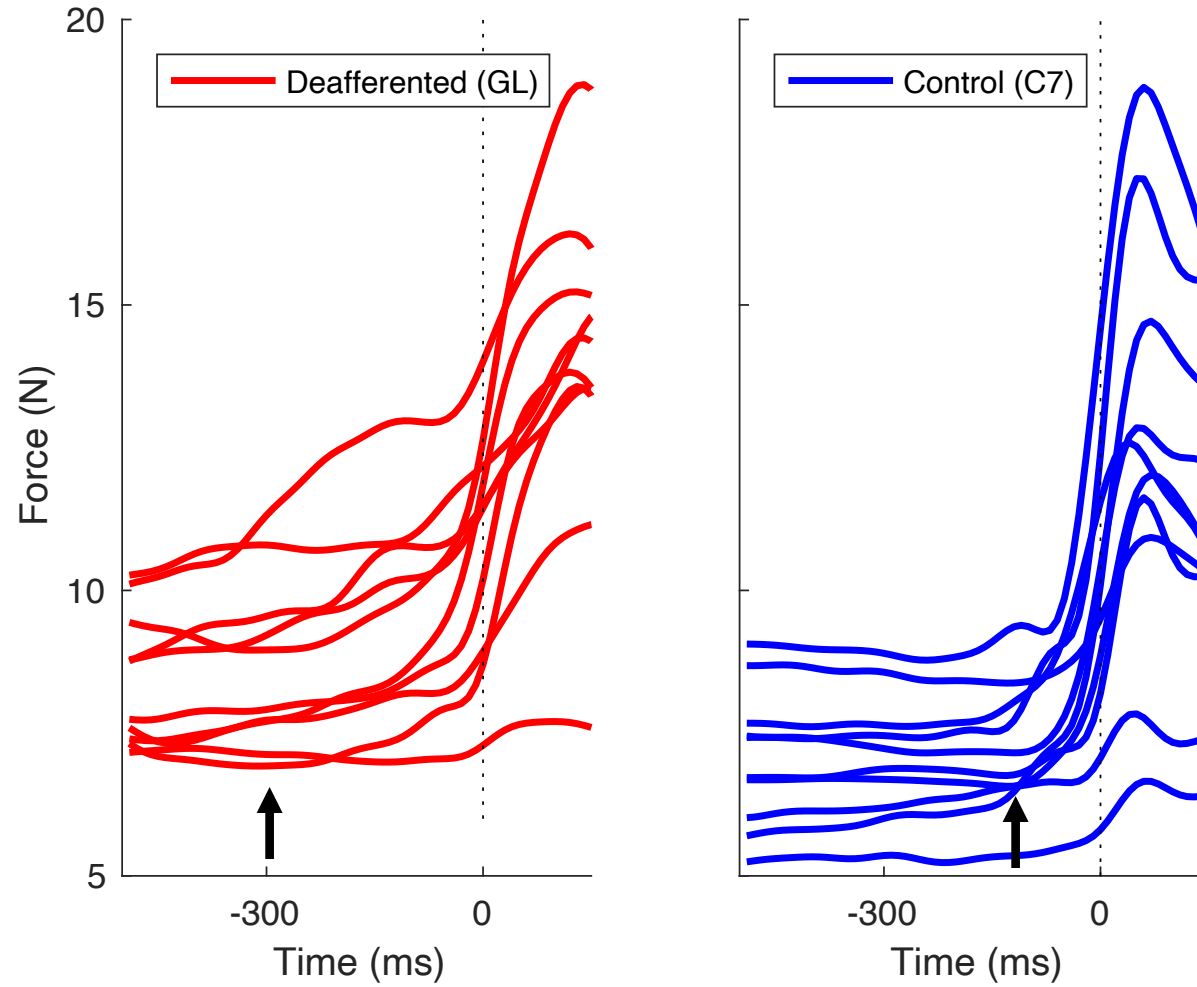


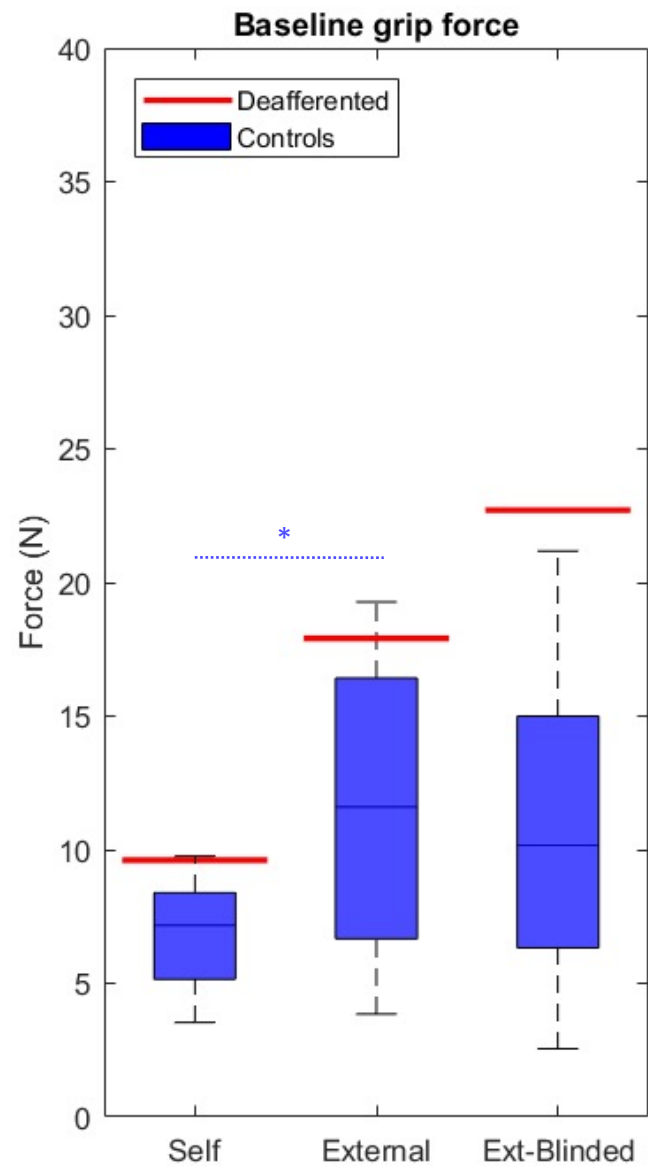
B



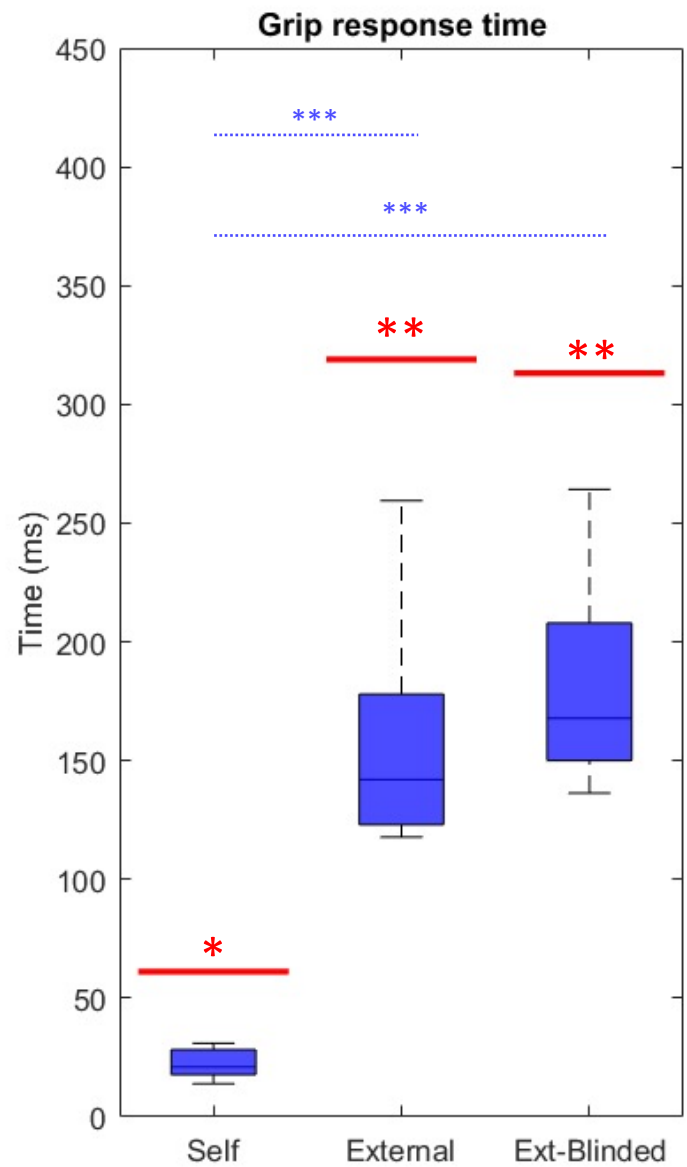


