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

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ABSTRACT

The purpose of this study was to determine the contributions of feedforward and feedback processes on grip force regulation and object orientation during functional manipulation tasks. One patient with massive somatosensory loss resulting from large fibre sensory neuropathy, and ten control participants were recruited. Three experiments were conducted: 1) perturbation to static holding; 2) discrete vertical movement; and 3) functional grasp and place. The availability of visual feedback was also manipulated to assess the nature of compensatory mechanisms. Results from experiment 1 indicated that both the deafferented patient and controls used anticipatory grip force adjustments prior to self-induced perturbation to static holding. The patient exhibited increased grip response time, but the magnitude of grip force adjustments remained correlated with perturbation forces in the self-induced and external perturbation conditions. In experiment 2, the patient applied peak grip force substantially in advance of maximum load force. Unlike controls, the patient's ability to regulate object orientation was impaired without visual feedback. In experiment 3, the duration of unloading, transport and release phases were longer for the patient, with increased deviation of object orientation at phase transitions. These findings show that the deafferented patient uses distinct modes of anticipatory control according to task constraints, and that responses to perturbations are mediated by alternative afferent information. The loss of somatosensory feedback thus appears to impair control of object orientation, while variation in the temporal organization of functional tasks may reflect strategies to mitigate object instability associated with changes in movement dynamics.

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

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

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

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

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

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

2. MATERIALS AND METHODS

2.1 Participants

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

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

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

2.2 Apparatus

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

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

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

Insert figure 1 about here

2.3 Experiment 1: Perturbation to static holding

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

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

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

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

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

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

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

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

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

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

2.4 Experiment 2: Vertical displacement of handheld object

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

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

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

- Baseline grip force during holding: minimum value for grip force during the 500ms prior to onset of movement
- Maximum acceleration: value for maximum acceleration during the movement window
- Maximum grip force: value for maximum grip force and the instant it occurred after movement onset
- Magnitude of grip force increase: difference between baseline and maximum grip force
- Time series correlation of grip force and load force: correlation coefficient for grip force and load force signals during the 1500ms window from movement onset
- Ratio of maximum grip to maximum load: calculated by dividing the maximum grip force value from each trial by the maximum load force value from each trial
- Grip-load time delay: interval between the time points for the maximum grip force and the maximum load force values
- Average object angle: mean alpha angle calculated across time points for the duration of each trial
- Variability of object angle: standard deviation of the alpha angle calculated across time points for the duration of each trial

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

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

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

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

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

2.6 Statistical analysis

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

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

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

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

3. RESULTS

The deafferented patient was evaluated as being right hand dominant (laterality quotient 80). The control group comprised 9 right handed participants (laterality quotient 90 ± 8) and 1 left handed participant (laterality quotient -100). Maximum grip strength for GL was 17.2kg for the dominant hand and 18.1kg for the non-dominant hand. These values did not significantly differ to $29.1\pm6.5\text{kg}$ for the dominant hand ($p=0.12$) and $26.9\pm7.1\text{kg}$ ($p=0.27$) for the non-dominant hand in the control group (NB: control averages in the 6 females were $24.8\pm3.5\text{kg}$ and $22.8\pm1.7\text{kg}$ for dominant and non-dominant hands respectively). Differences between grip strength in the right and left hands of the control group were not statistically significant ($p=0.14$). The deafferented patient scored 25/100 on a QuickDASH questionnaire, indicating functional upper limb deficits with daily living tasks compared to females of a similar age group (46, 51).

3.1 Experiment 1: Perturbation to static holding

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

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

Insert figures 2 and 3 about here

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

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

Insert figure 4 about here

3.2 Experiment 2: Vertical displacement of handheld object

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

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

Insert figure 5 about here

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

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

Insert figure 6 about here

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

Insert figure 7 about here

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

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

Insert figure 8 about here

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

Insert figure 9 about here

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

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

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

Insert figure 10 about here

3.4 Grip force control in the deafferented patient across experimental tasks

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

Insert figure 11 about here

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

4. DISCUSSION

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

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

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

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

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

4.2 Compensation for somatosensory deficits in reactive grip force scaling

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

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

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

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

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

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

4.3 Object handling across sequential phases in functional grasp and place

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

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

4.4 Limitations of the study

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

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

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

5. CONCLUSION

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

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

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

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

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

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

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

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

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

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

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

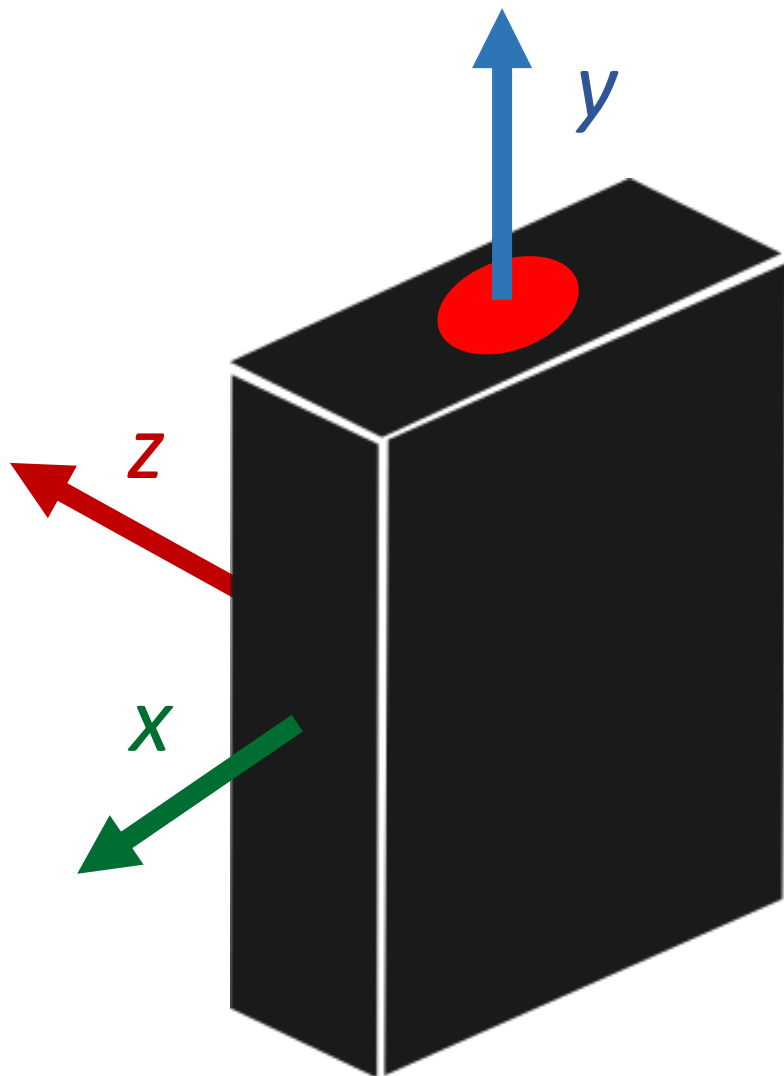
Figure 7. Experiment 2: Object orientation during vertical movement. (A/B) Object orientation profiles during upward movement without visual feedback for the deafferented patient (GL, red) and one representative control subject (C1, blue). (C) Boxplot summary of average object orientation during vertical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

