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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

4 Ross Parry¹, Fabrice R. Sarlegna², Nathanaël Jarrassé³, Agnès Roby-Brami³.

5

6 1. LINP2 - Laboratoire Interdisciplinaire en Neurosciences, Physiologie et Psychologie: Activité
7 Physique, Santé et Apprentissages, UPL, Université Paris Nanterre, France.

8 2. Aix Marseille Univ, CNRS, ISM, Marseille, France

9 3. Institut des Systèmes Intelligents et de Robotique, Paris, France

10

11 Correspondence should be addressed to:

12 Ross Parry

13 Bâtiment Alice Miliat

14 UFR Sciences et Techniques des Activités Physiques et Sportives

15 Université Paris Nanterre

16 200 avenue de la République

17 92001 Nanterre Cedex

18

19

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

63 Experimental studies of motor control in humans with somatosensory deficits have
64 provided specific insights into the role of feedforward and feedback control mechanisms
65 underlying object handling (23, 25–28). Using a precision grip with an object held between
66 the thumb and index finger, healthy adults regulate grip force according to the displacement
67 of the handheld object, concurrent with the associated load force variation (a product of the
68 mass and acceleration of the handheld object) (29). This behaviour has served as a model for
69 studying feedforward sensorimotor control processes (30, 31). Under similar conditions,
70 persons suffering from sensory deficits exhibit grip forces with increased magnitude and, in
71 most cases, decreased temporal precision (25, 32). This has been interpreted as a breakdown
72 in feedforward control whereby decreased afferent input precludes the ability to update
73 internal models allowing to anticipate the effects of movement kinematics upon inertial loads
(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 ± 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 ($>0.4\text{N}$) 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 ± 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 ± 6.5 kg for the dominant hand ($p=0.12$) and 26.9 ± 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 ± 3.5 kg
331 and 22.8 ± 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 7.9N ($\pm 5.6\text{N}$), significantly greater than the control group at
355 4.3N ($\pm 3.39\text{N}$; $p=0.043$).

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 (2.1ms^{-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 (537ms) being
399 greater than for controls (range 21ms — 390ms ; $p=0.001$).

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 (± 0.15 s) for GL, longer than for controls (1.29 ± 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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471

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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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

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677

678 **References**

679 1. **Bernstein NA.** *Dexterity and Its Development.* Taylor& Francis, 1996.

- 680 2. **Johansson RS, Flanagan JR.** Coding and use of tactile signals from the fingertips in object
681 manipulation tasks. *Nature Reviews Neuroscience* 10: 345–359, 2009. doi: 10.1038/nrn2621.
- 682 3. **Proske U, Gandevia SC.** The Proprioceptive Senses: Their Roles in Signaling Body Shape,
683 Body Position and Movement, and Muscle Force. *Physiological Reviews* 92: 1651–1697, 2012.
684 doi: 10.1152/physrev.00048.2011.
- 685 4. **Pruszynski JA, Flanagan JR, Johansson RS.** Fast and accurate edge orientation processing
686 during object manipulation. *eLife* 7: e31200, 2018. doi: 10.7554/eLife.31200.
- 687 5. **Taub E, Goldberg IA, Taub P.** Deafferentation in monkeys: Pointing at a target without visual
688 feedback. *Experimental Neurology* 46: 178–186, 1975. doi: 10.1016/0014-4886(75)90040-0.
- 689 6. **Gauthier GM, Mussa Ivaldi F.** Oculo-manual tracking of visual targets in monkey: role of the
690 arm afferent information in the control of arm and eye movements. *Experimental Brain Research*
691 73: 138–154, 1988. doi: 10.1007/BF00279668.
- 692 7. **Augurelle A-S, Smith AM, Lejeune T, Thonnard J-L.** Importance of cutaneous feedback in
693 maintaining a secure grip during manipulation of hand-held objects. *J Neurophysiol* 89: 665–
694 671, 2003. doi: 10.1152/jn.00249.2002.
- 695 8. **Carteron A, McPartlan K, Gioeli C, Reid E, Turturro M, Hahn B, Benson C, Zhang W.**
696 Temporary Nerve Block at Selected Digits Revealed Hand Motor Deficits in Grasping Tasks.
697 *Front Hum Neurosci* 10, 2016. doi: 10.3389/fnhum.2016.00596.
- 698 9. **Johansson RS, Westling G.** Roles of glabrous skin receptors and sensorimotor memory in
699 automatic control of precision grip when lifting rougher or more slippery objects. *Exp Brain Res*
700 56: 550–564, 1984.
- 701 10. **Monzée J, Lamarre Y, Smith AM.** The effects of digital anesthesia on force control using a
702 precision grip. *J Neurophysiol* 89: 672–683, 2003. doi: 10.1152/jn.00434.2001.
- 703 11. **Nowak DA, Hermsdörfer J, Glasauer S, Philipp J, Meyer L, Mai N.** The effects of digital
704 anaesthesia on predictive grip force adjustments during vertical movements of a grasped object:
705 Digital anaesthesia and predictive grip force adjustments. *European Journal of Neuroscience* 14:
706 756–762, 2001. doi: 10.1046/j.0953-816x.2001.01697.x.
- 707 12. **Westling G, Johansson RS.** Factors influencing the force control during precision grip. *Exp*
708 *Brain Res* 53: 277–284, 1984. doi: 10.1007/BF00238156.
- 709 13. **Witney AG, Wing A, Thonnard J-L, Smith AM.** The cutaneous contribution to adaptive
710 precision grip. *Trends Neurosci* 27: 637–643, 2004. doi: 10.1016/j.tins.2004.08.006.
- 711 14. **Forget R, Lamarre Y.** Rapid elbow flexion in the absence of proprioceptive and cutaneous
712 feedback. *Hum Neurobiol* 6: 27–37, 1987.
- 713 15. **Medina J, Jax SA, Brown MJ, Coslett HB.** Contributions of Efference Copy to Limb
714 Localization: Evidence from Deafferentation. *Brain Res* 1355: 104–111, 2010. doi:
715 10.1016/j.brainres.2010.07.063.
- 716 16. **Nowak DA, Hermsdörfer J.** Selective deficits of grip force control during object manipulation
717 in patients with reduced sensibility of the grasping digits. *Neuroscience Research* 47: 65–72,
718 2003. doi: 10.1016/S0168-0102(03)00182-2.

- 719 17. **Jayasinghe SAL, Sarlegna FR, Scheidt RA, Sainburg RL.** The neural foundations of
720 handedness: insights from a rare case of deafferentation. *Journal of Neurophysiology* 124: 259–
721 267, 2020. doi: 10.1152/jn.00150.2020.
- 722 18. **Polit A, Bizzi E.** Characteristics of motor programs underlying arm movements in monkeys. *J*
723 *Neurophysiol* 42: 183–194, 1979. doi: 10.1152/jn.1979.42.1.183.
- 724 19. **Sarlegna FR, Sainburg RL.** The Roles of Vision and Proprioception in the Planning of
725 Reaching Movements. *Adv Exp Med Biol* 629: 317–335, 2009. doi: 10.1007/978-0-387-77064-
726 2_16.
- 727 20. **Rothwell JC, Traub MM, Day BL, Obeso JA, Thomas PK, Marsden CD.** Manual motor
728 performance in a deafferented man. *Brain* 105: 515–542, 1982. doi: 10.1093/brain/105.3.515.
- 729 21. **Nowak DA, Hermsdörfer J, Marquardt C, Topka H.** Moving objects with clumsy fingers:
730 how predictive is grip force control in patients with impaired manual sensibility? *Clin*
731 *Neurophysiol* 114: 472–487, 2003.
- 732 22. **Melchior H, Vatine J-J, Weiss PPL.** Is there a relationship between light touch-pressure
733 sensation and functional hand ability? *Disability and Rehabilitation* 29: 567–575, 2007. doi:
734 10.1080/09638280600902547.
- 735 23. **Cuadra C, Falaki A, Sainburg R, Sarlegna FR, Latash ML.** Case Studies in Neuroscience:
736 The central and somatosensory contributions to finger interdependence and coordination: lessons
737 from a study of a “deafferented person”. *J Neurophysiol* 121: 2083–2087, 2019. doi:
738 10.1152/jn.00153.2019.
- 739 24. **Miall RC, Rosenthal O, Ørstavik K, Cole JD, Sarlegna FR.** Loss of haptic feedback impairs
740 control of hand posture: a study in chronically deafferented individuals when grasping and lifting
741 objects. .
- 742 25. **Hermsdörfer J, Elias Z, Cole JD, Quaney BM, Nowak DA.** Preserved and Impaired Aspects
743 of Feed-Forward Grip Force Control After Chronic Somatosensory Deafferentation.
744 *Neurorehabilitation and Neural Repair* 22: 374–384, 2008. doi: 10.1177/1545968307311103.
- 745 26. **Nowak DA, Glasauer S, Hermsdörfer J.** How predictive is grip force control in the complete
746 absence of somatosensory feedback? *Brain* 127: 182–192, 2004. doi: 10.1093/brain/awh016.
- 747 27. **Nowak DA, Hermsdörfer J.** Objective evaluation of manual performance deficits in
748 neurological movement disorders. *Brain Research Reviews* 51: 108–124, 2006. doi:
749 10.1016/j.brainresrev.2005.10.003.
- 750 28. **Thonnard J-L, Detrembleur C, Van den Bergh PYK.** Assessment of hand function in a
751 patient with chronic sensory demyelinating neuropathy. *Neurology* 49: 253–257, 1997. doi:
752 10.1212/WNL.49.1.253.
- 753 29. **Flanagan JR, Tresilian JR.** Grip-load force coupling: a general control strategy for transporting
754 objects. *J Exp Psychol Hum Percept Perform* 20: 944–957, 1994.
- 755 30. **Flanagan JR, Bowman MC, Johansson RS.** Control strategies in object manipulation tasks.
756 *Current Opinion in Neurobiology* 16: 650–659, 2006. doi: 10.1016/j.conb.2006.10.005.
- 757 31. **Nowak DA, Glasauer S, Hermsdörfer J.** Force control in object manipulation—A model for
758 the study of sensorimotor control strategies. *Neuroscience & Biobehavioral Reviews* 37: 1578–
759 1586, 2013. doi: 10.1016/j.neubiorev.2013.06.003.