### Preparatory actions in self-induced perturbation

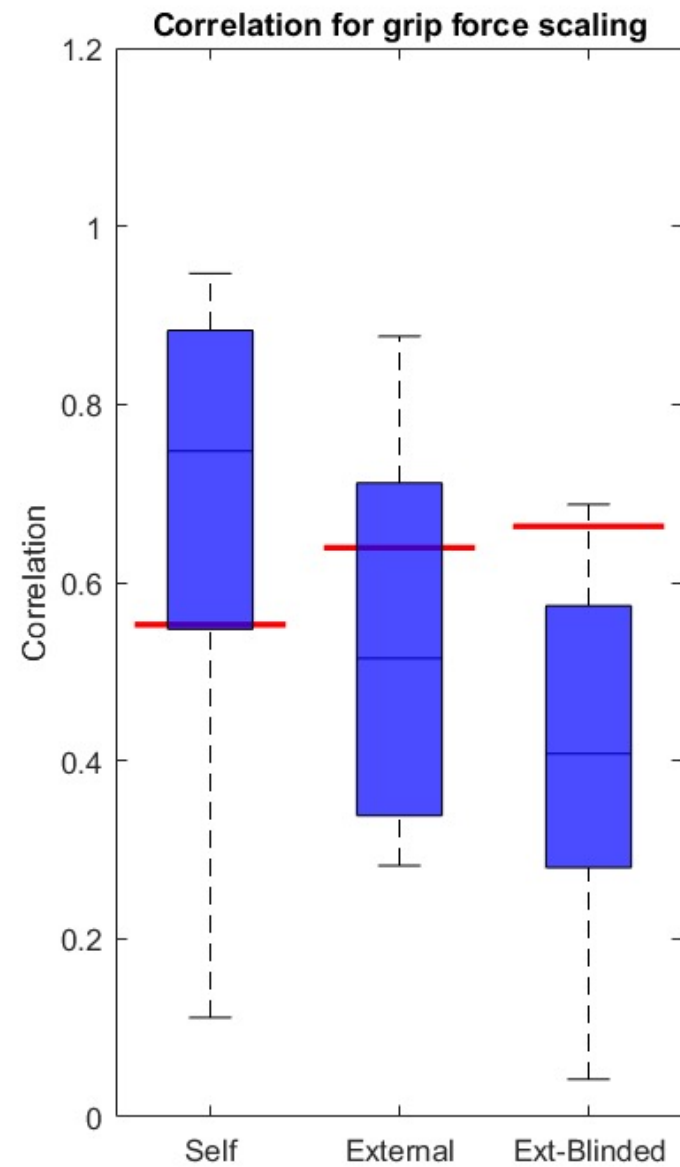




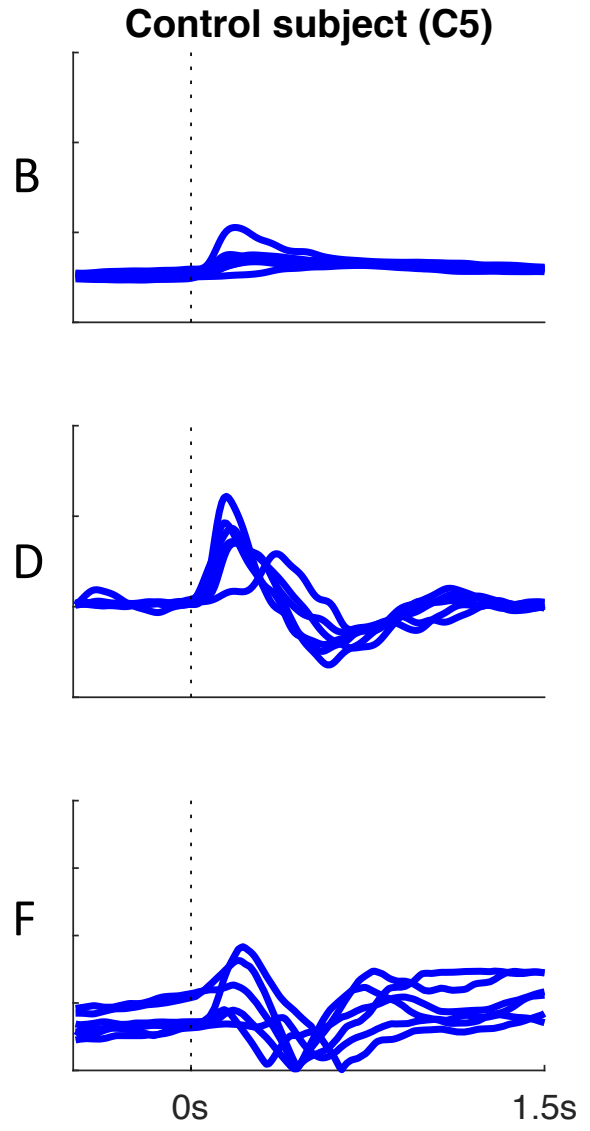
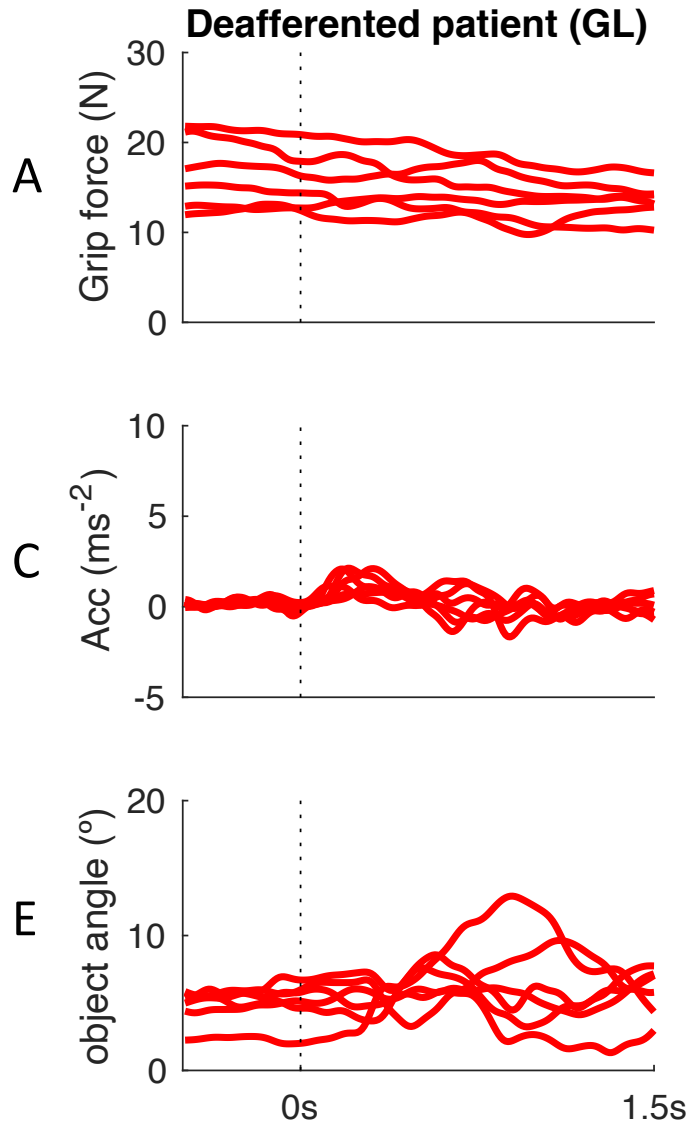