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

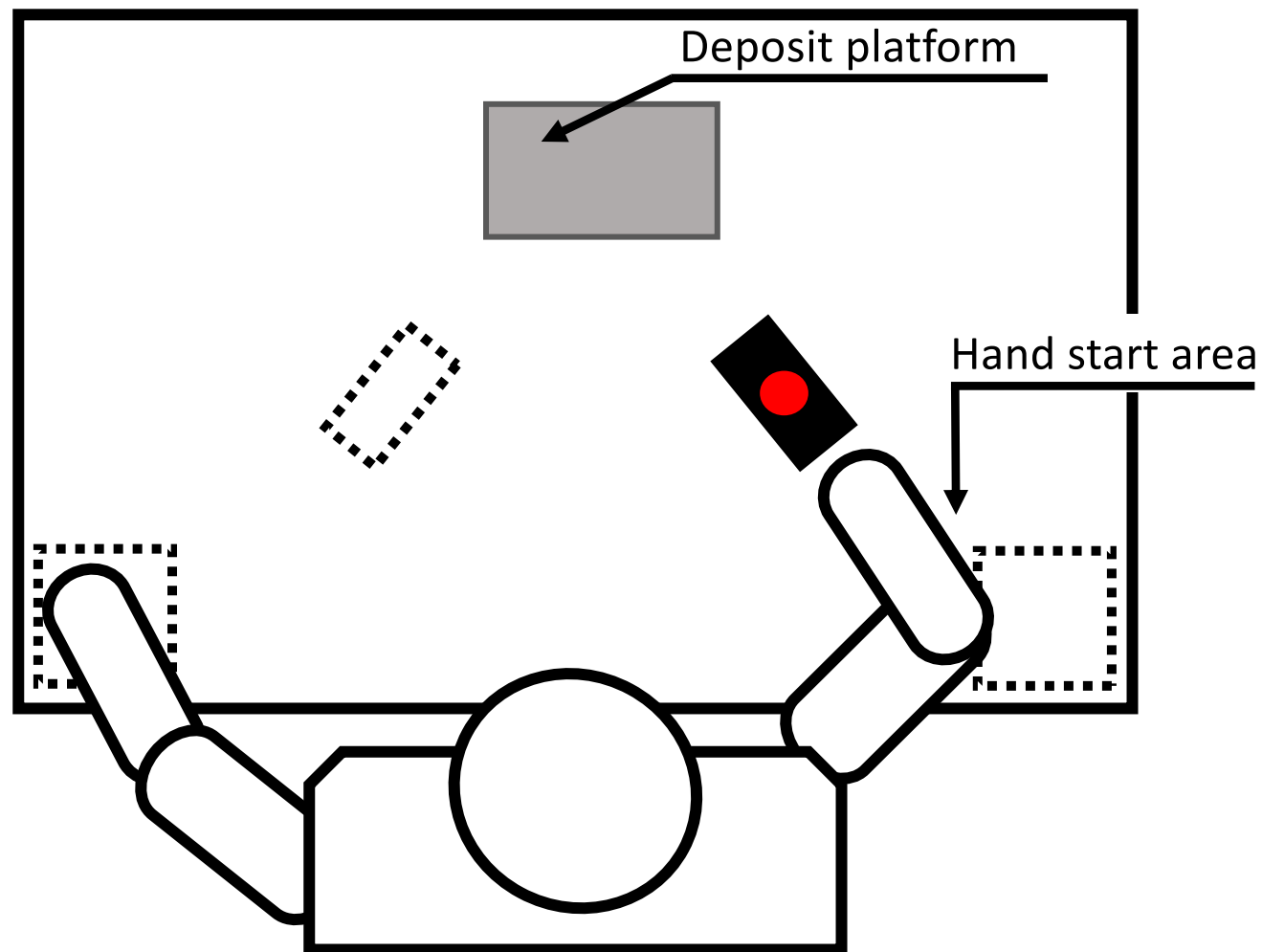
Figure 9. Boxplot summary of results for grasp, transport and place task. (A) Duration of component phases during the task. (B) Average grip-load force ratio during the different phases. (C) Object angle at transitions between phases of the task. Blue boxplot data indicates values for control group data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