- 760 32. **Hermisdörfer J, Hagl E, Nowak DA.** Deficits of anticipatory grip force control after damage to
761 peripheral and central sensorimotor systems. *Human Movement Science* 23: 643–662, 2004. doi:
762 10.1016/j.humov.2004.10.005.
- 763 33. **Scott SH, Cluff T, Lowrey CR, Takei T.** Feedback control during voluntary motor actions.
764 *Current Opinion in Neurobiology* 33: 85–94, 2015. doi: 10.1016/j.conb.2015.03.006.
- 765 34. **Johansson RS, Riso R, Häger C, Bäckström L.** Somatosensory control of precision grip
766 during unpredictable pulling loads. I. Changes in load force amplitude. *Exp Brain Res* 89: 181–
767 191, 1992.
- 768 35. **Johansson RS, Westling G.** Programmed and triggered actions to rapid load changes during
769 precision grip. *Experimental Brain Research* 71, 1988. doi: 10.1007/BF00247523.
- 770 36. **Macefield VaughanG, Rothwell JohnC, Day BrianL.** The contribution of transcortical
771 pathways to long-latency stretch and tactile reflexes in human hand muscles. *Exp Brain Res* 108,
772 1996. doi: 10.1007/BF00242912.
- 773 37. **Macefield VG, Johansson RS.** Loads applied tangential to a fingertip during an object restraint
774 task can trigger short-latency as well as long-latency EMG responses in hand muscles.
775 *Experimental Brain Research* 152: 143–149, 2003. doi: 10.1007/s00221-003-1421-9.
- 776 38. **Ghez C, Gordon J, Ghilardi MF.** Impairments of reaching movements in patients without
777 proprioception. II. Effects of visual information on accuracy. *J Neurophysiol* 73: 361–372, 1995.
778 doi: 10.1152/jn.1995.73.1.361.
- 779 39. **Saunders JA, Knill DC.** Humans use continuous visual feedback from the hand to control fast
780 reaching movements. *Exp Brain Res* 152: 341–352, 2003. doi: 10.1007/s00221-003-1525-2.
- 781 40. **Sarlegna FR, Malfait N, Bringoux L, Bourdin C, Vercher J-L.** Force-field adaptation without
782 proprioception: Can vision be used to model limb dynamics? *Neuropsychologia* 48: 60–67,
783 2010. doi: 10.1016/j.neuropsychologia.2009.08.011.
- 784 41. **Takamuku S, Gomi H.** Better grip force control by attending to the controlled object: Evidence
785 for direct force estimation from visual motion. *Scientific Reports* 9: 13114, 2019. doi:
786 10.1038/s41598-019-49359-8.
- 787 42. **Danion F, Sarlegna FR.** Can the Human Brain Predict the Consequences of Arm Movement
788 Corrections When Transporting an Object? Hints from Grip Force Adjustments. *J Neurosci* 27:
789 12839–12843, 2007. doi: 10.1523/JNEUROSCI.3110-07.2007.
- 790 43. **Martin-Brevet S, Jarrassé N, Burdet E, Roby-Brami A.** Taxonomy based analysis of force
791 exchanges during object grasping and manipulation. *PLOS ONE* 12: e0178185, 2017. doi:
792 10.1371/journal.pone.0178185.
- 793 44. **Schambra HM, Parnandi A, Pandit NG, Uddin J, Wirtanen A, Nilsen DM.** A Taxonomy of
794 Functional Upper Extremity Motion. *Frontiers in Neurology* 10, 2019. doi:
795 10.3389/fneur.2019.00857.
- 796 45. **Oldfield RC.** The assessment and analysis of handedness: the Edinburgh inventory.
797 *Neuropsychologia* 9: 97–113, 1971.
- 798 46. **Hunsaker FG, Cioffi DA, Amadio PC, Wright JG, Caughlin B.** The American academy of
799 orthopaedic surgeons outcomes instruments: normative values from the general population. *J*
800 *Bone Joint Surg Am* 84: 208–215, 2002. doi: 10.2106/00004623-200202000-00007.

- 801 47. **Jarrassé N, Kuhne M, Roach N, Hussain A, Balasubramanian S, Burdet E, Roby-Brami A.**
802 Analysis of grasping strategies and function in hemiparetic patients using an instrumented
803 object. In: *Rehabilitation Robotics (ICORR), 2013 IEEE International Conference on*. IEEE,
804 2013, p. 1–8.
- 805 48. **Nowak DA, Hermsdörfer J, Topka H.** When Motor Execution Is Selectively Impaired: Control
806 of Manipulative Finger Forces in Amyotrophic Lateral Sclerosis. *Motor Control* 7: 304–320,
807 2003. doi: 10.1123/mcj.7.3.304.
- 808 49. **Parry R, Macias Soria S, Pradat-Diehl P, Marchand-Pauvert V, Jarrassé N, Roby-Brami**
809 **A.** Effects of Hand Configuration on the Grasping, Holding, and Placement of an Instrumented
810 Object in Patients With Hemiparesis. *Front Neurol* 10, 2019. doi: 10.3389/fneur.2019.00240.
- 811 50. **Crawford JR, Garthwaite PH.** Investigation of the single case in neuropsychology: confidence
812 limits on the abnormality of test scores and test score differences. *Neuropsychologia* 40: 1196–
813 1208, 2002. doi: 10.1016/S0028-3932(01)00224-X.
- 814 51. **Angst F, Schwyzer H-K, Aeschlimann A, Simmen BR, Goldhahn J.** Measures of adult
815 shoulder function: Disabilities of the Arm, Shoulder, and Hand Questionnaire (DASH) and Its
816 Short Version (QuickDASH), Shoulder Pain and Disability Index (SPADI), American Shoulder
817 and Elbow Surgeons (ASES) Society Standardized Shoulder Assessment Form, Constant
818 (Murley) Score (CS), Simple Shoulder Test (SST), Oxford Shoulder Score (OSS), Shoulder
819 Disability Questionnaire (SDQ), and Western Ontario Shoulder Instability Index (WOSI).
820 *Arthritis Care & Research* 63: S174–S188, 2011. doi: 10.1002/acr.20630.
- 821 52. **Nowak DA, Hermsdörfer J, Rost K, Timmann D, Topka H.** Predictive and reactive finger
822 force control during catching in cerebellar degeneration. *The Cerebellum* 3: 227–235, 2004. doi:
823 10.1080/14734220410019057.
- 824 53. **Wolpert DM, Miall RC, Kawato M.** Internal models in the cerebellum. *Trends Cogn Sci*
825 *(Regul Ed)* 2: 338–347, 1998.
- 826 54. **Sarlegna FR, Blouin J, Vercher J-L, Bresciani J-P, Bourdin C, Gauthier Gabriel M.** Online
827 control of the direction of rapid reaching movements. *Experimental Brain Research* 157, 2004.
828 doi: 10.1007/s00221-004-1860-y.
- 829 55. **Blake R, Shiffrar M.** Perception of Human Motion. *Annual Review of Psychology* 58: 47–73,
830 2007. doi: 10.1146/annurev.psych.57.102904.190152.
- 831 56. **Knoblich G, Flach R.** Predicting the Effects of Actions: Interactions of Perception and Action.
832 *Psychological Science* 12: 467–472, 2001. doi: 10.1111/1467-9280.00387.
- 833 57. **Auvray M, Hoellinger T, Hanneton S, Roby-Brami A.** Perceptual Weight Judgments When
834 Viewing One’s Own and others’ Movements under Minimalist Conditions of Visual
835 Presentation. *Perception* 40: 1081–1103, 2011. doi: 10.1068/p6879.
- 836 58. **Vaziri-Pashkam M, Cormiea S, Nakayama K.** Predicting actions from subtle preparatory
837 movements. *Cognition* 168: 65–75, 2017. doi: 10.1016/j.cognition.2017.06.014.
- 838 59. **Fleury M, Bard C, Teasdale N, Paillard J, Cole J, Lajoie Y, Lamarre Y.** Weight judgment:
839 The discrimination capacity of a deafferented subject. *Brain* 118: 1149–1156, 1995. doi:
840 10.1093/brain/118.5.1149.
- 841 60. **Miall RC, Kitchen NM, Nam S-H, Lefumat H, Renault AG, Ørstavik K, Cole JD, Sarlegna**
842 **FR.** Proprioceptive loss and the perception, control and learning of arm movements in humans:

- 843 evidence from sensory neuronopathy. *Experimental Brain Research* 236: 2137–2155, 2018. doi:
844 10.1007/s00221-018-5289-0.
- 845 61. **Bringoux L, Scotto Di Cesare C, Borel L, Macaluso T, Sarlegna FR.** Do Visual and
846 Vestibular Inputs Compensate for Somatosensory Loss in the Perception of Spatial Orientation?
847 Insights from a Deafferented Patient. *Front Hum Neurosci* 10, 2016. doi:
848 10.3389/fnhum.2016.00181.
- 849 62. **Cole JD, Sedgwick EM.** The perceptions of force and of movement in a man without large
850 myelinated sensory afferents below the neck. *J Physiol* 449: 503–515, 1992.
- 851 63. **Miall RC, Ingram HA, Cole JD, Gauthier GM.** Weight estimation in a “deafferented” man
852 and in control subjects: are judgements influenced by peripheral or central signals? *Exp Brain*
853 *Res* 133: 491–500, 2000.
- 854 64. **Lacquaniti F, Maioli C.** Anticipatory and reflex coactivation of antagonist muscles in catching.
855 *Brain Research* 406: 373–378, 1987. doi: 10.1016/0006-8993(87)90810-9.
- 856 65. **Danna J, Velay J-L.** On the Auditory-Proprioception Substitution Hypothesis: Movement
857 Sonification in Two Deafferented Subjects Learning to Write New Characters. *Front Neurosci*
858 11, 2017. doi: 10.3389/fnins.2017.00137.
- 859 66. **Lessard N, Paré M, Lepore F, Lassonde M.** Early-blind human subjects localize sound sources
860 better than sighted subjects. *Nature* 395: 278–280, 1998. doi: 10.1038/26228.
- 861 67. **Bagesteiro LB, Sarlegna FR, Sainburg RL.** Differential influence of vision and proprioception
862 on control of movement distance. *Exp Brain Res* 171: 358, 2005. doi: 10.1007/s00221-005-0272-
863 y.
- 864 68. **Sainburg RL, Ghilardi MF, Poizner H, Ghez C.** Control of limb dynamics in normal subjects
865 and patients without proprioception. *Journal of Neurophysiology* 73: 820–835, 1995. doi:
866 10.1152/jn.1995.73.2.820.
- 867 69. **Cardinali L, Brozzoli C, Luauté J, Roy AC, Farnè A.** Proprioception Is Necessary for Body
868 Schema Plasticity: Evidence from a Deafferented Patient. *Front Hum Neurosci* 10, 2016. doi:
869 10.3389/fnhum.2016.00272.
- 870 70. **Arnold G, Sarlegna FR, Fernandez LG, Auvray M.** Somatosensory Loss Influences the
871 Adoption of Self-Centered Versus Decentered Perspectives. *Frontiers in Psychology* 10, 2019.
872 doi: 10.3389/fpsyg.2019.00419.
- 873 71. **Cameron BD, de la Malla C, López-Moliner J.** The role of differential delays in integrating
874 transient visual and proprioceptive information. *Front Psychol* 5, 2014. doi:
875 10.3389/fpsyg.2014.00050.
- 876 72. **Kristjánsson Á, Moldoveanu A, Jóhannesson ÓI, Balan O, Spagnol S, Valgeirsdóttir VV,**
877 **Unnthorsson R.** Designing sensory-substitution devices: Principles, pitfalls and potential1.
878 *Restorative Neurology and Neuroscience* 34: 769–787, 2016. doi: 10.3233/RNN-160647.
- 879

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. Experiment1: 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.

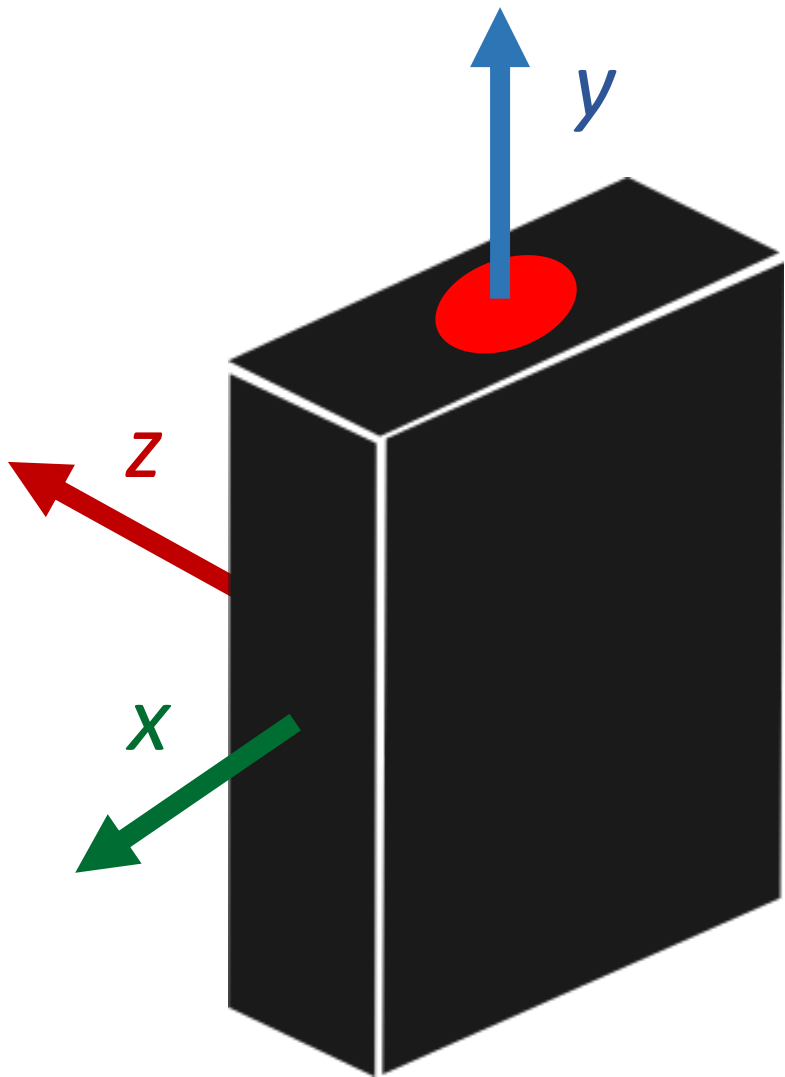
926 Figure 8. Experiment 3: Examples of signals from grasp, transport and place task for
927 deafferented patient (GL, red) and one control subject (C1, blue). (A/B) Angle measuring the
928 deviation of the iBox from the vertical. (C/D) Vertical (along the Y axis) acceleration of the
929 iBox. (E/F) 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 = $p < 0.01$, *** = $p < 0.001$.