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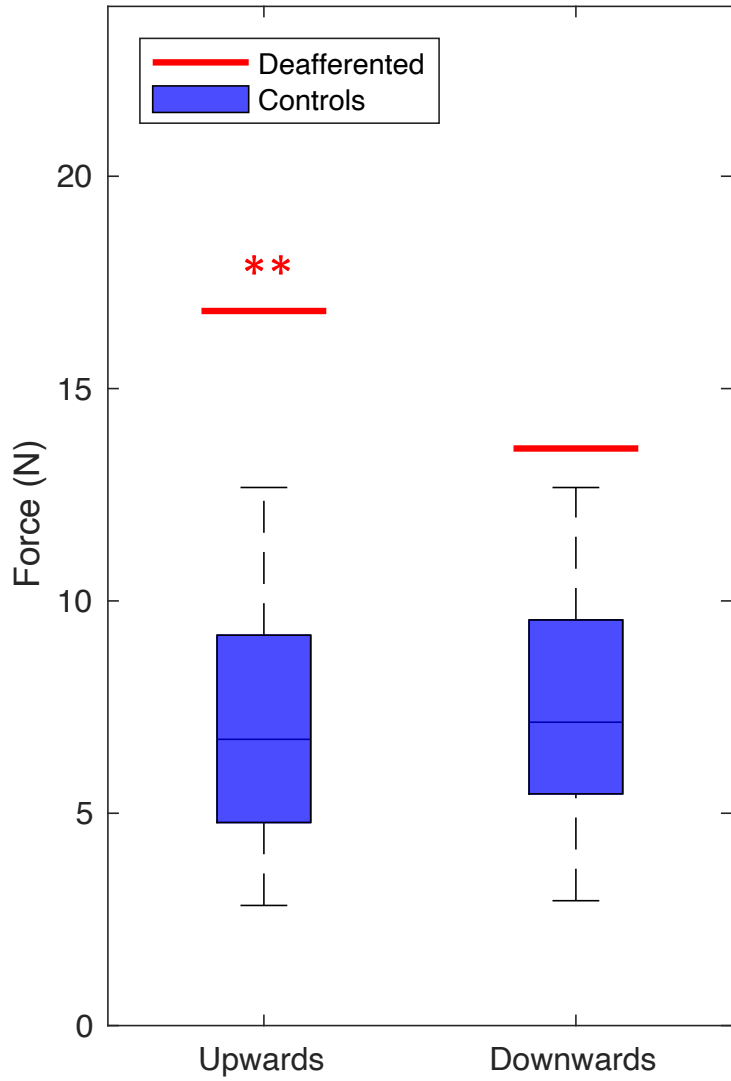
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C