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

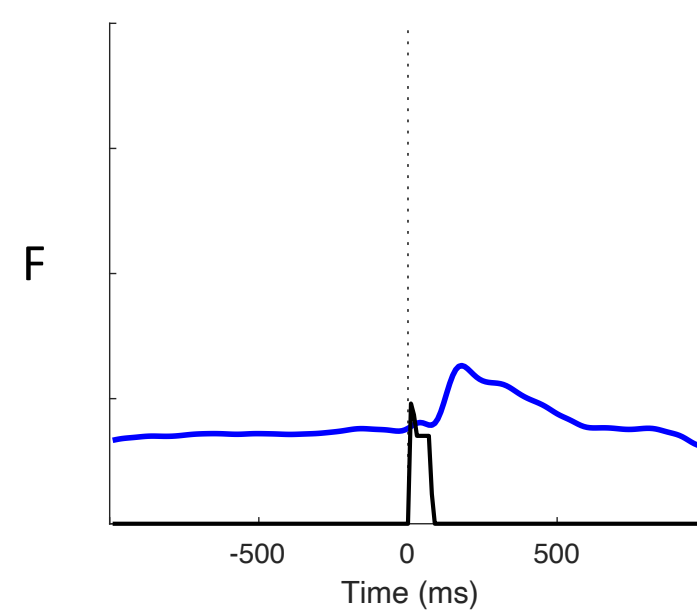
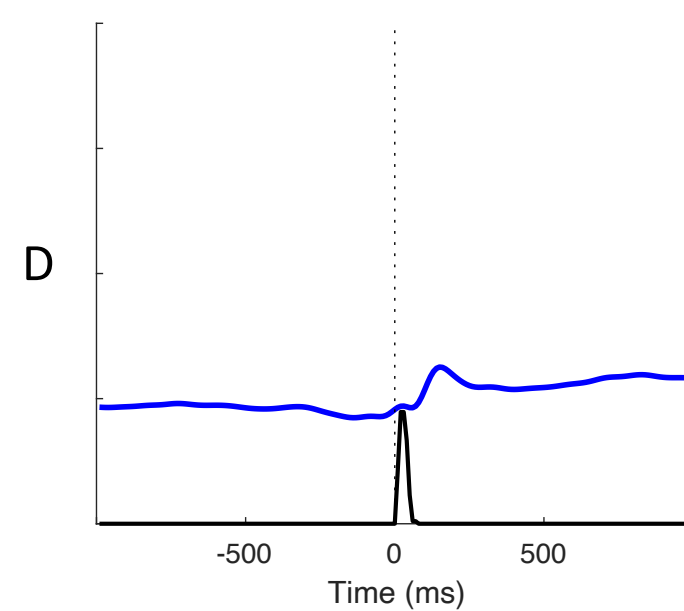
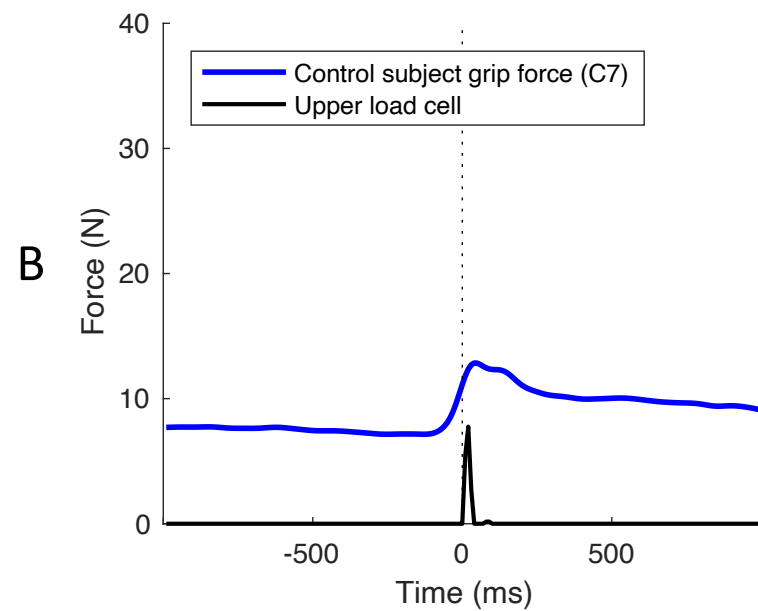
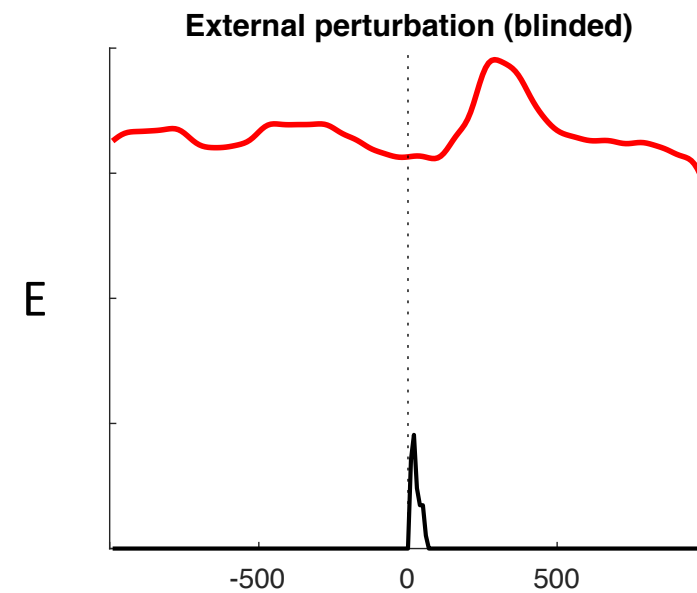
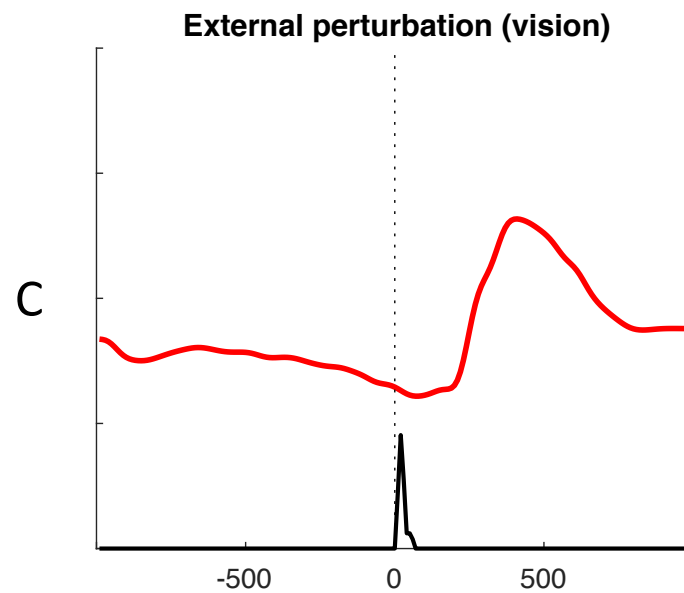
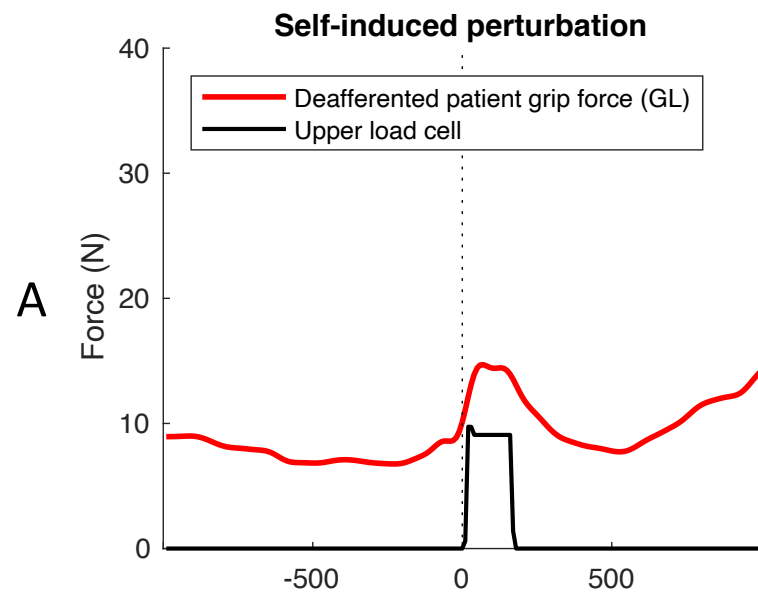
Figure 11. Baseline grip force for the deafferented patient across tasks with static holding phases. Black asterisks indicate results from post-hoc testing. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.