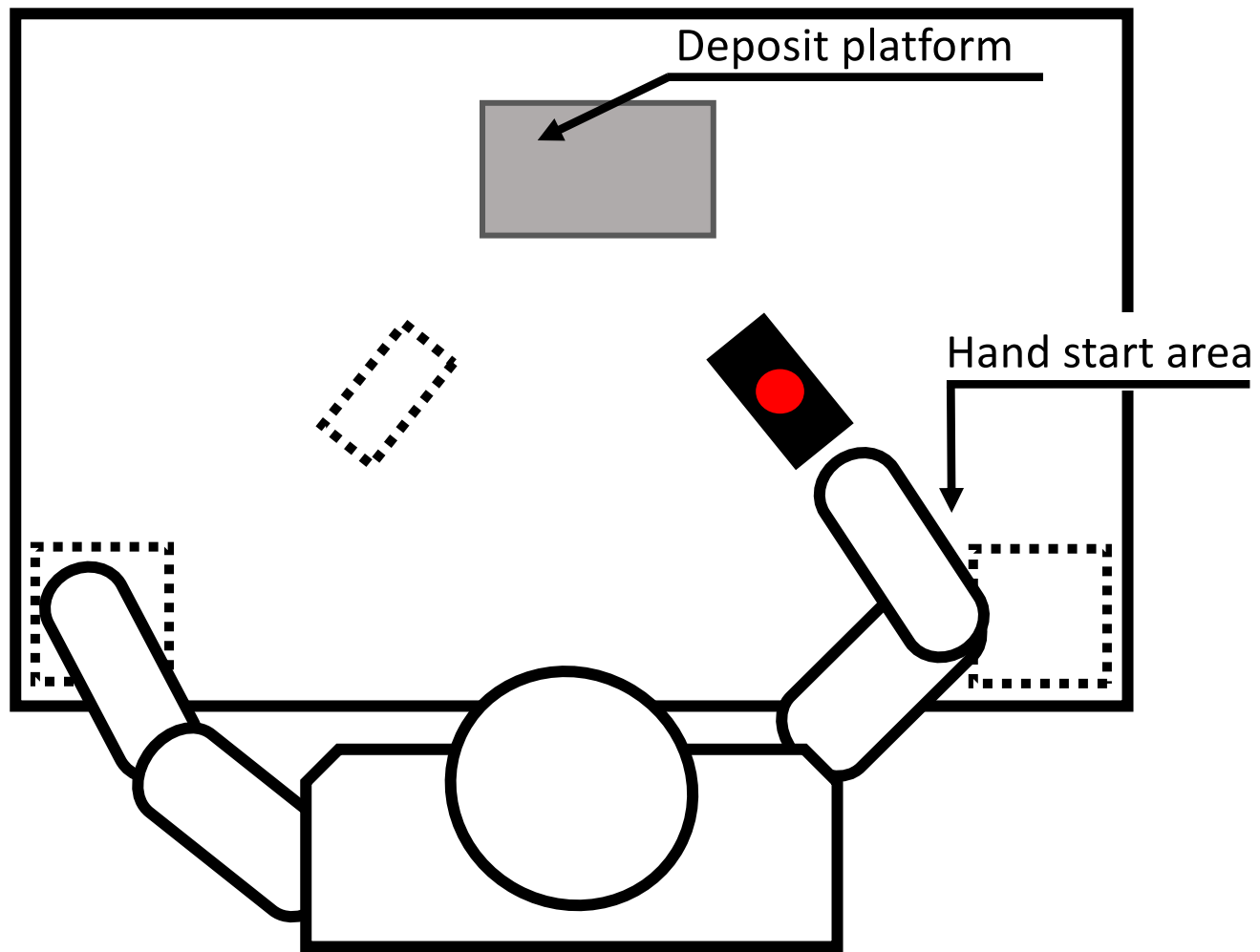
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943 Figure 10. (A) Frequency of touch errors prior to onset of grasp, and push errors through the
944 unloading phase. NB: Absence of variation precluded establishing quartile values for touch
945 error boxplot, for this reason, individual values are 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).

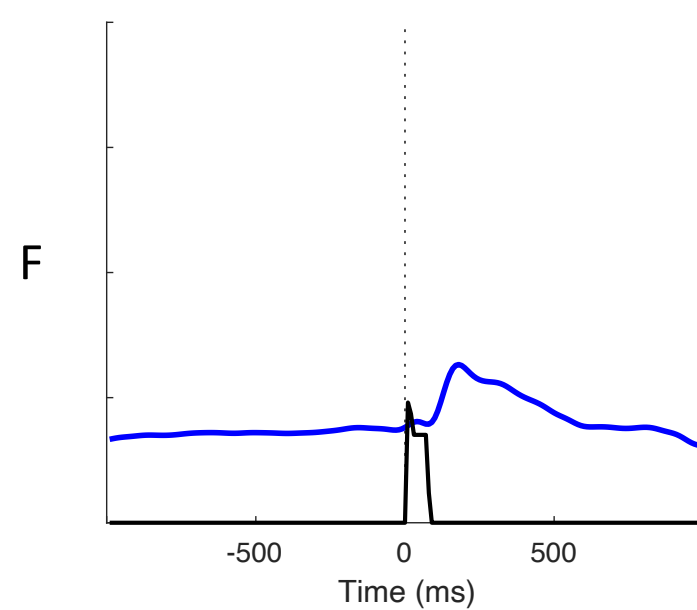
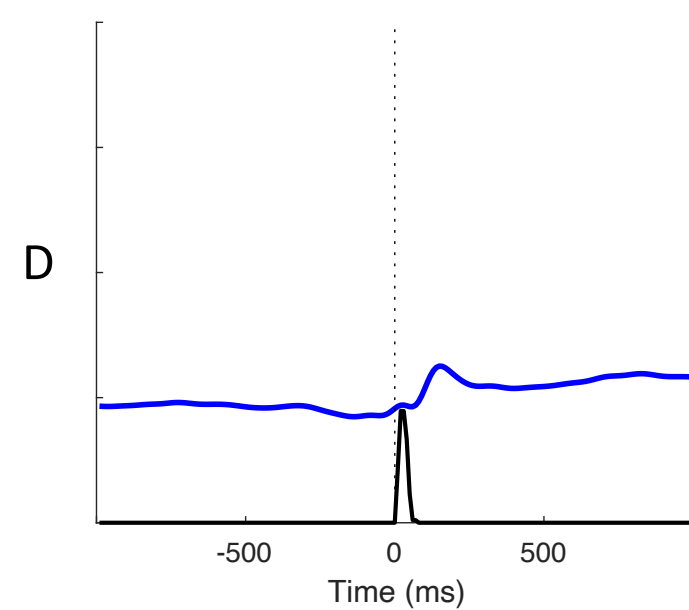
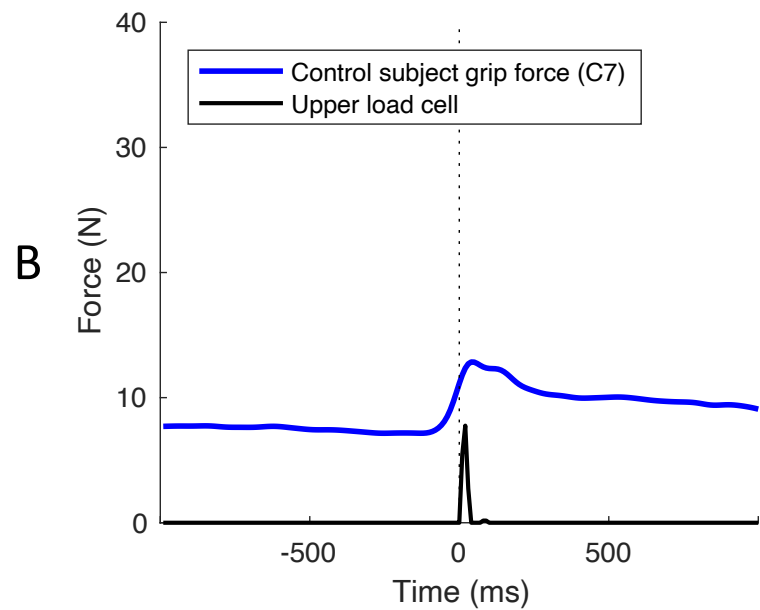
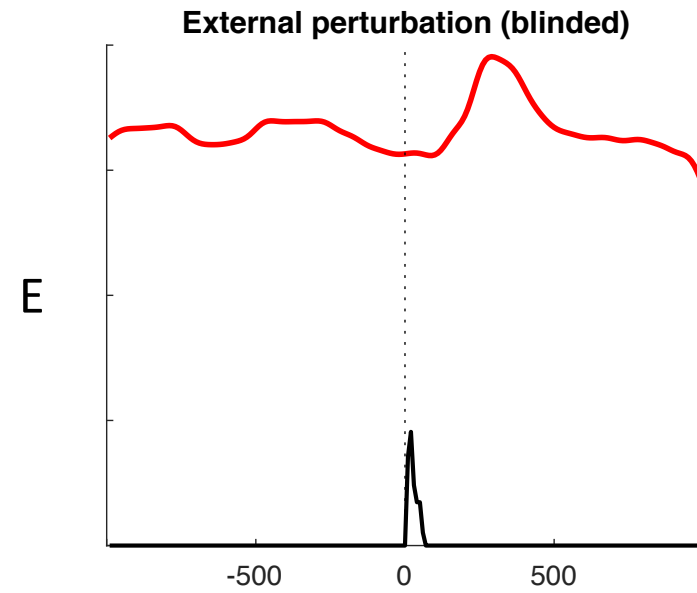
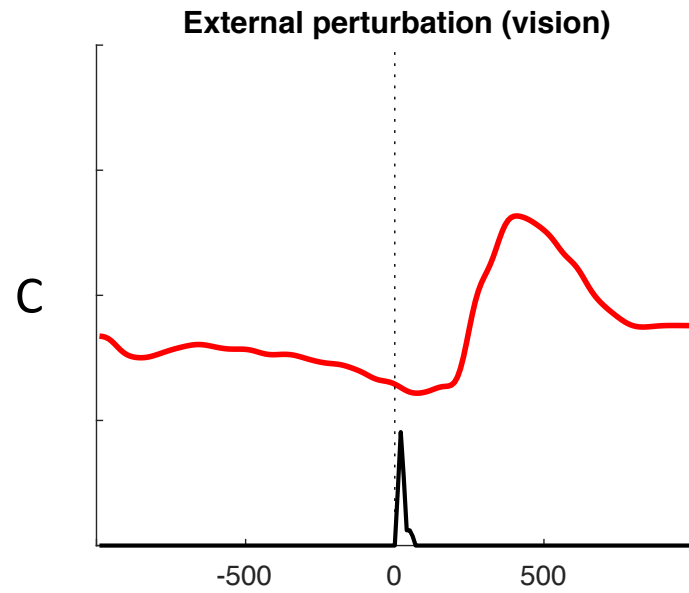
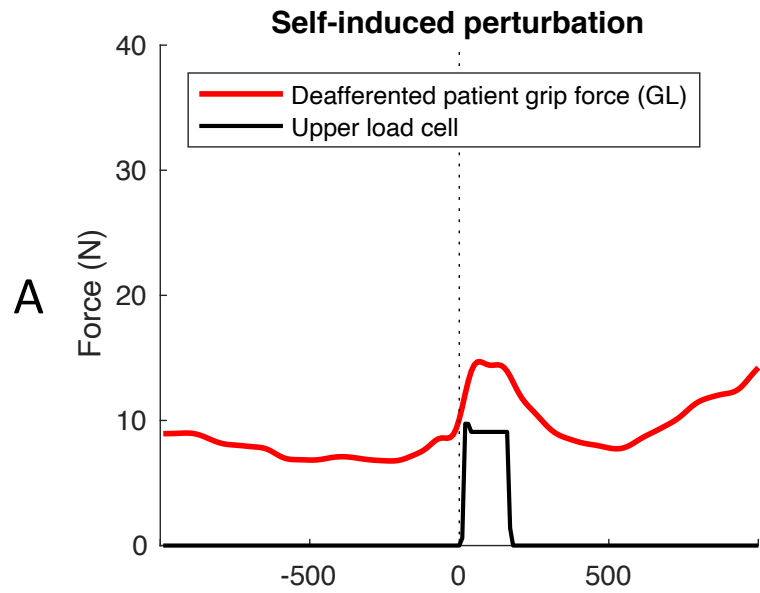
952 Figure 11. Baseline grip force for the deafferented patient across tasks with static holding
953 phases. Black asterisks indicate results from post-hoc testing. * = $p < 0.05$, ** = $p < 0.01$, *** =
954 $p < 0.001$.