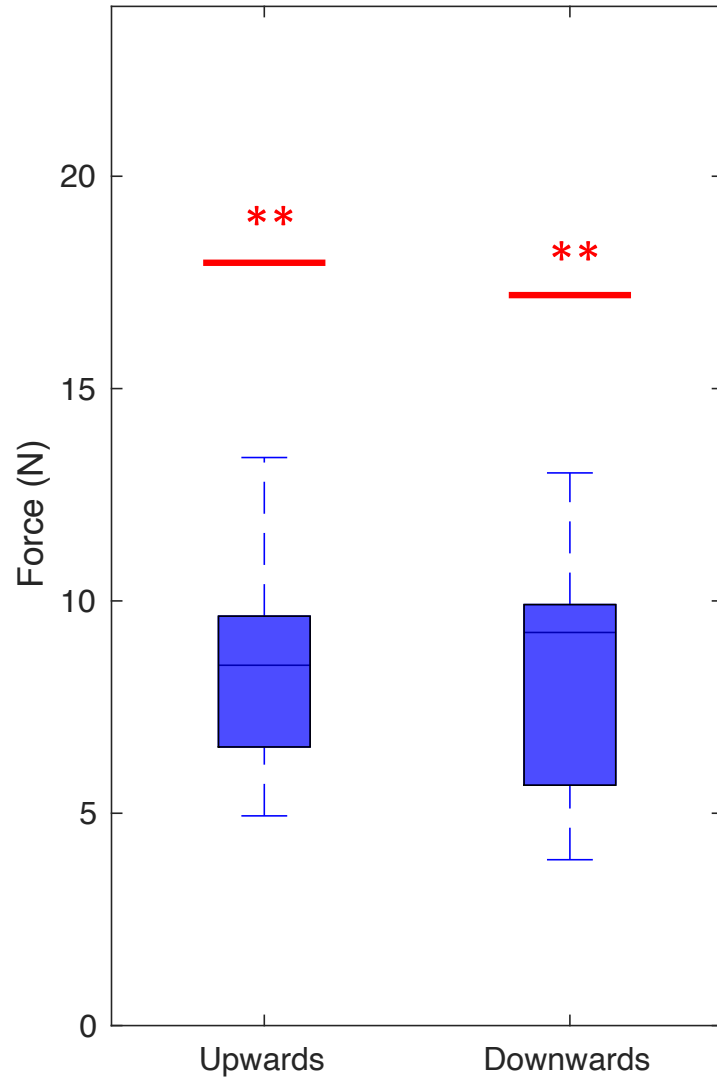


**Baseline grip force**



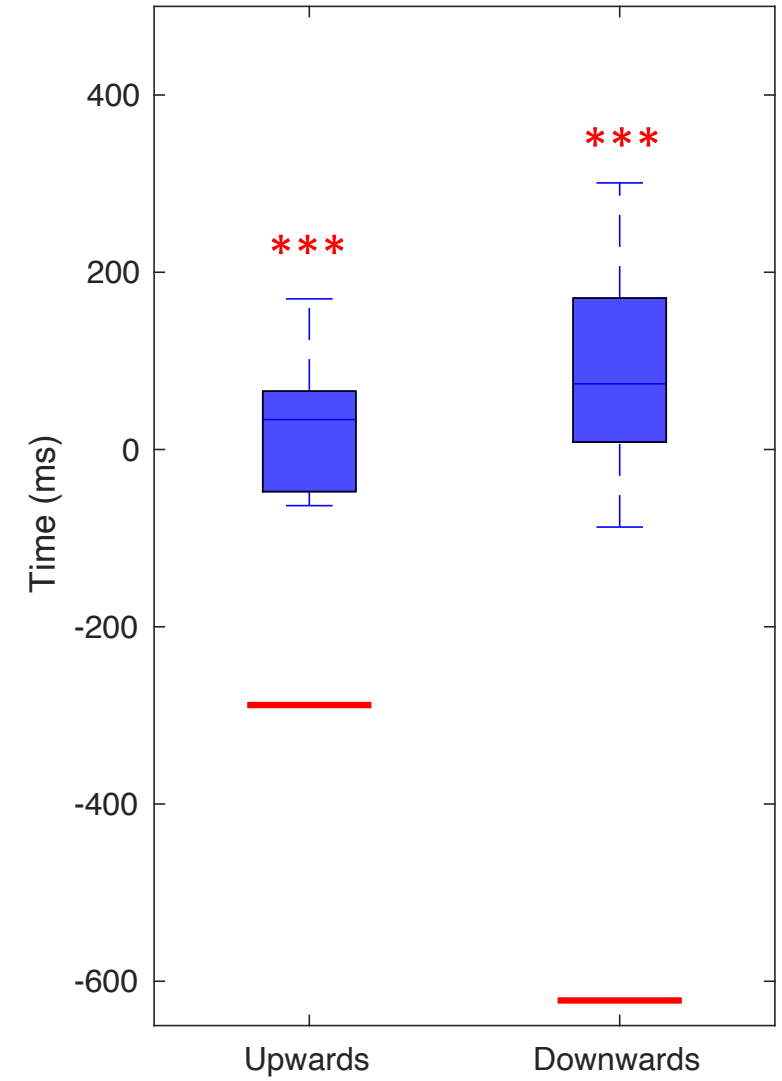
A

**Maximum grip force**

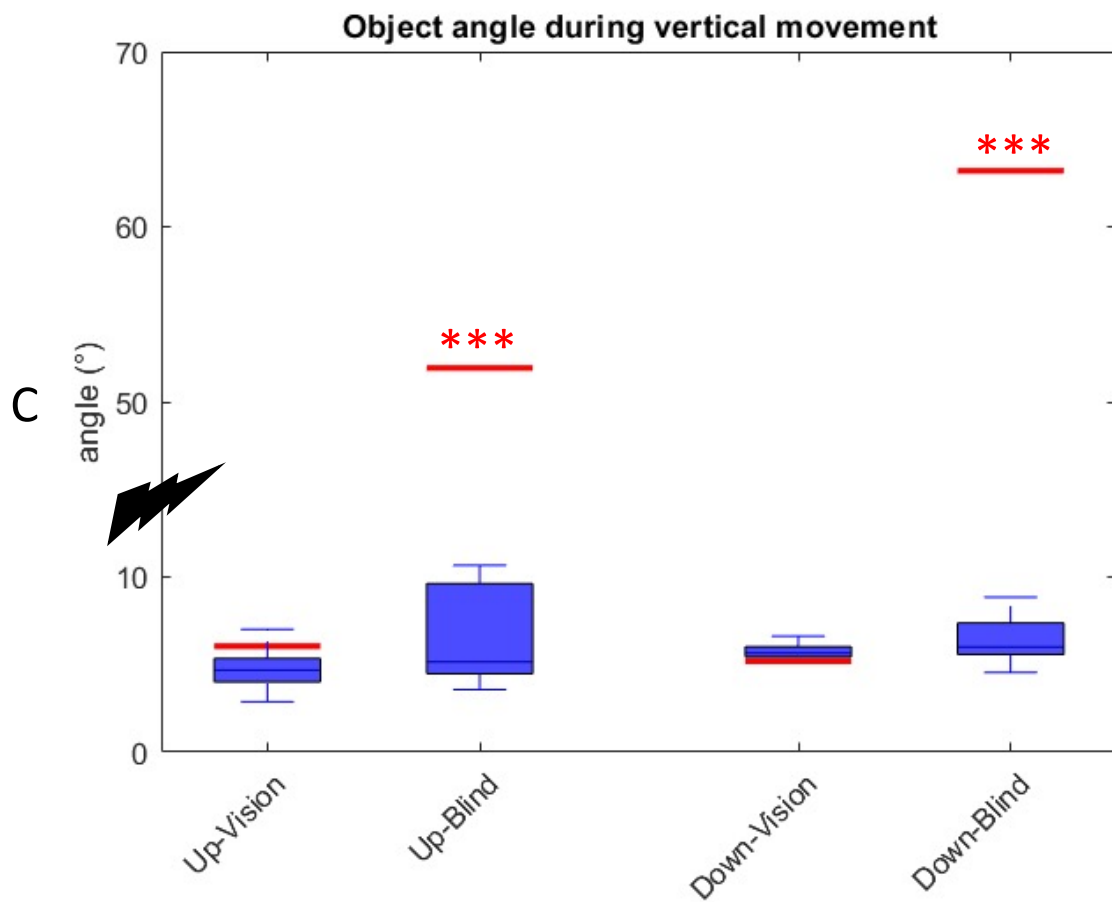
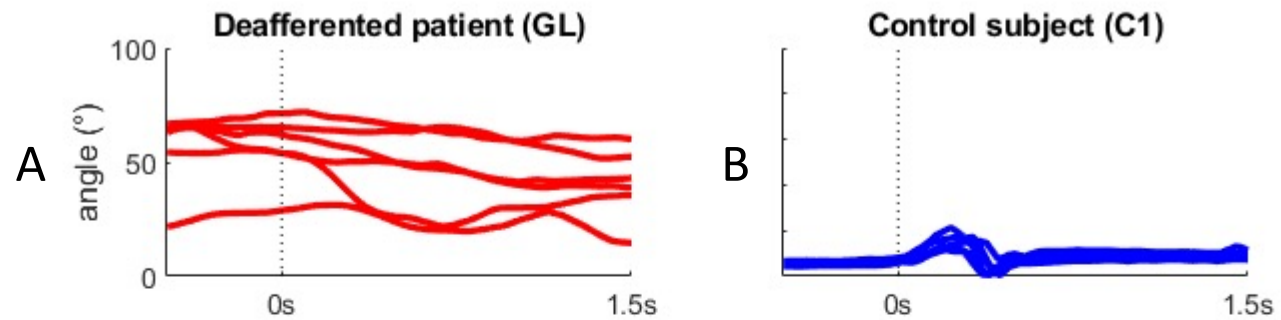