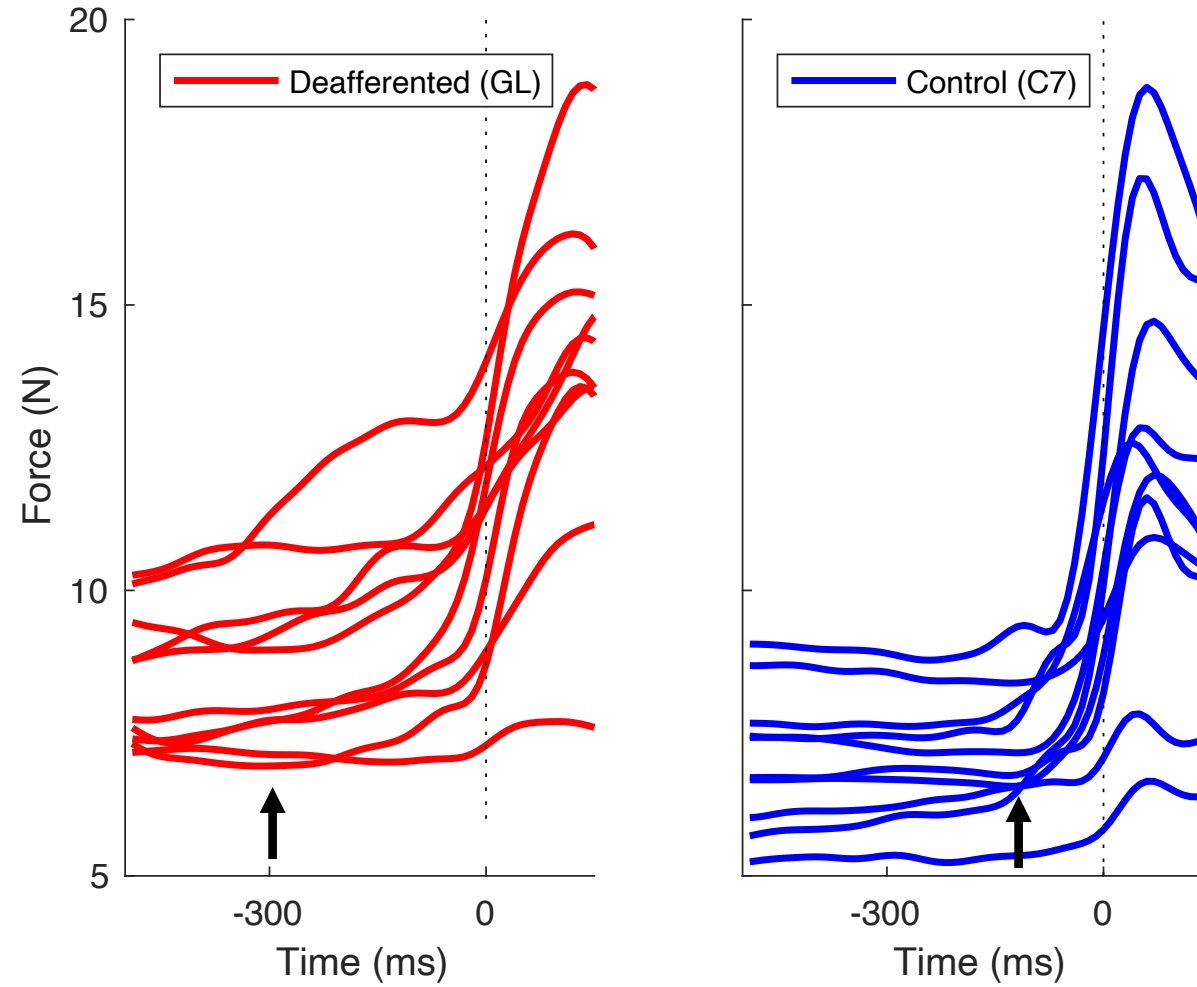
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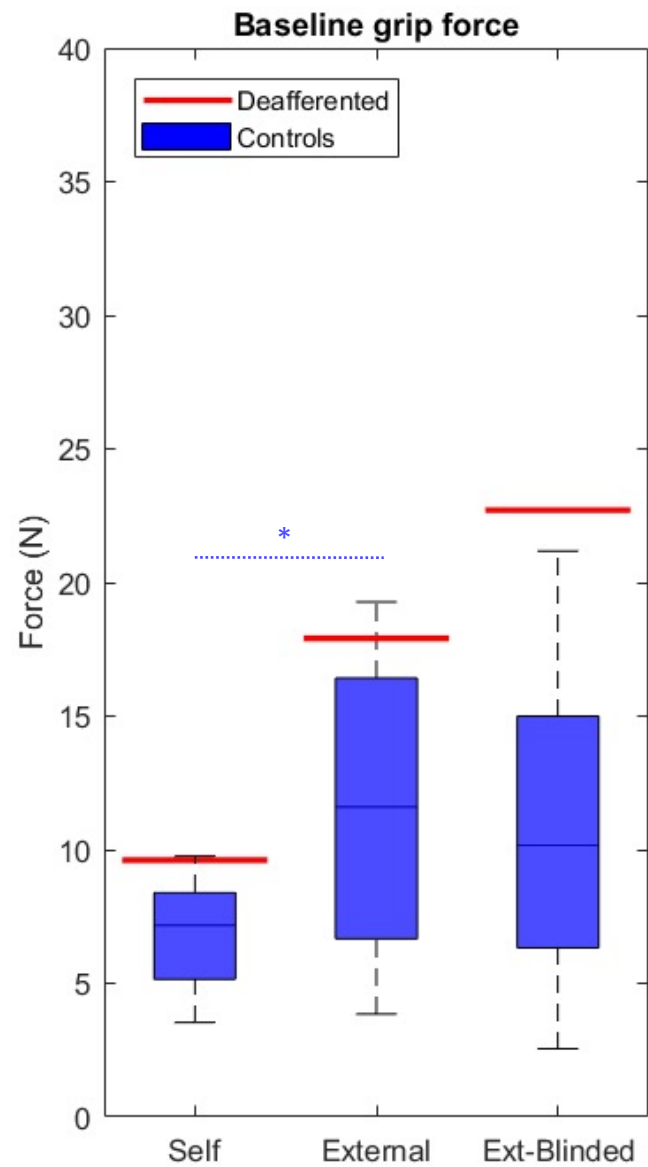