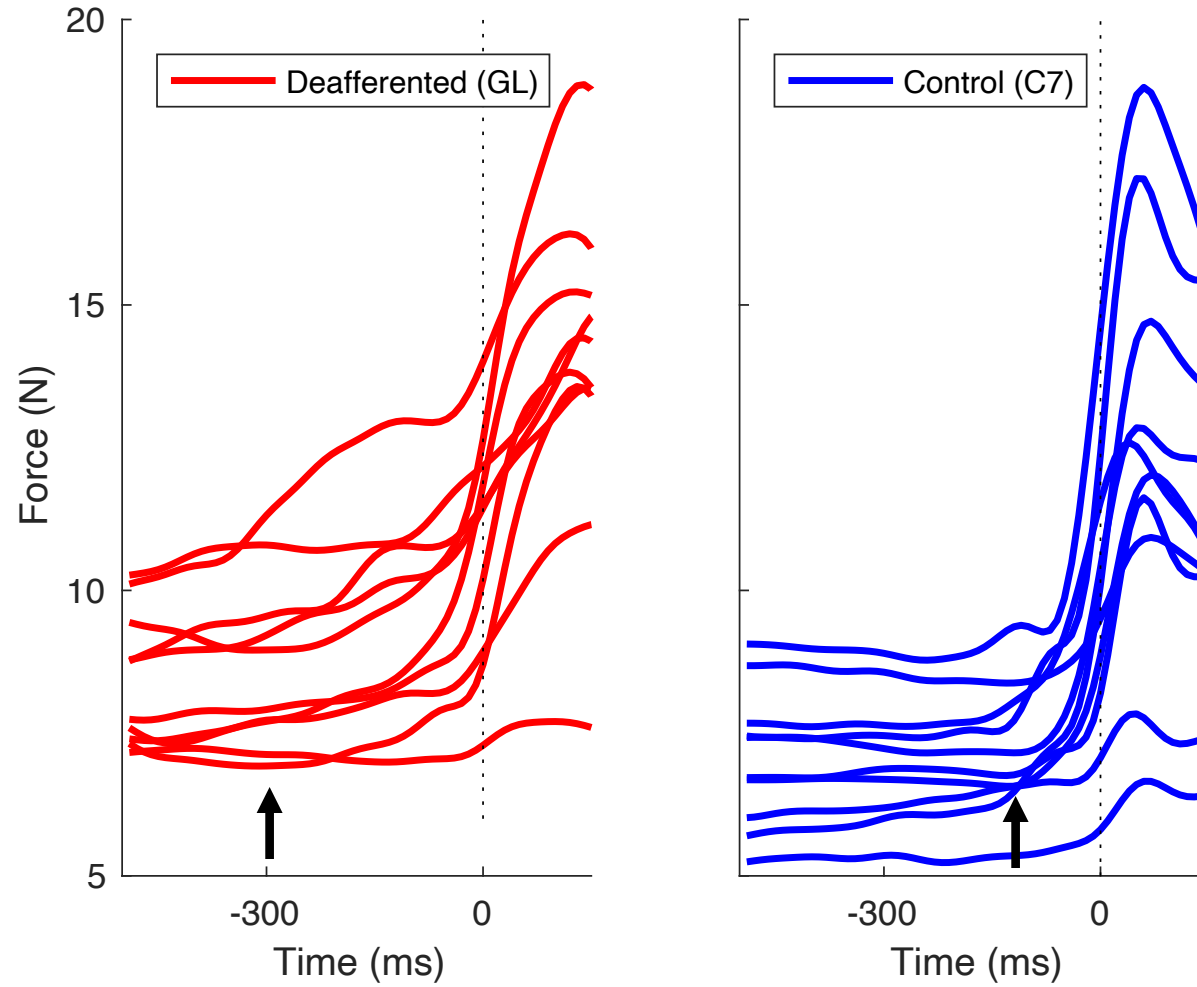
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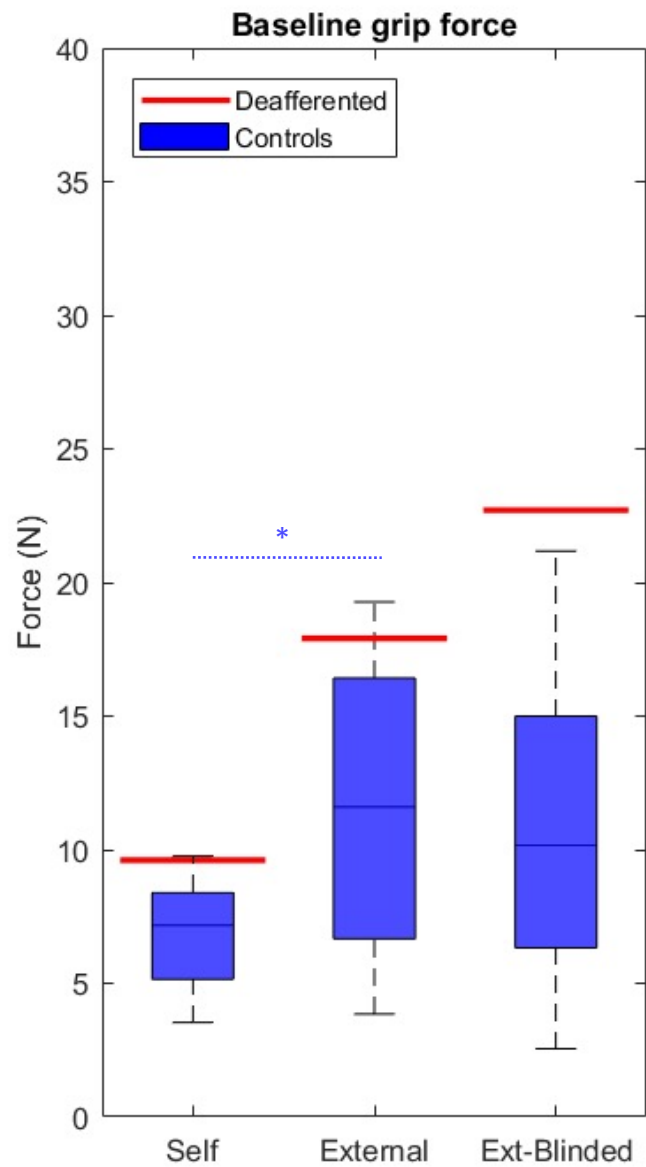