B

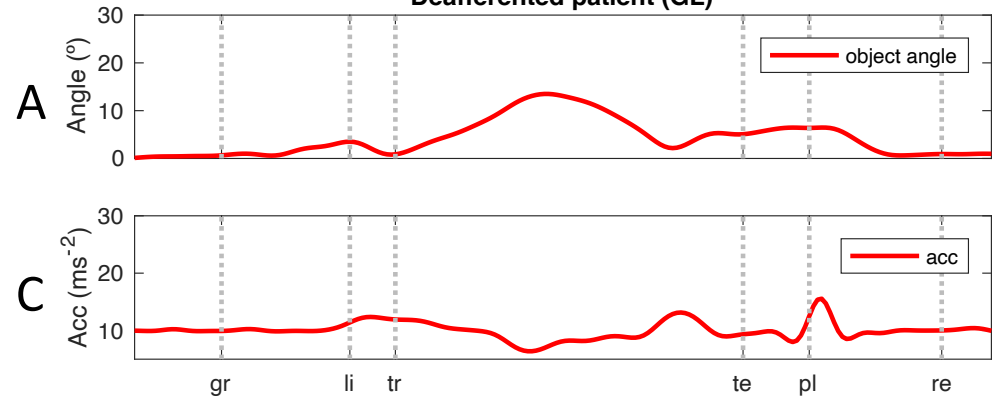
**Grip-load time delay**



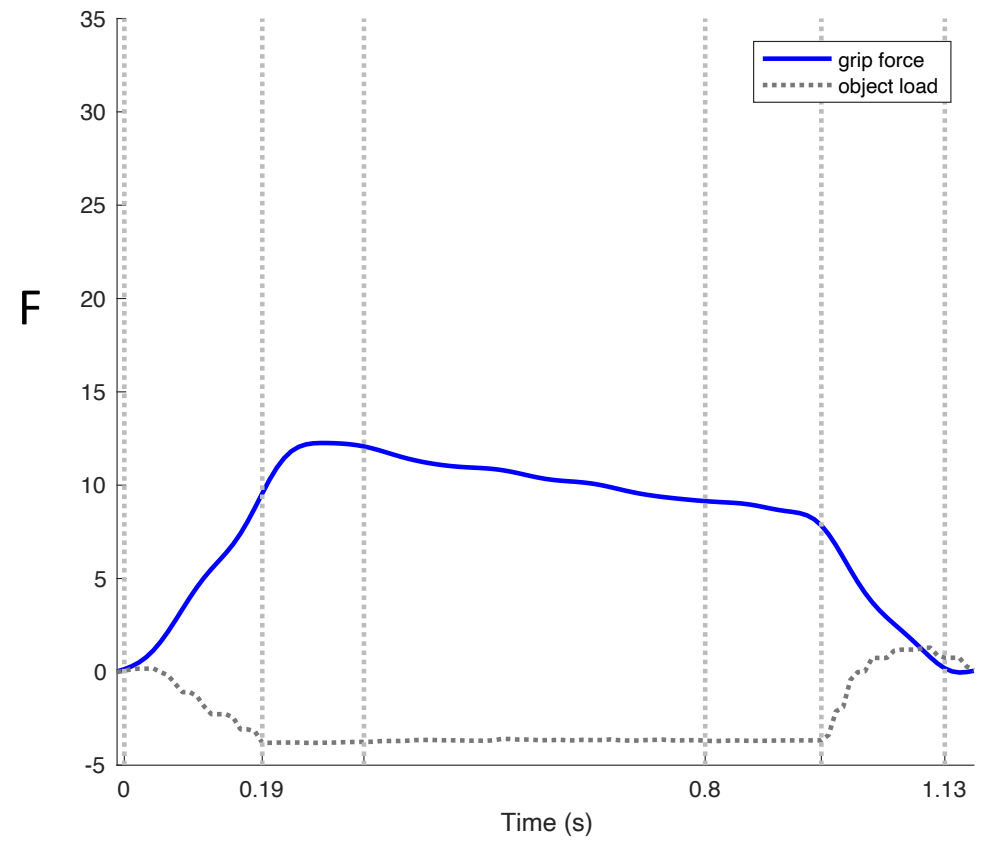
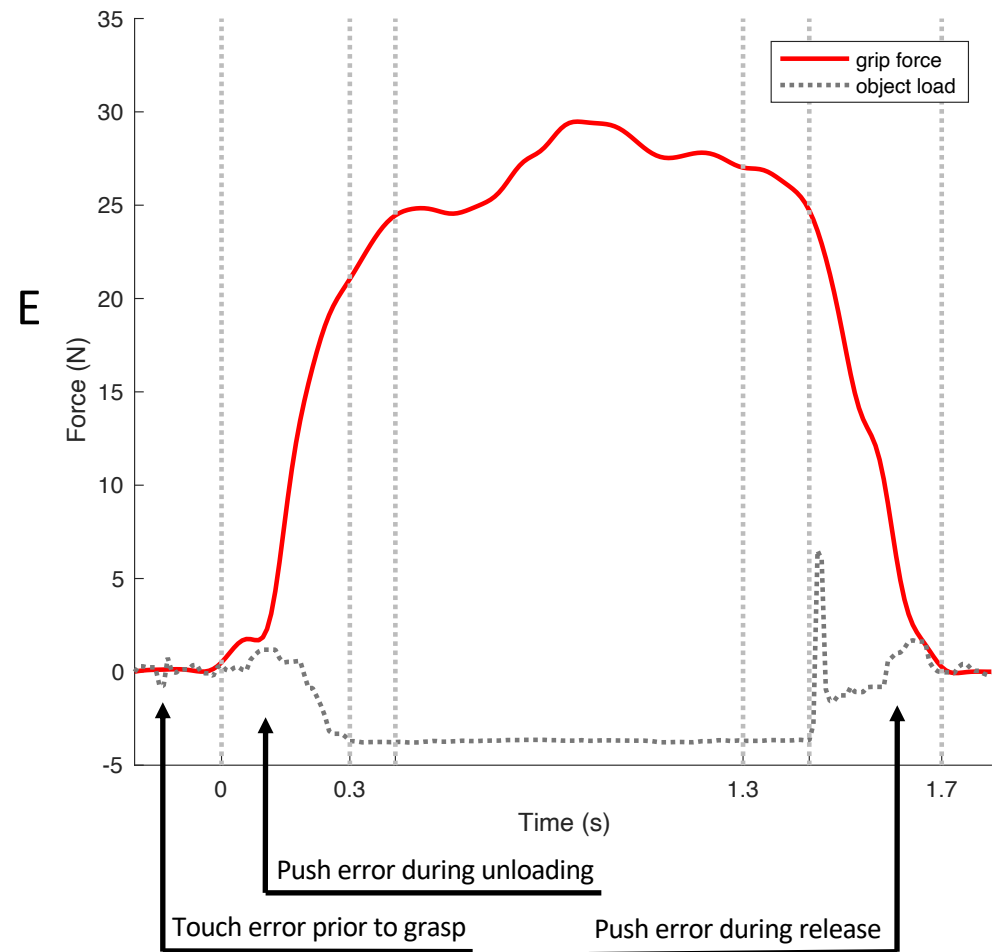
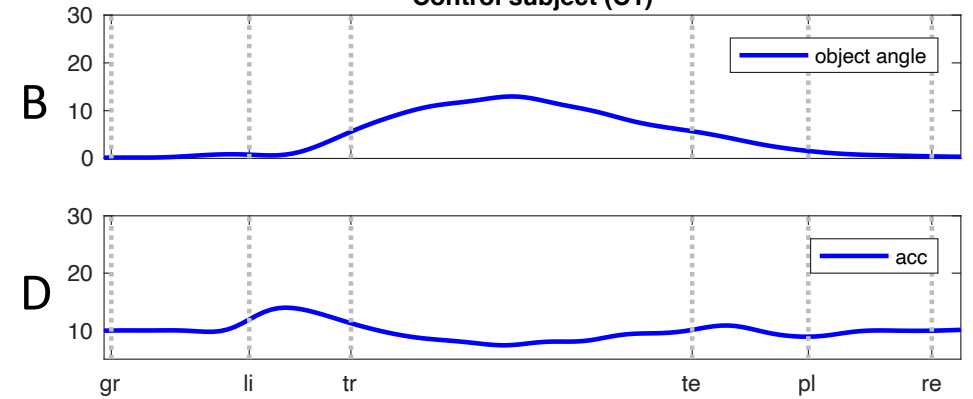