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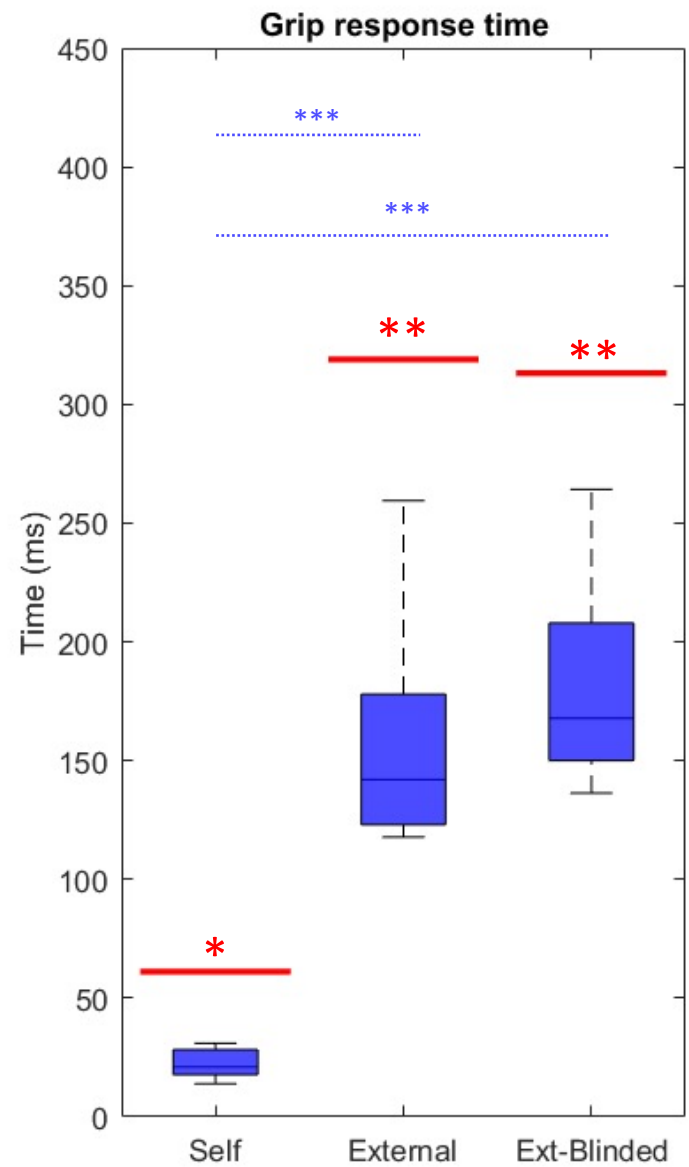