B

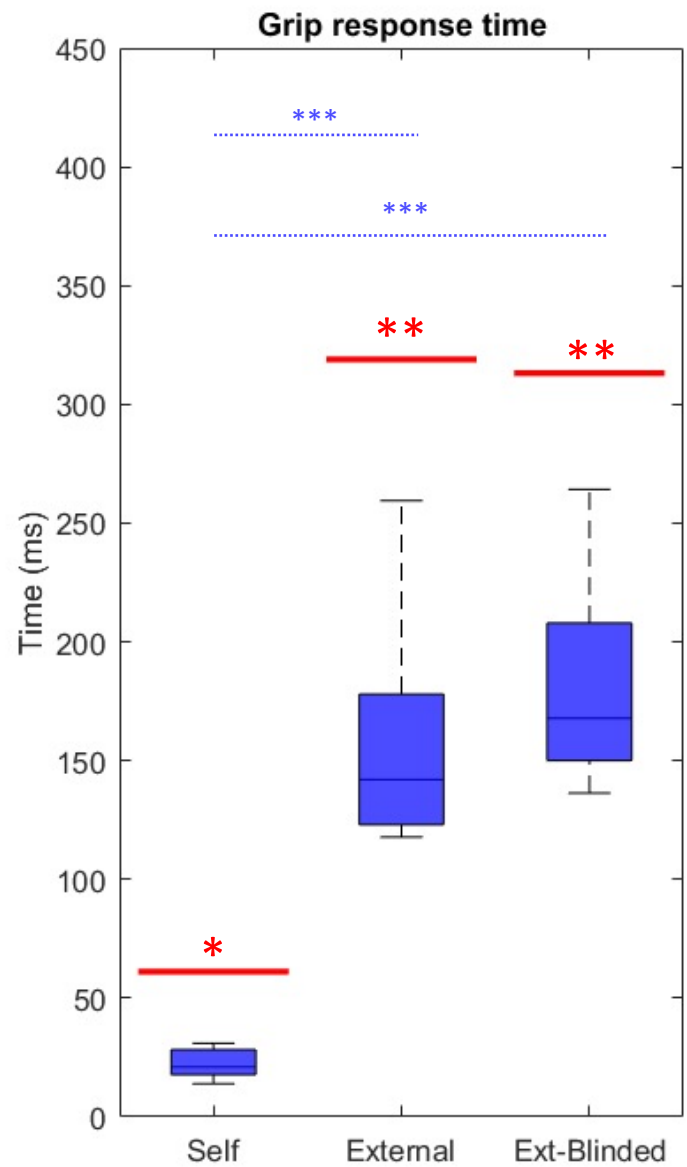


Preparatory actions in self-induced perturbation

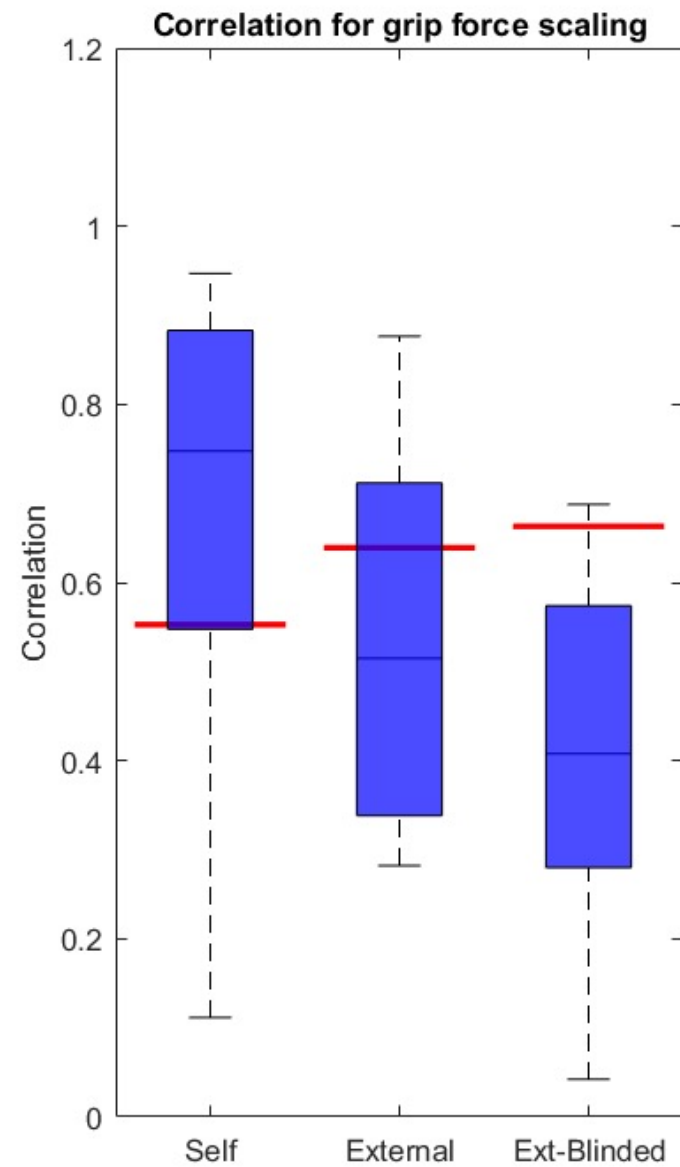




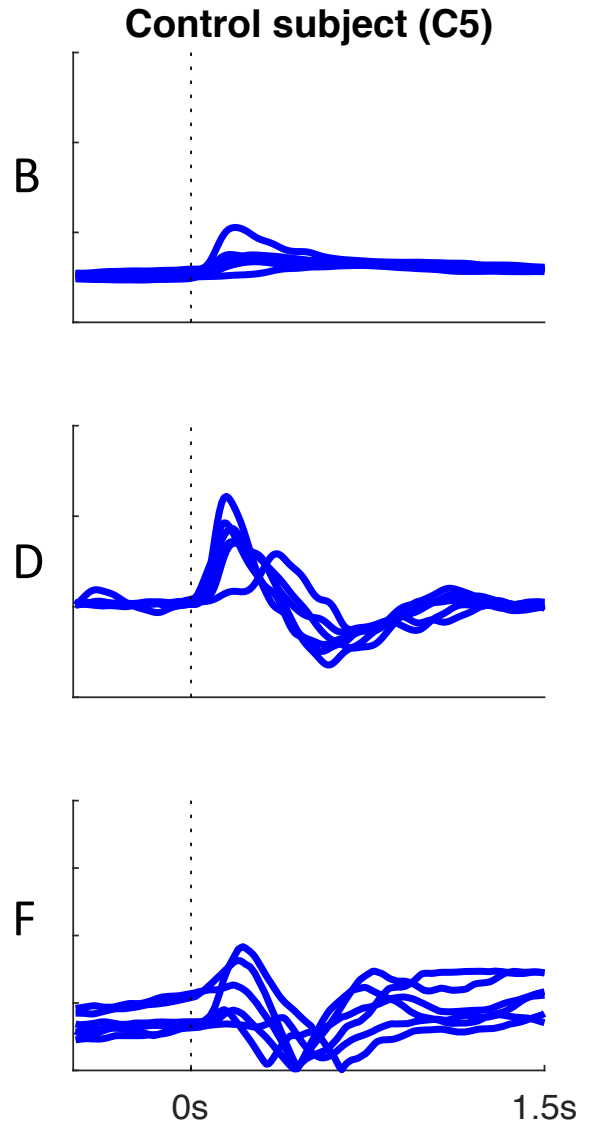
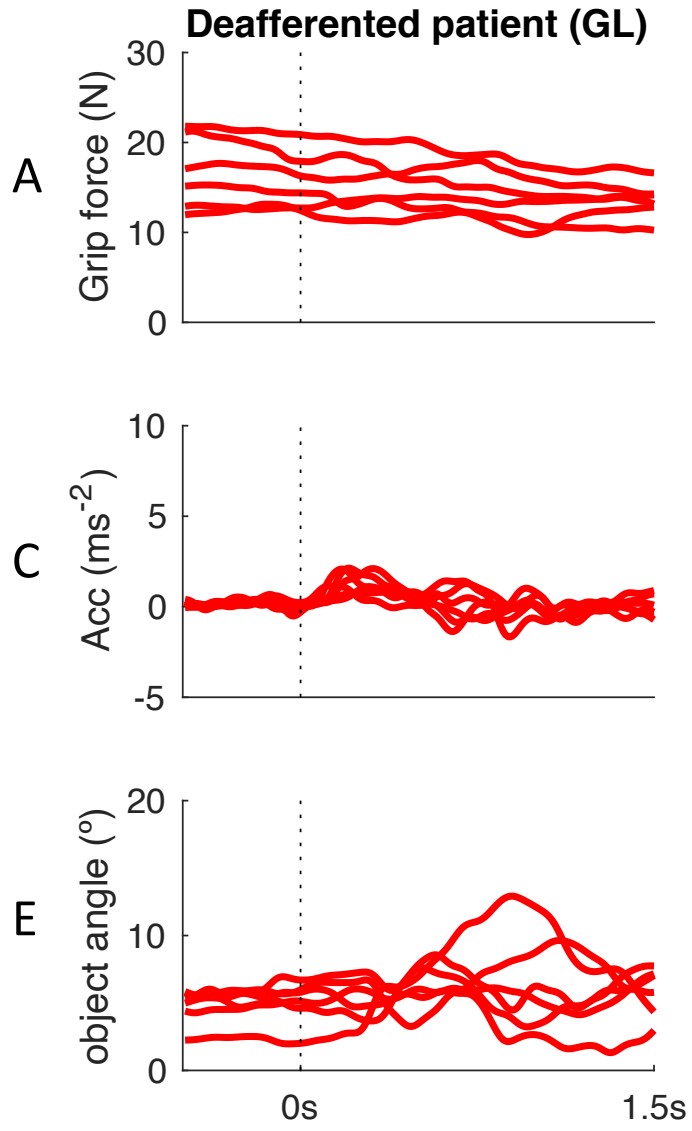
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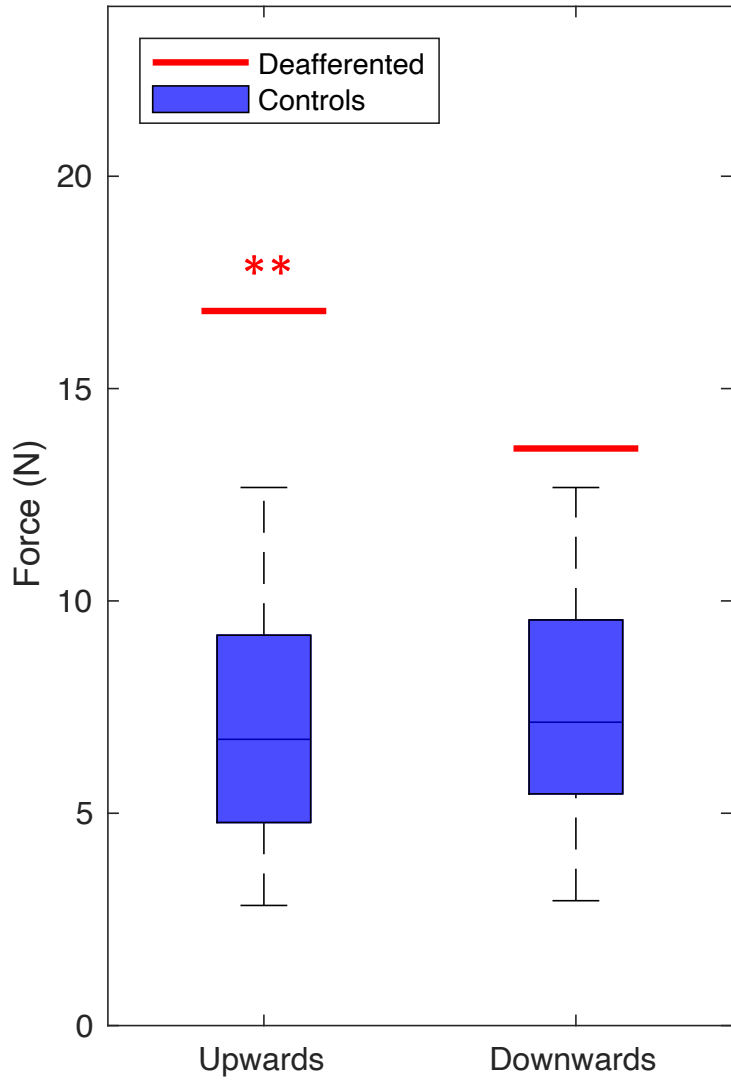
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C