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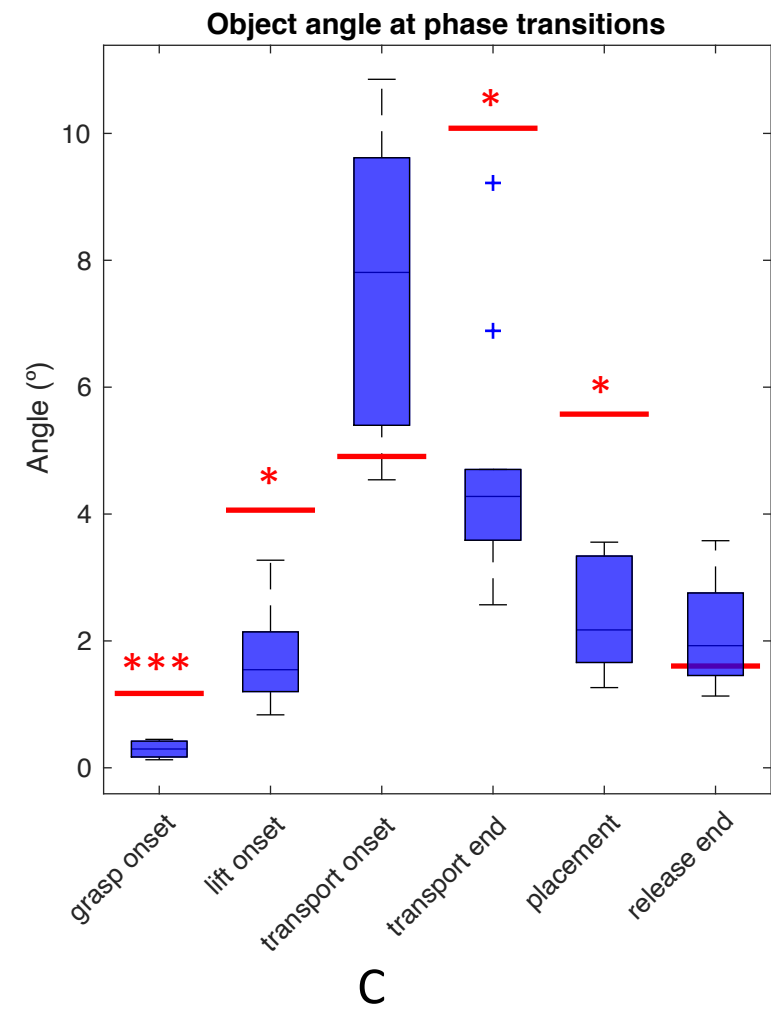
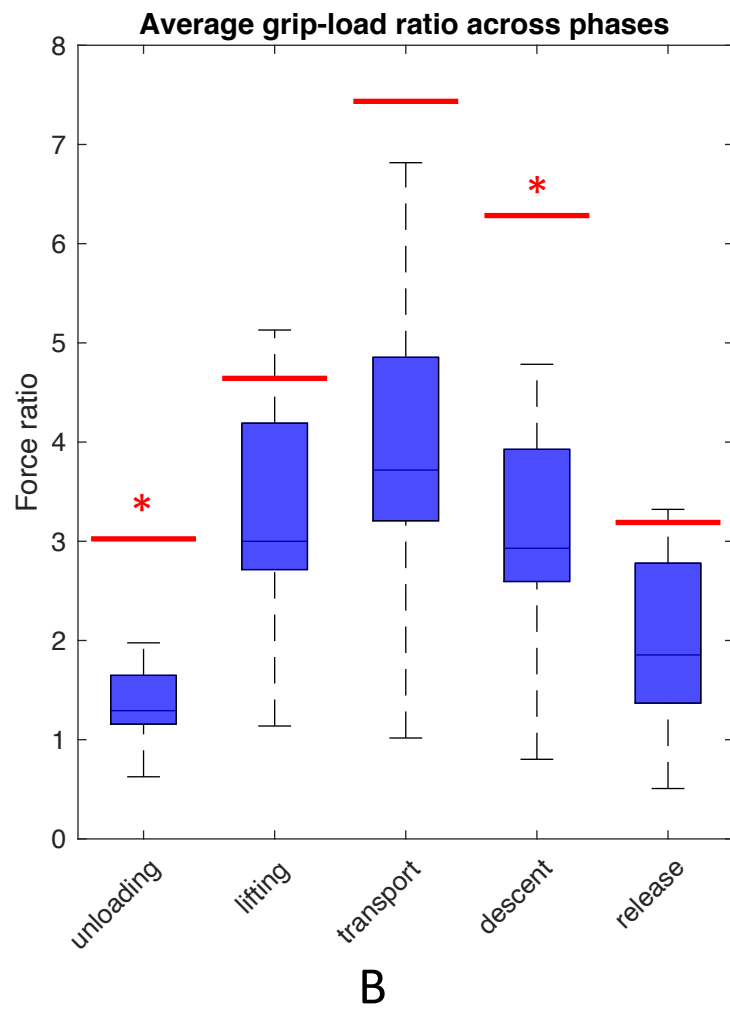
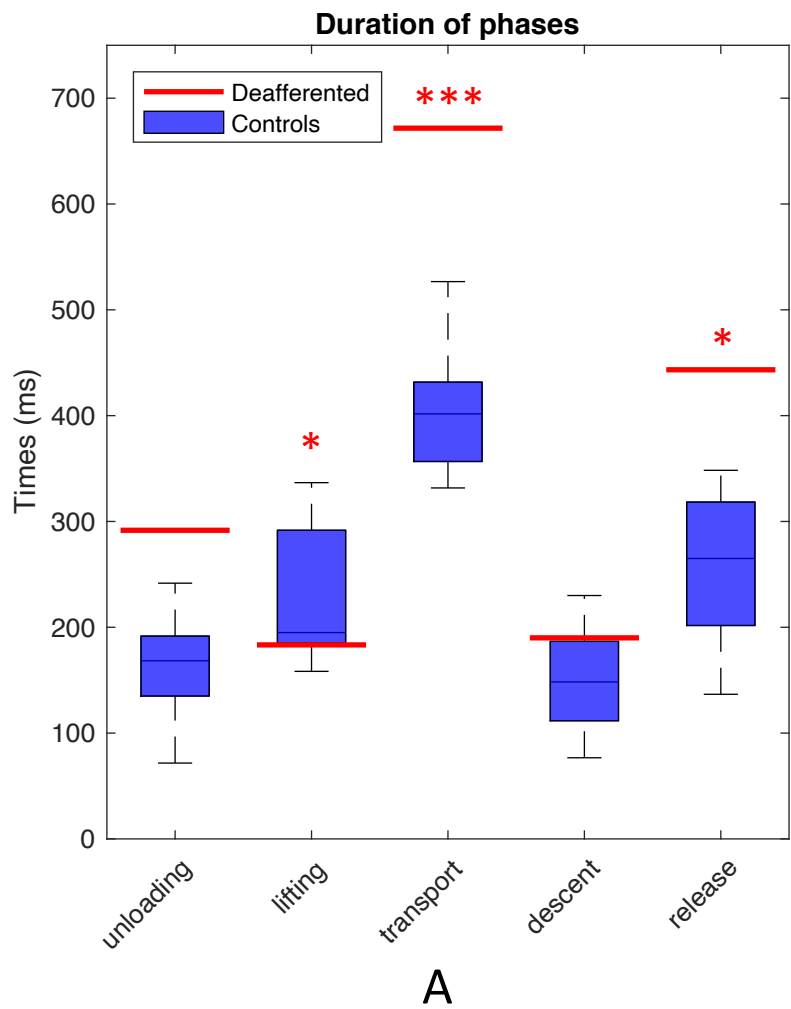