Preparatory actions in self-induced perturbation

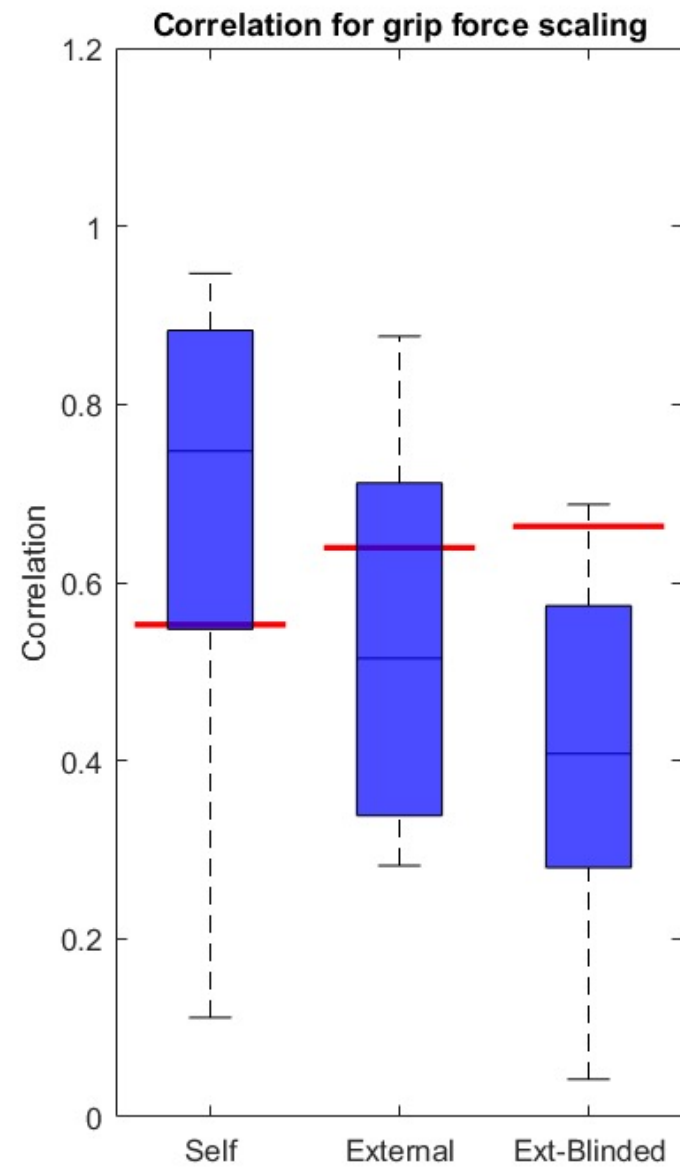




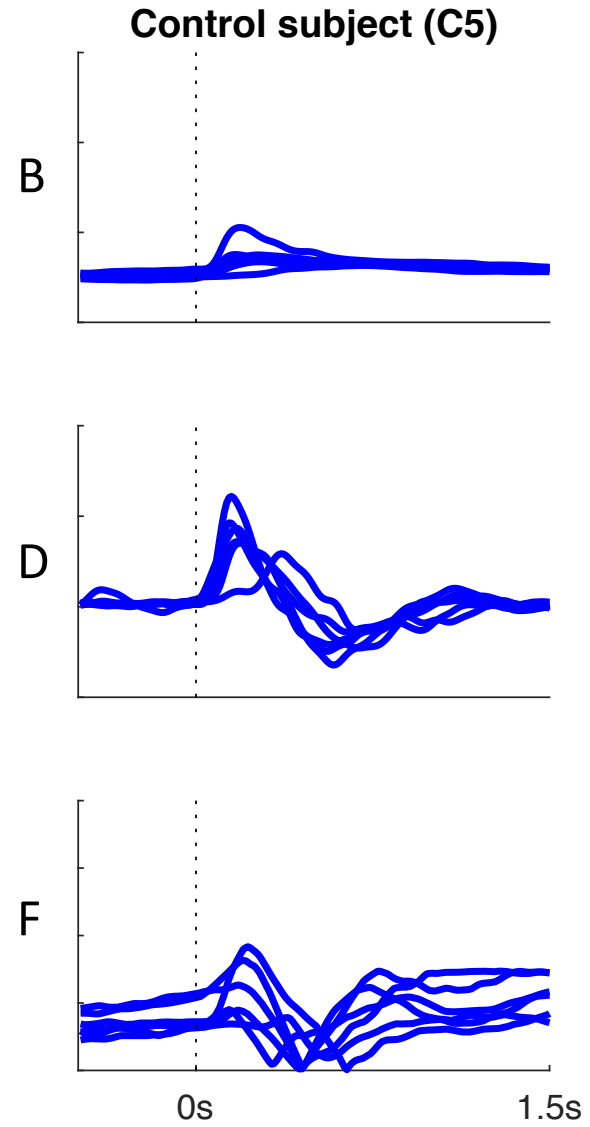
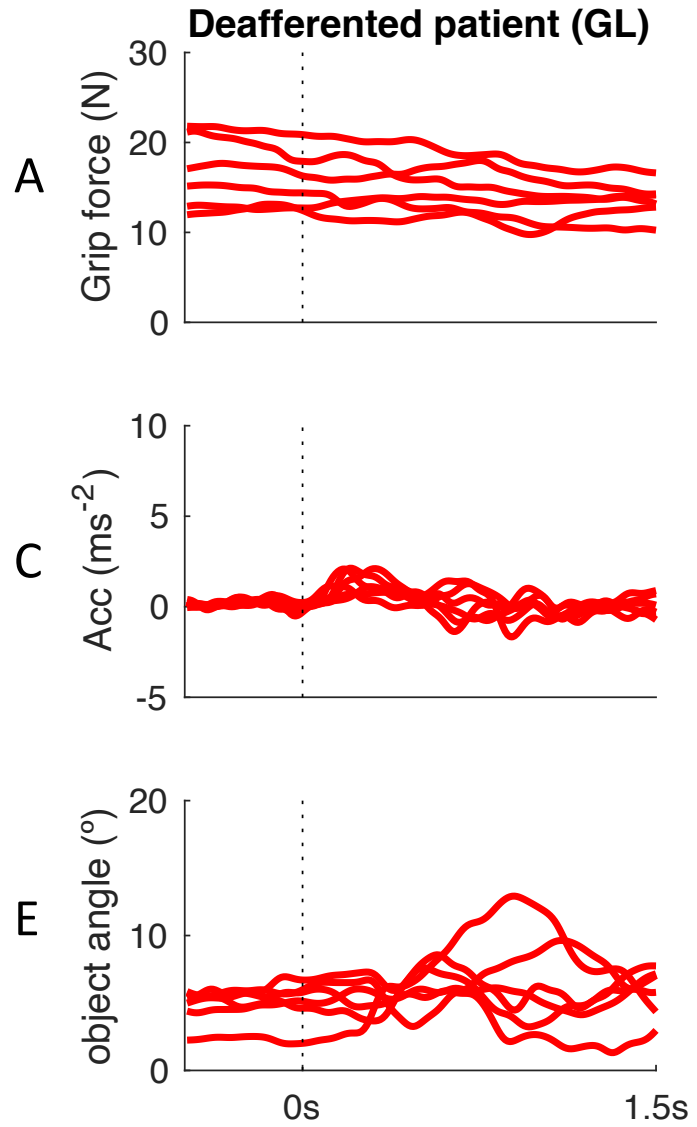
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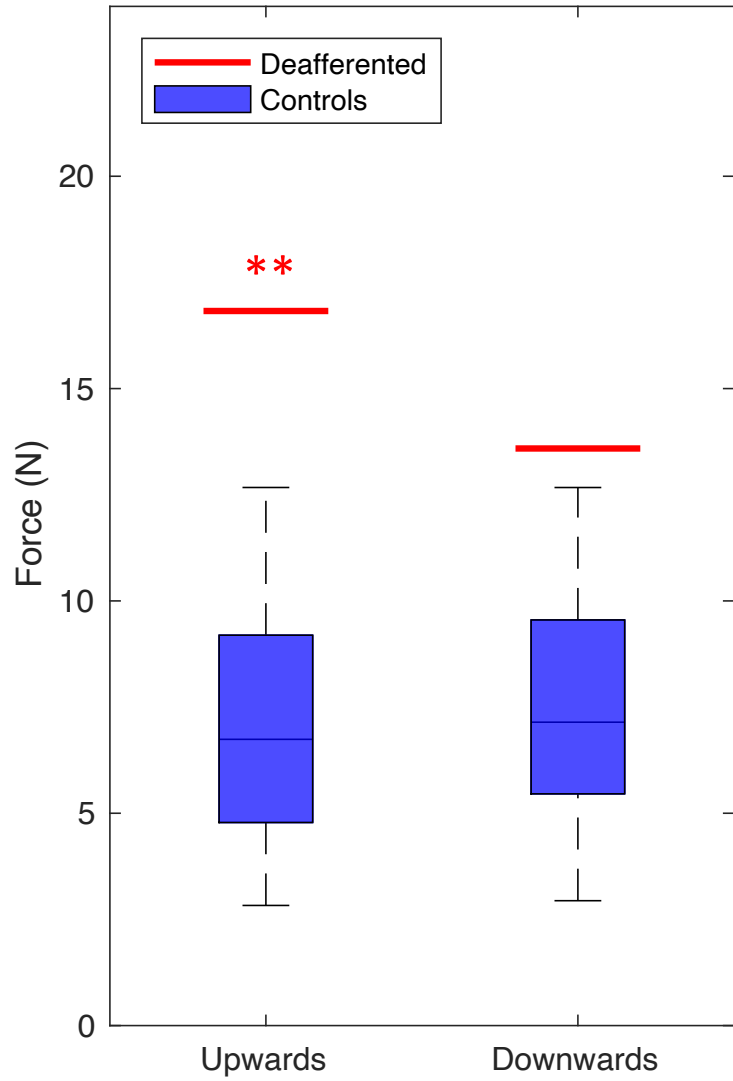
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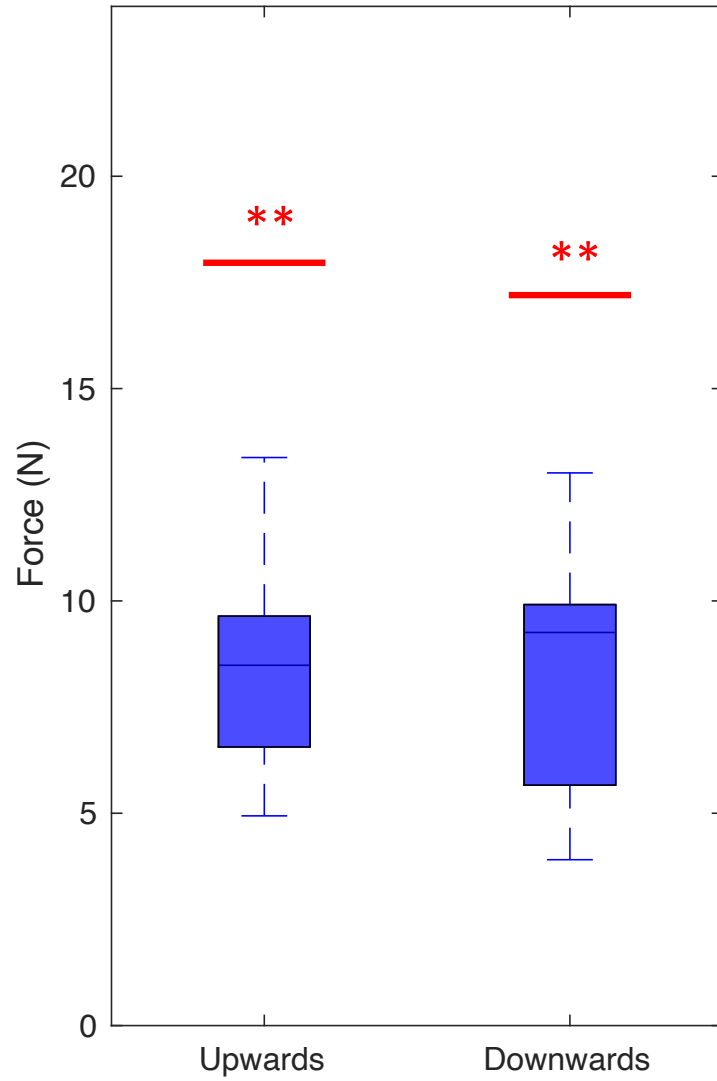