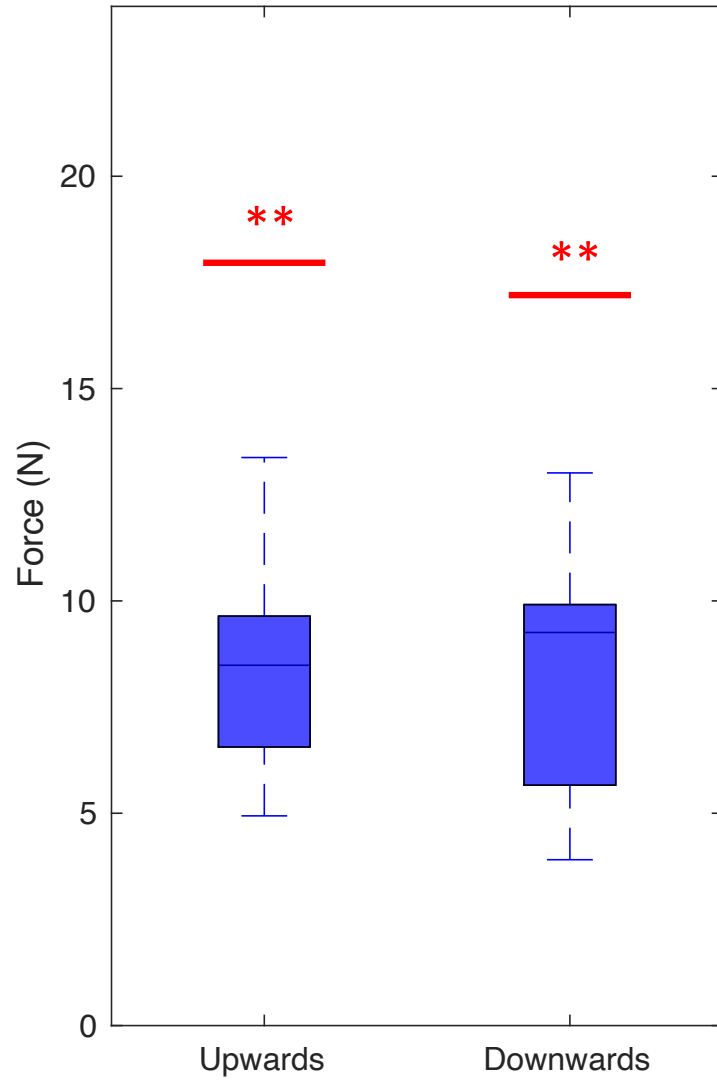


Baseline grip force



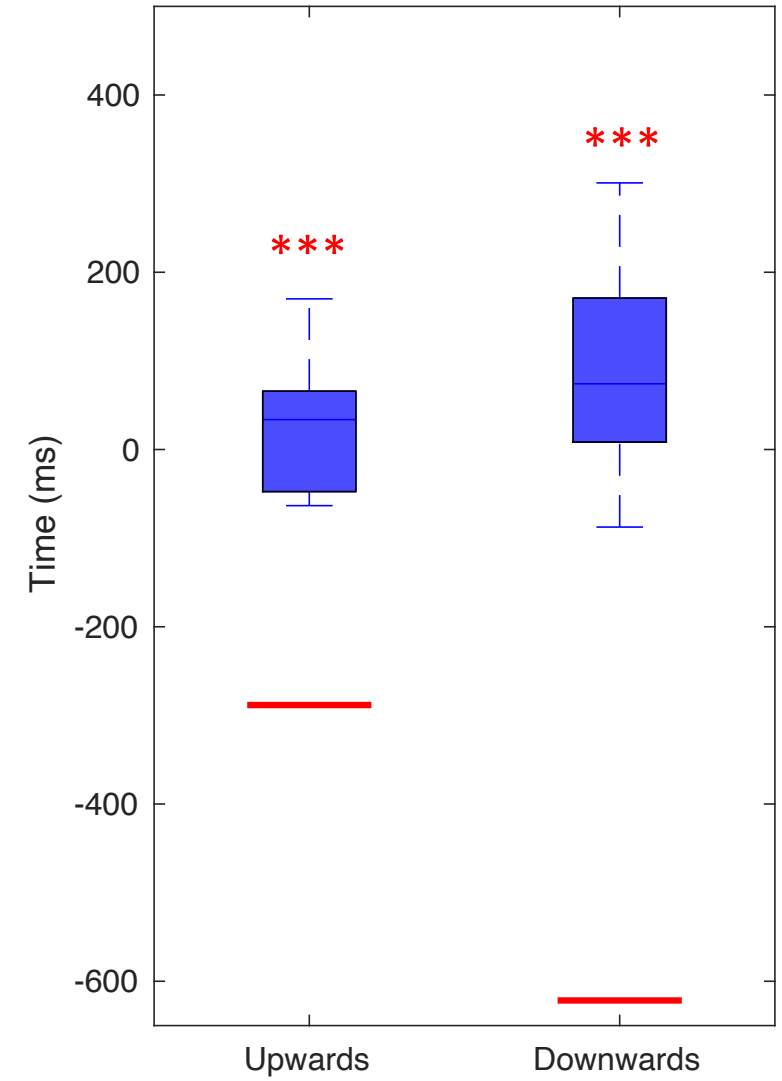
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Maximum grip force

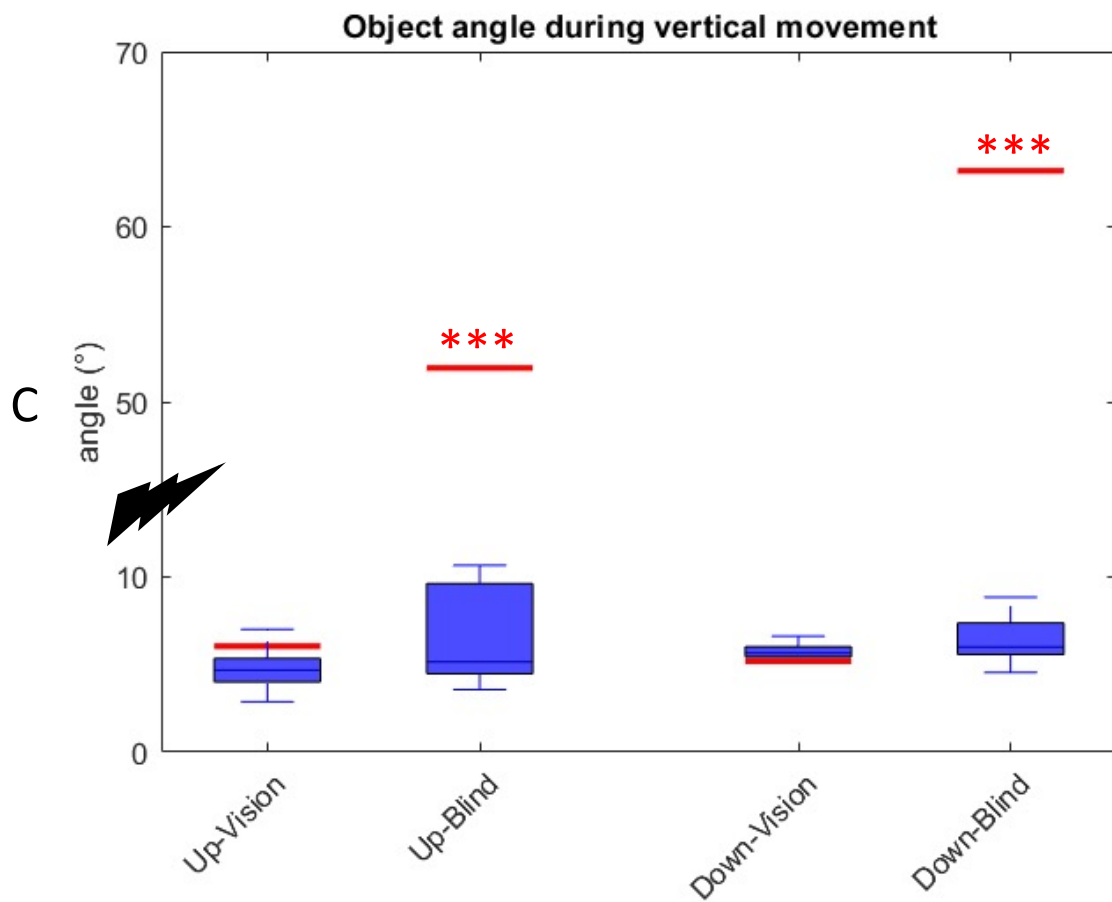
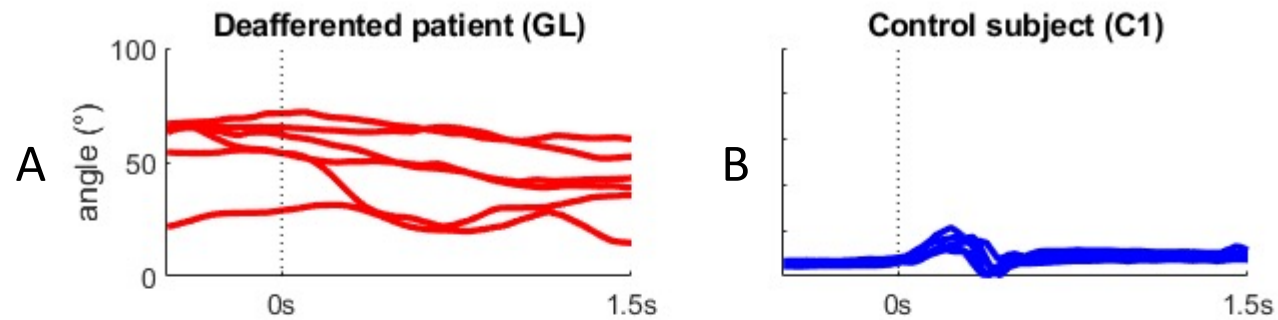


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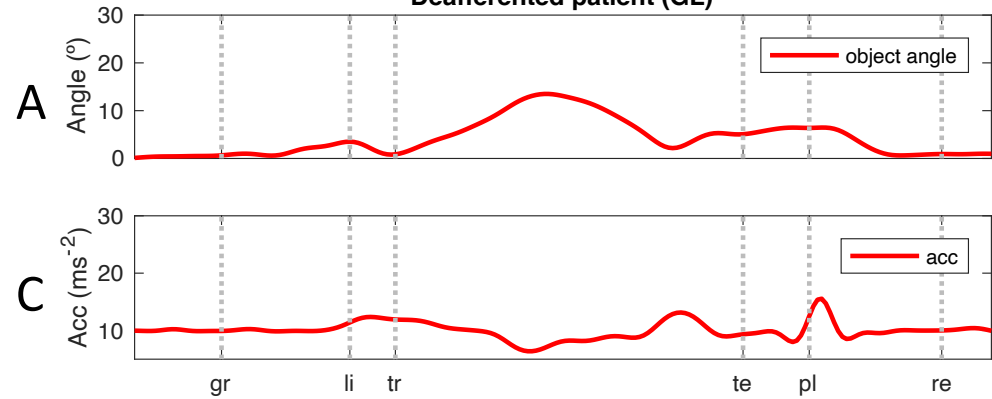
Grip-load time delay