Deafferented patient (GL)

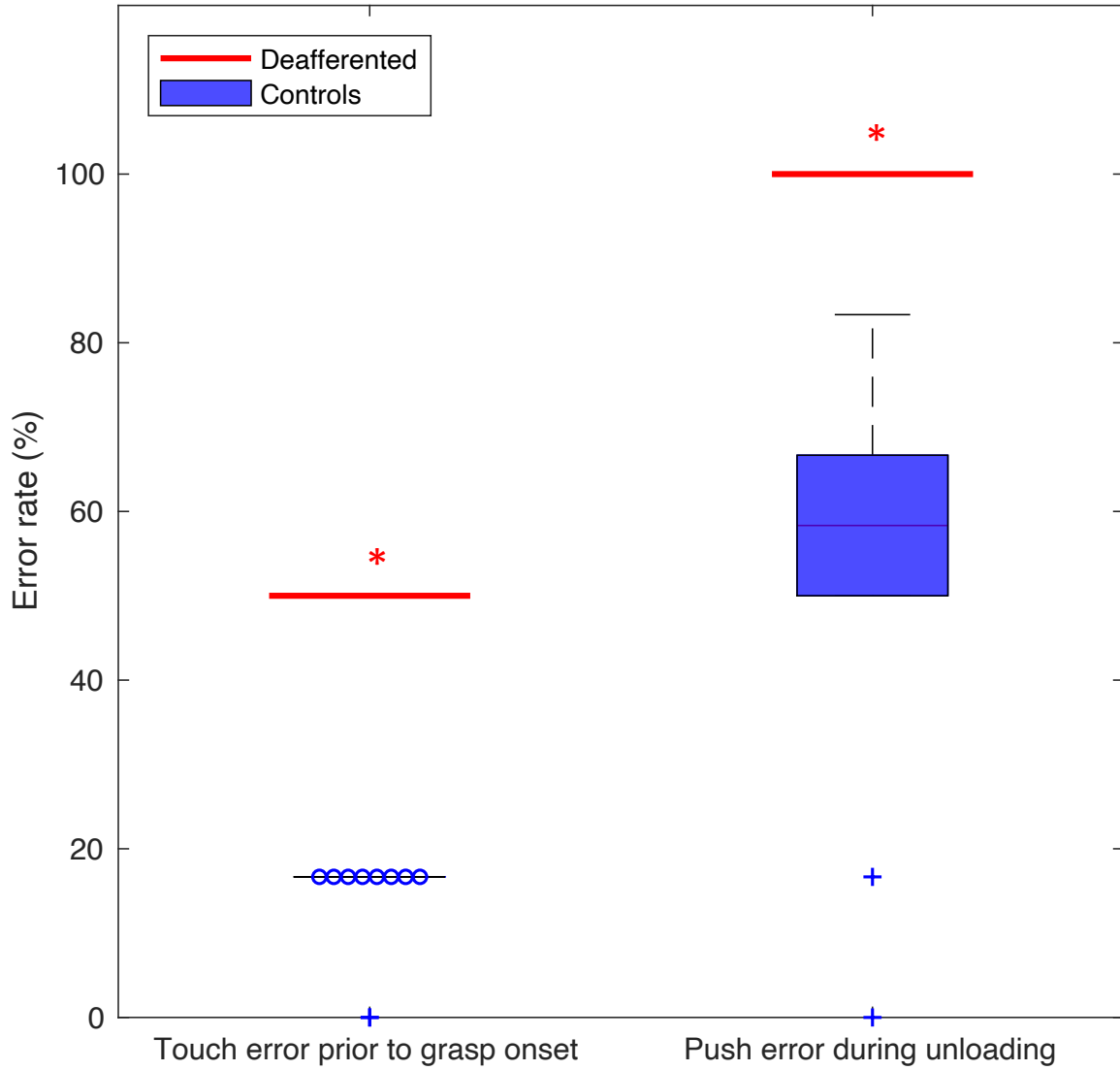


Control subject (C1)