Baseline grip force



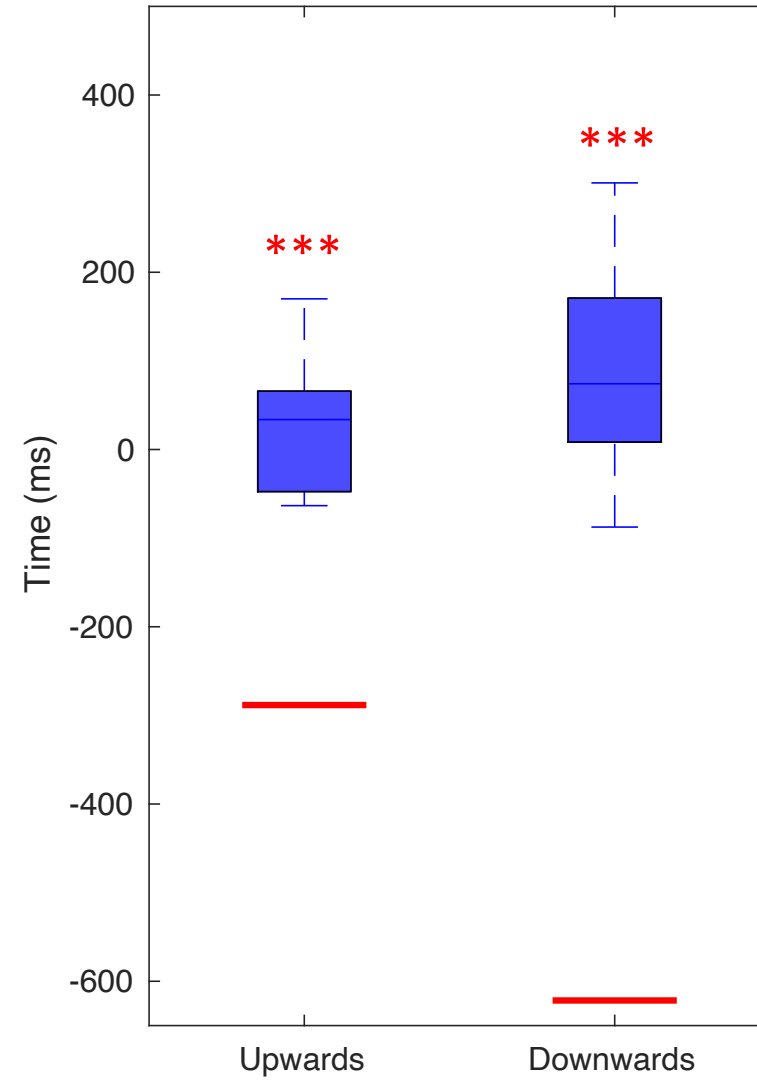
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Maximum grip force

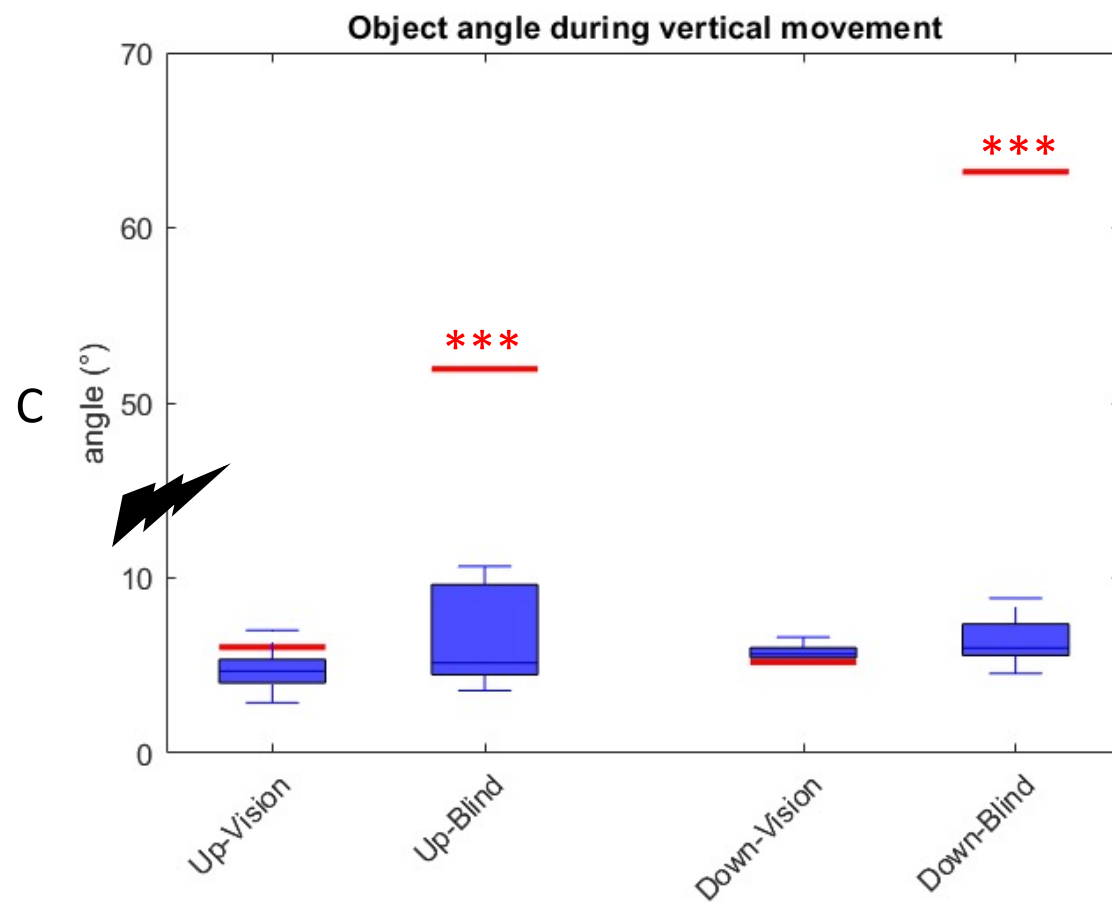
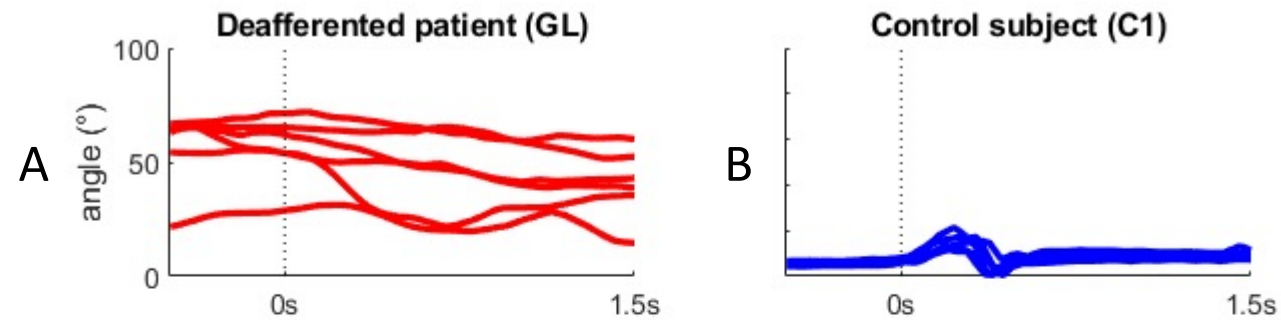