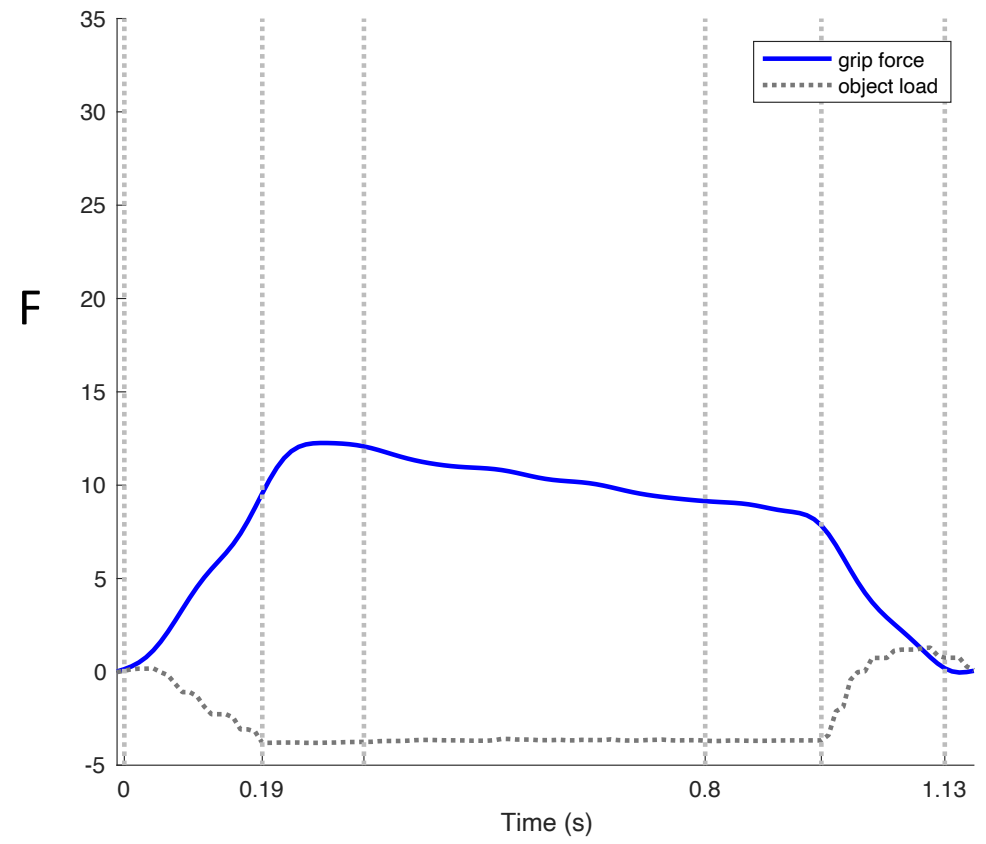
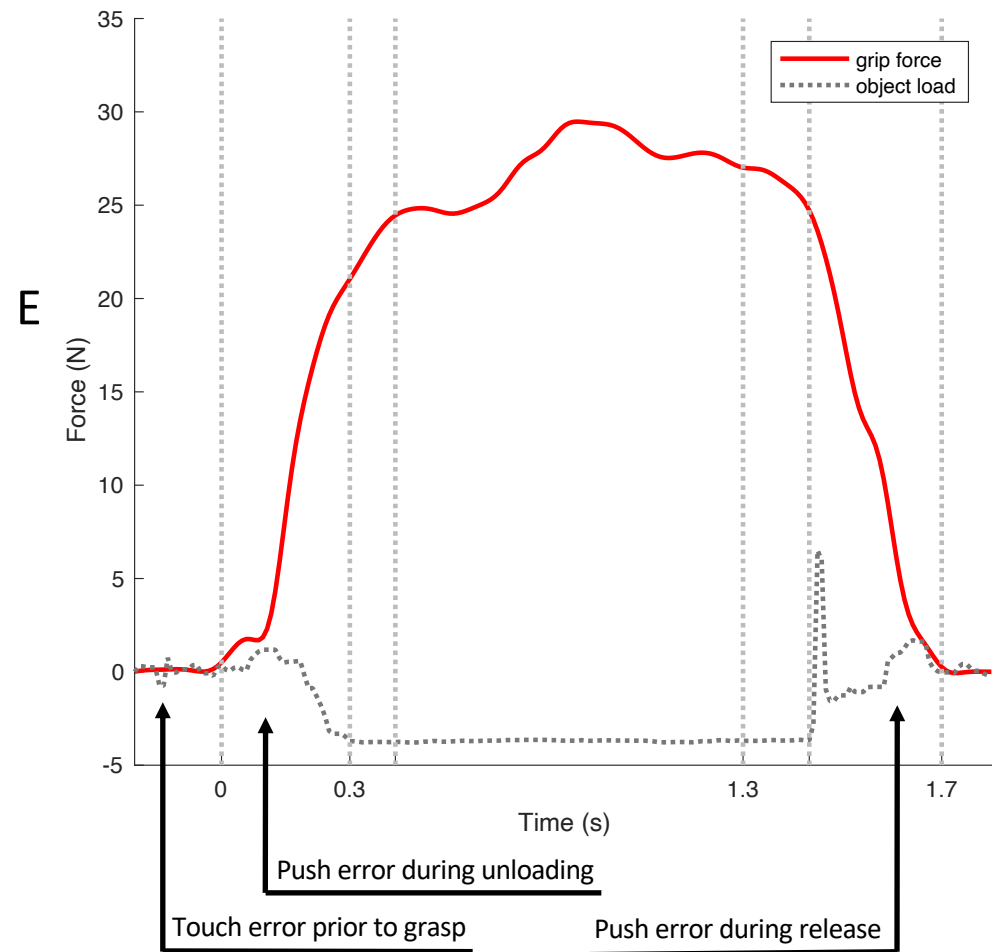
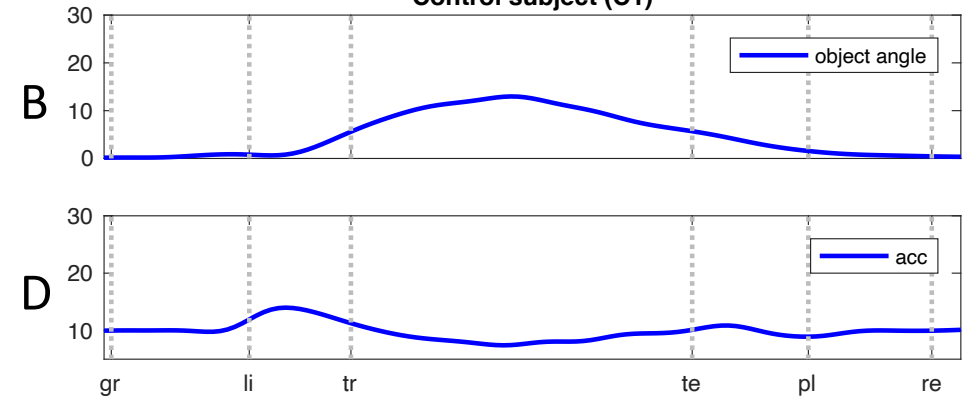
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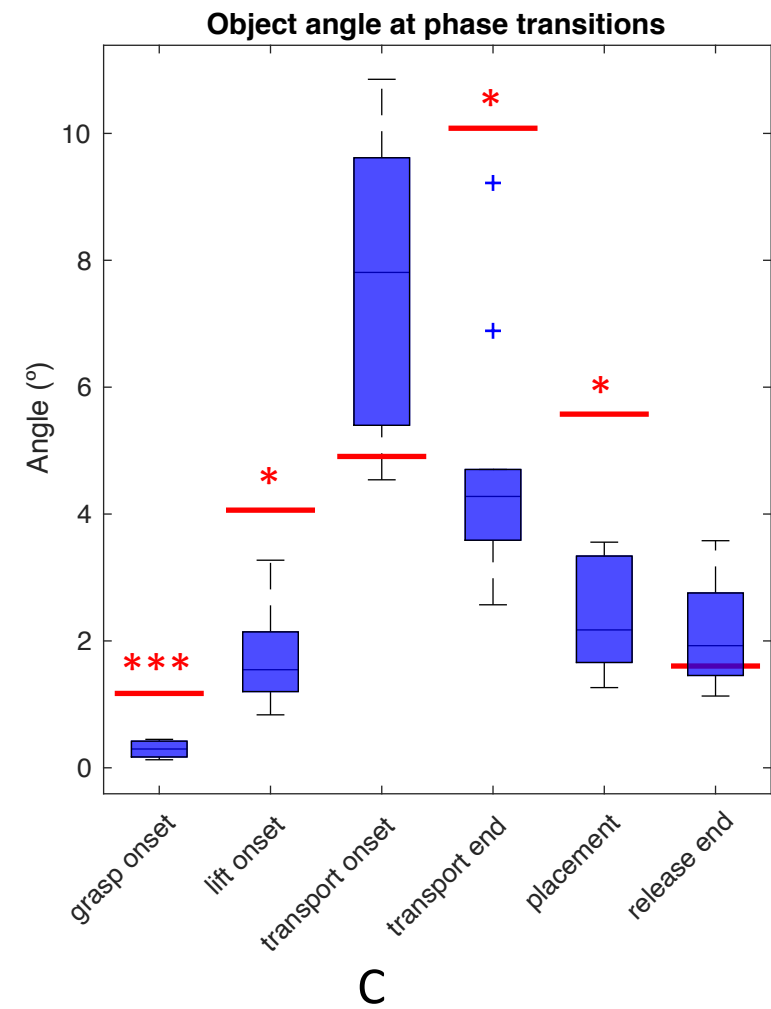
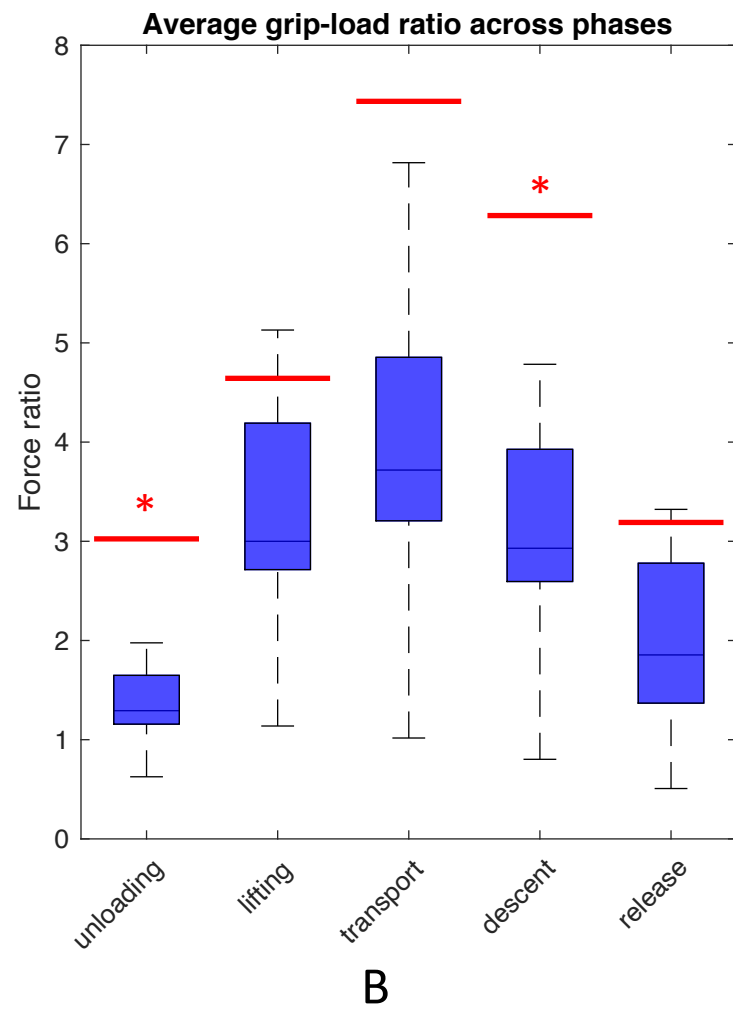
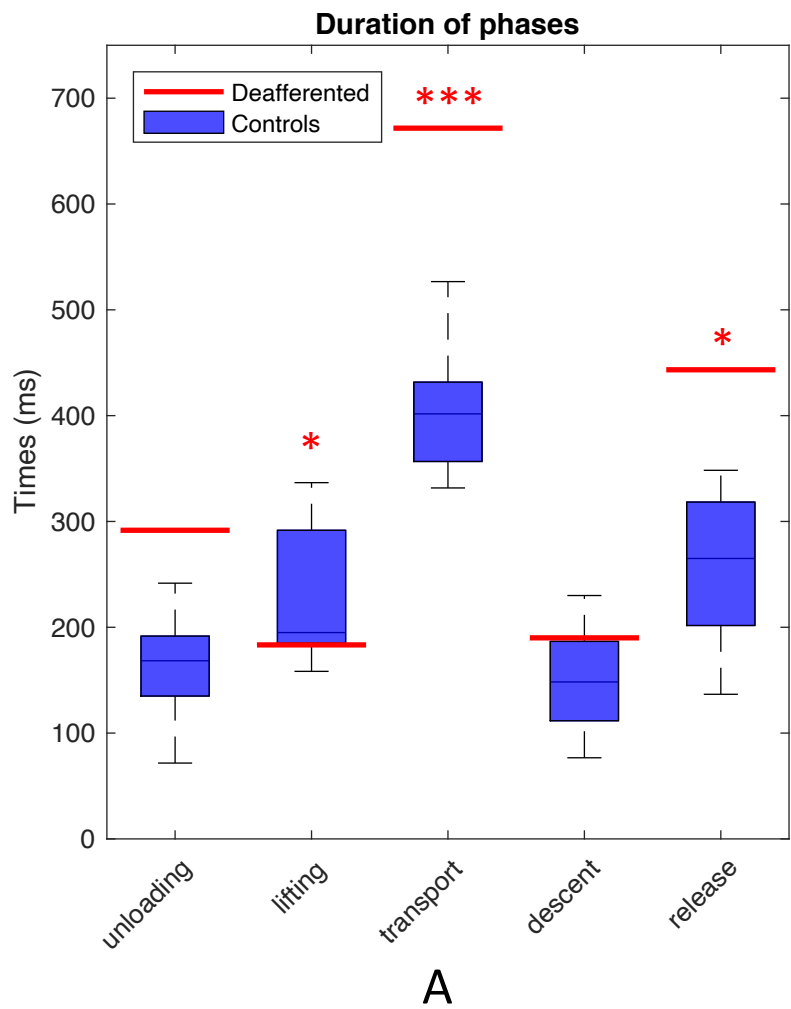


Deafferented patient (GL)