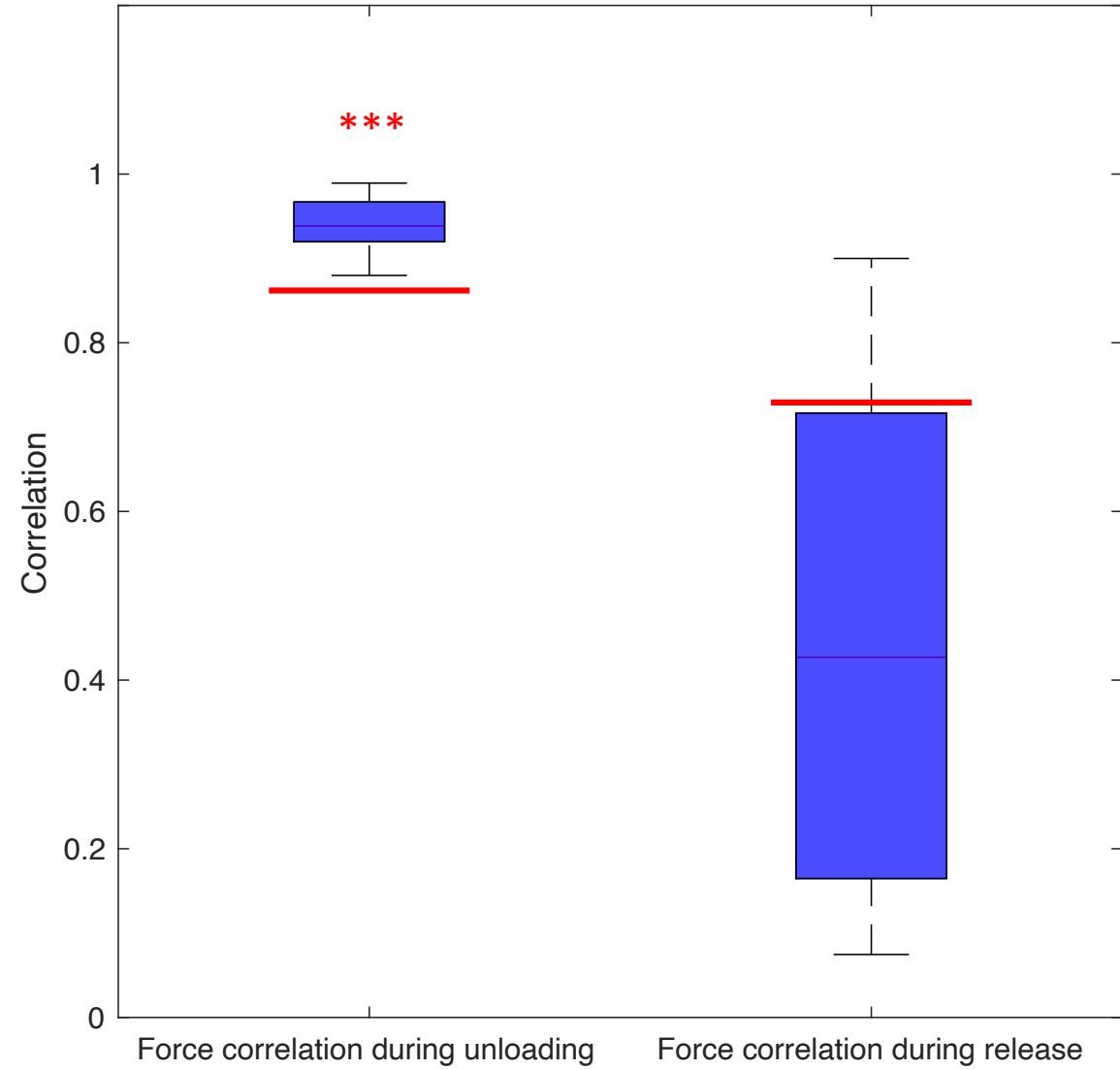




Touch and push errors upon task initiation

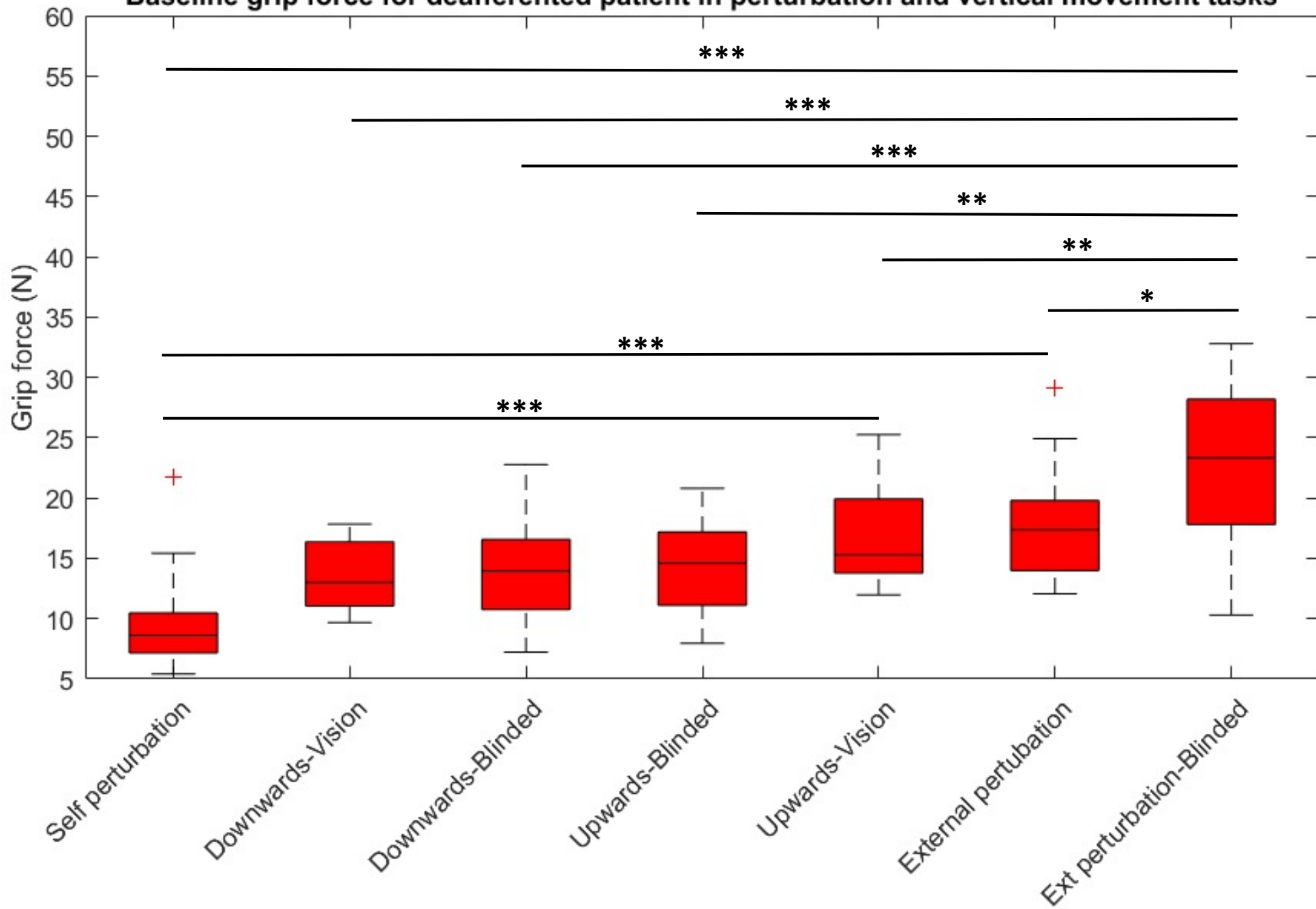


Time series correlation of grip force and base load cell



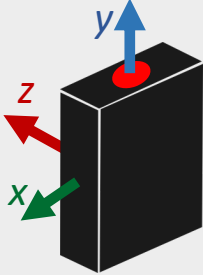


**Baseline grip force for deafferented patient in perturbation and vertical movement tasks**



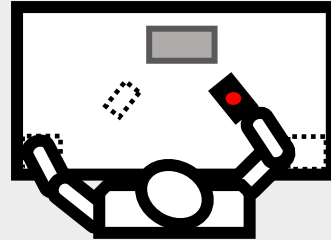
# Anticipation and compensation for somatosensory deficits in object handling: Evidence from a patient with large fibre sensory neuropathy

Instrumented object with load cells, IMU



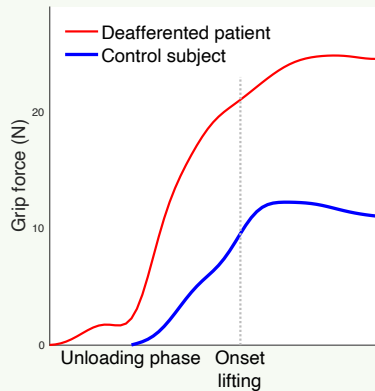
→ grip force, acceleration, orientation

Object handling assessed in 1) perturbation to static holding; 2) vertical movement; 3) grasp and place tasks

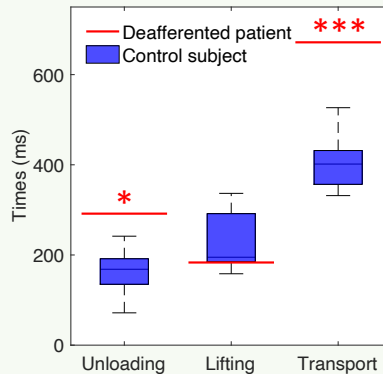


→ comparison of deafferented patient and healthy controls

Increased grip forces on object



Changes in phase duration



Object deviation at phase transitions