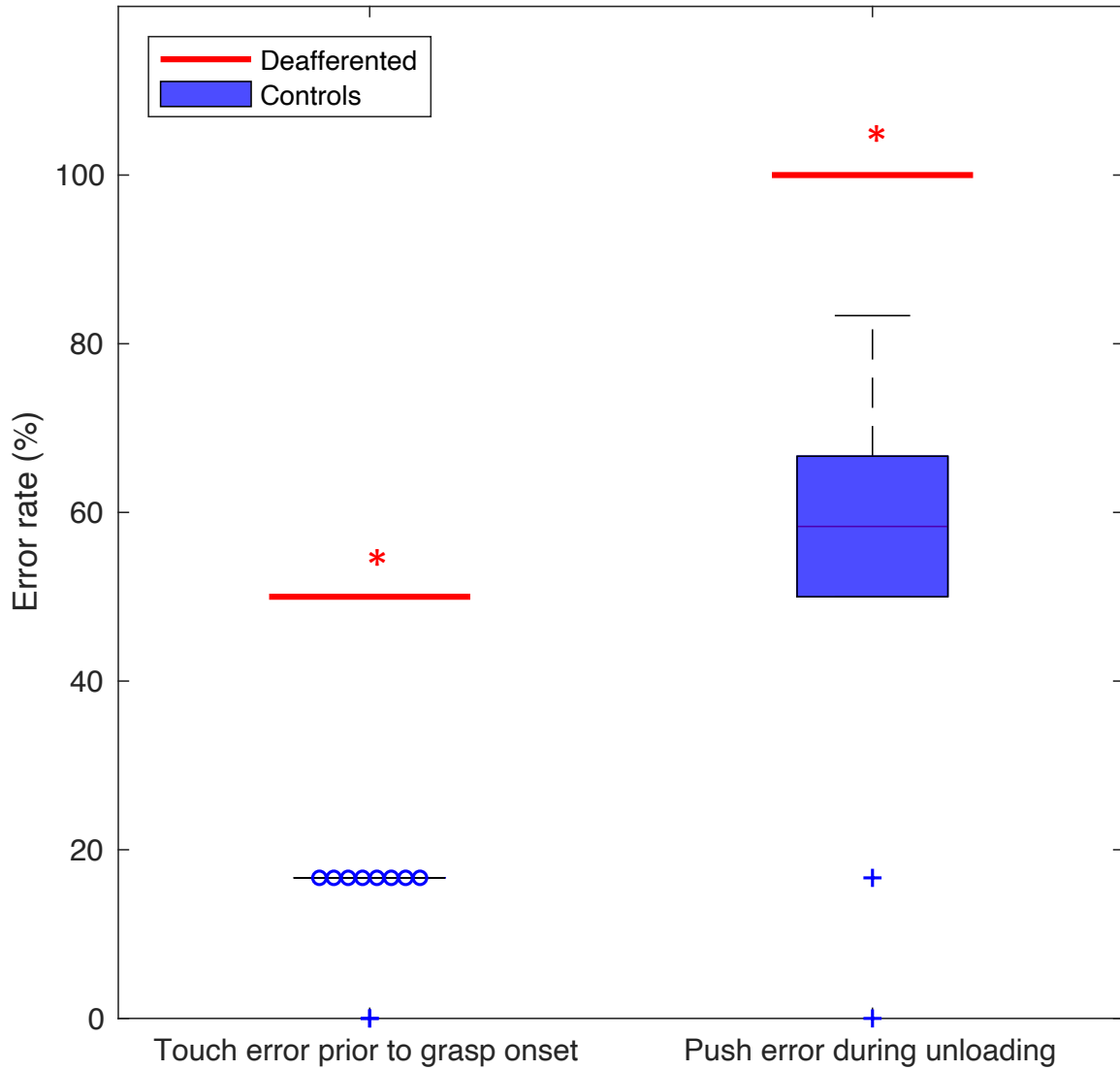


Control subject (C1)

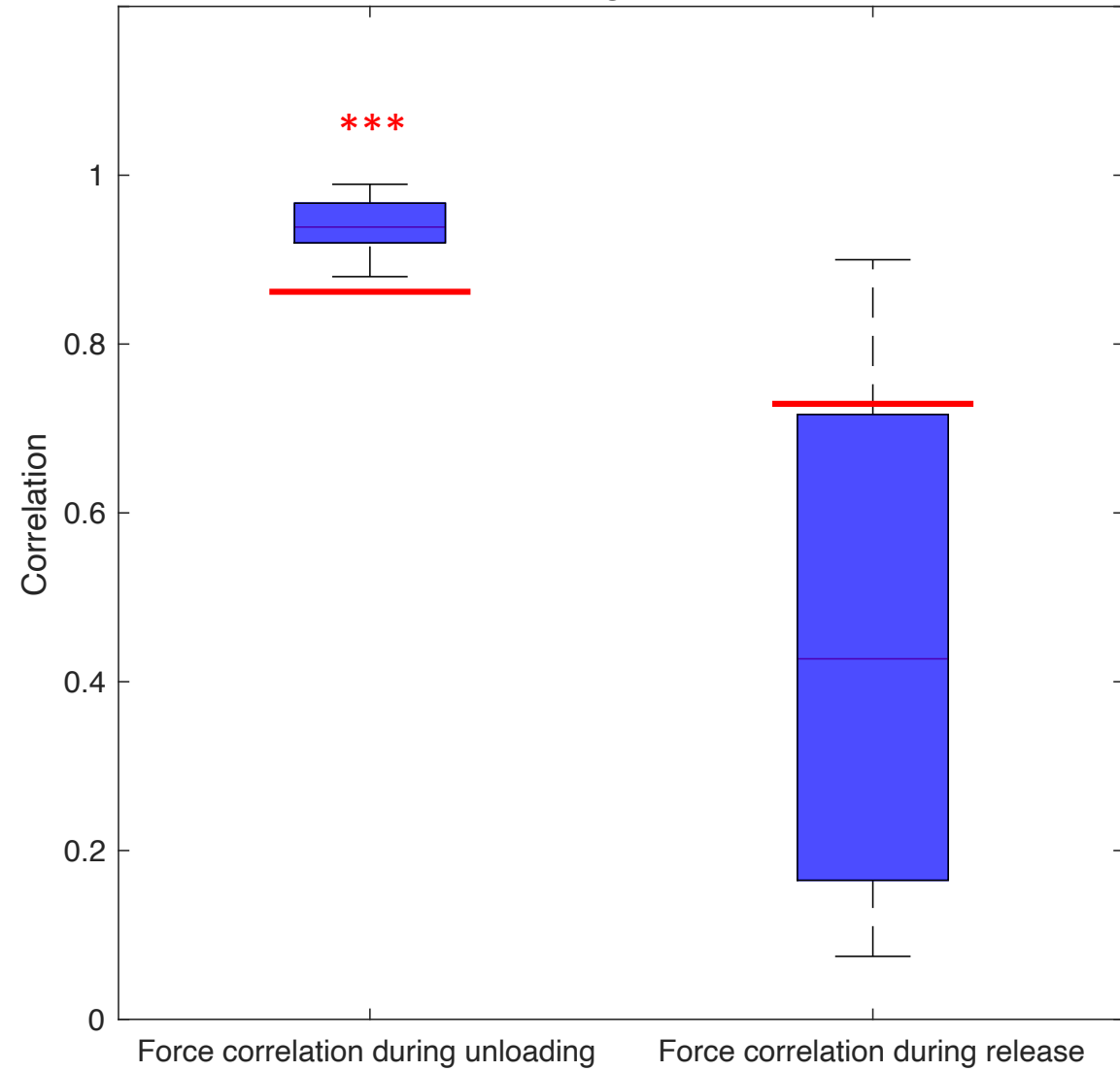




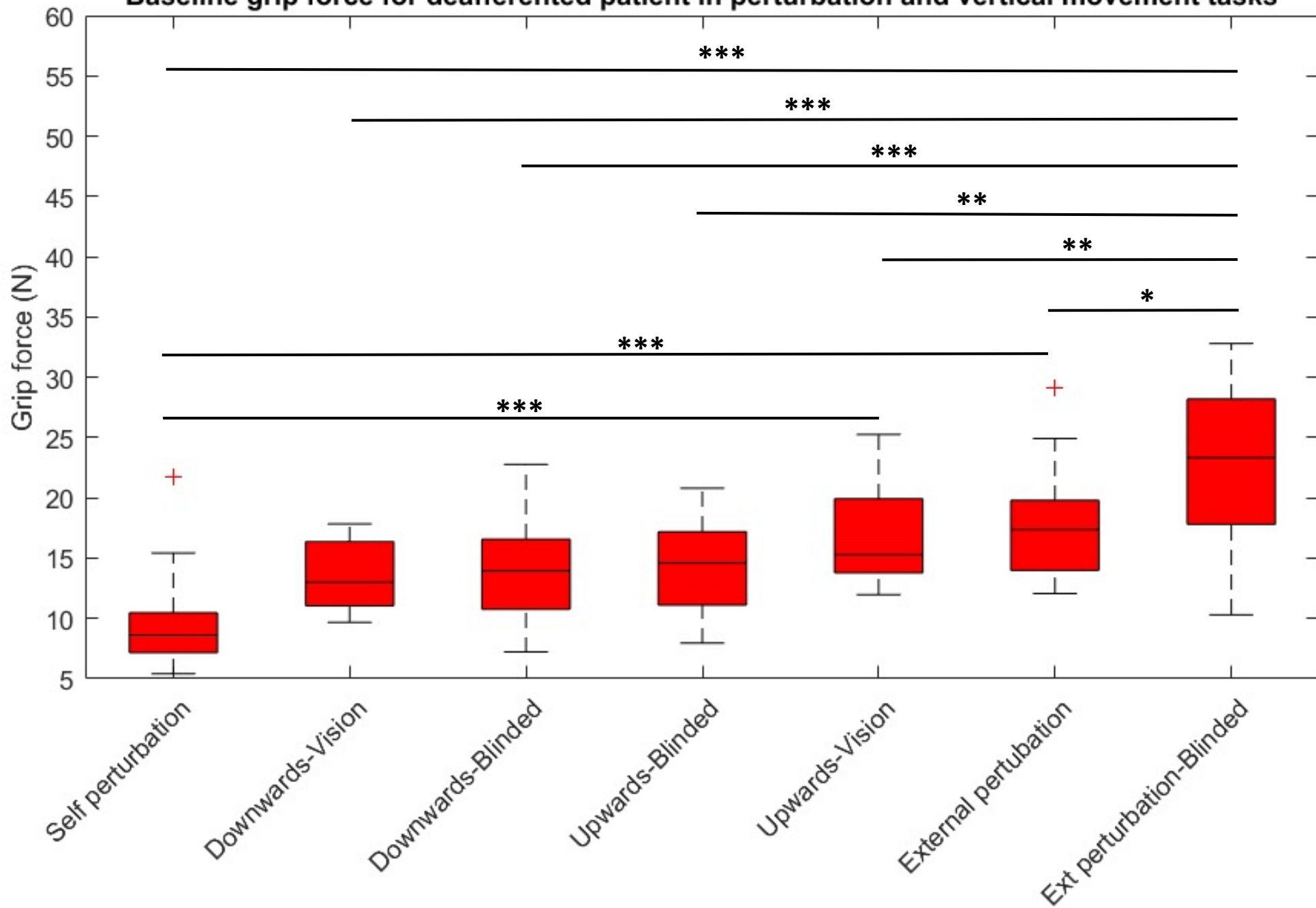
Touch and push errors upon task initiation



Time series correlation of grip force and base load cell

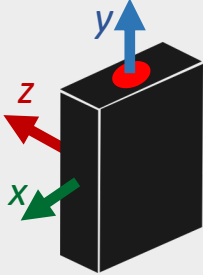


Baseline grip force for deafferented patient in perturbation and vertical movement tasks



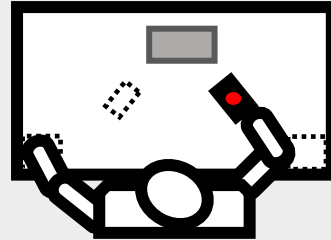
Anticipation and compensation for somatosensory deficits in object handling: Evidence from a patient with large fibre sensory neuropathy

Instrumented object with load cells, IMU



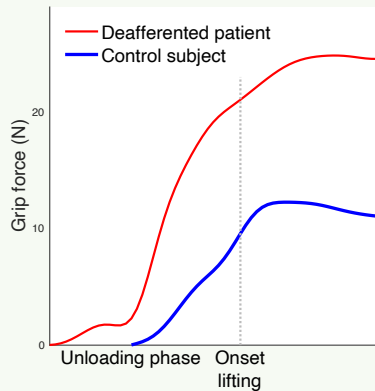
→ grip force, acceleration, orientation

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

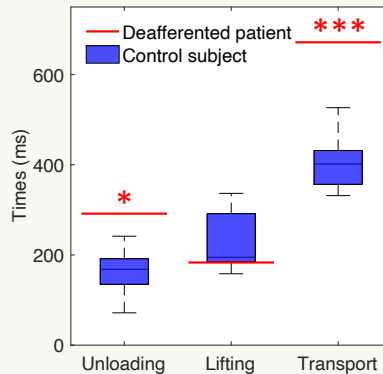


→ comparison of deafferented patient and healthy controls

Increased grip forces on object



Changes in phase duration



Object deviation at phase transitions