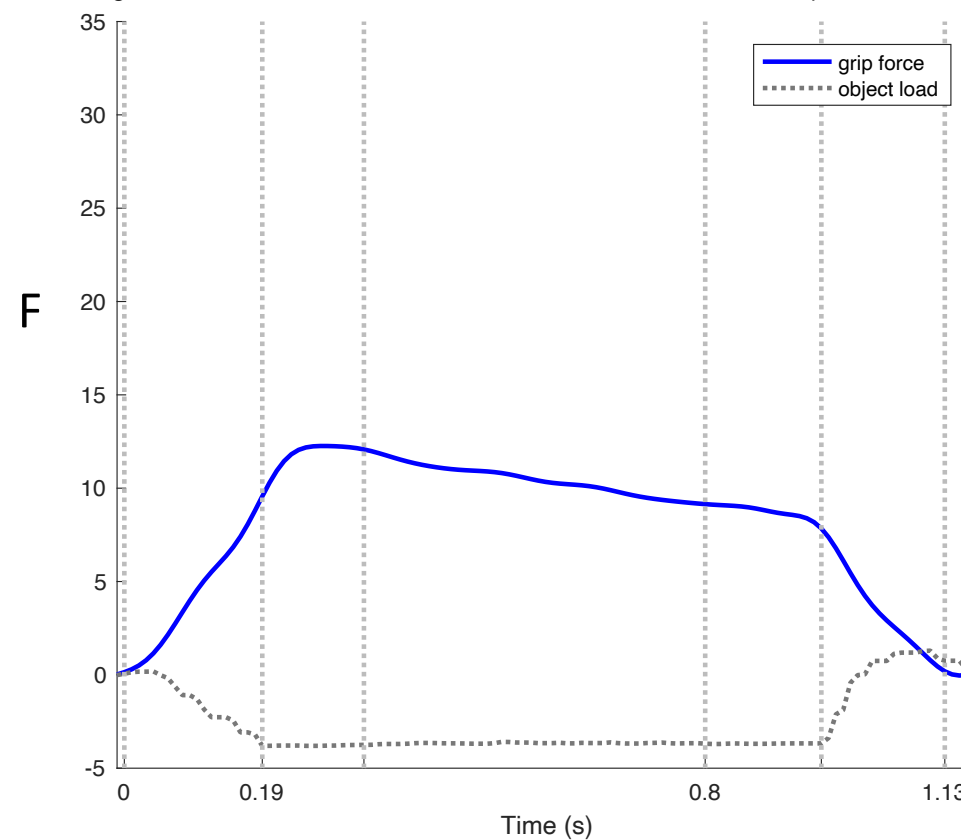
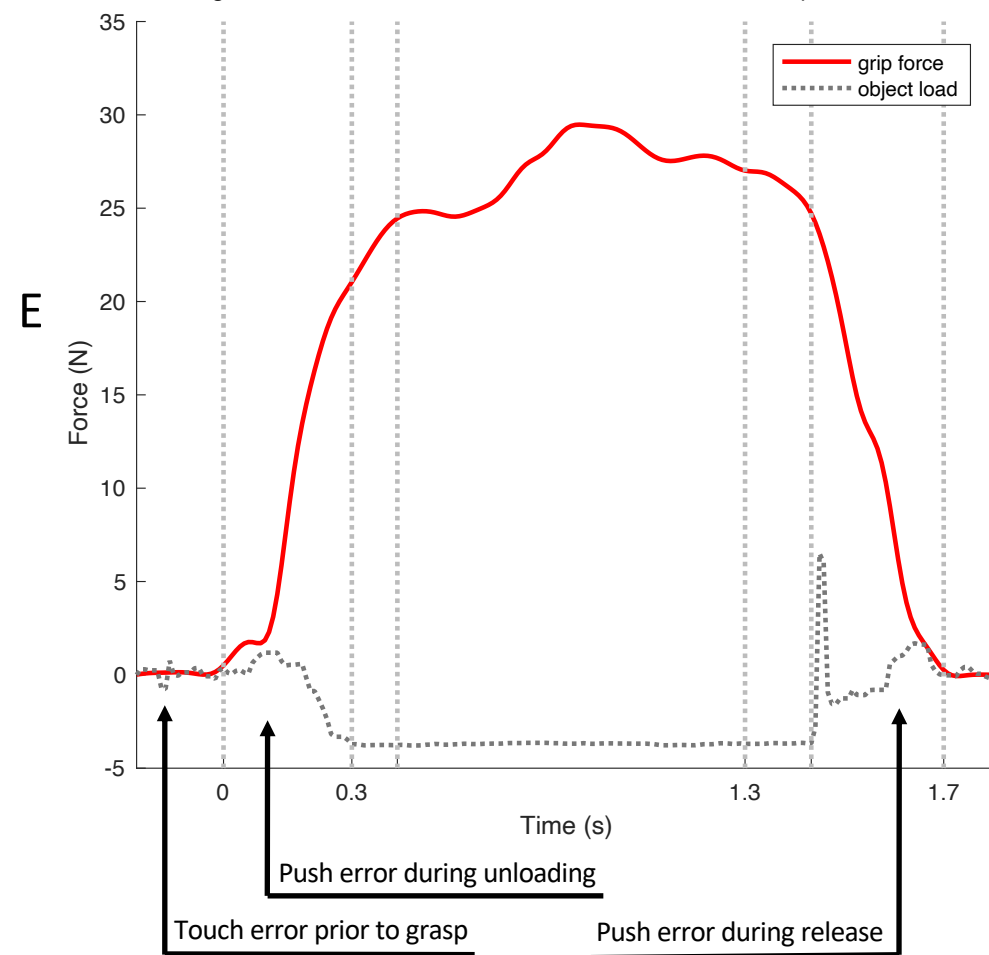
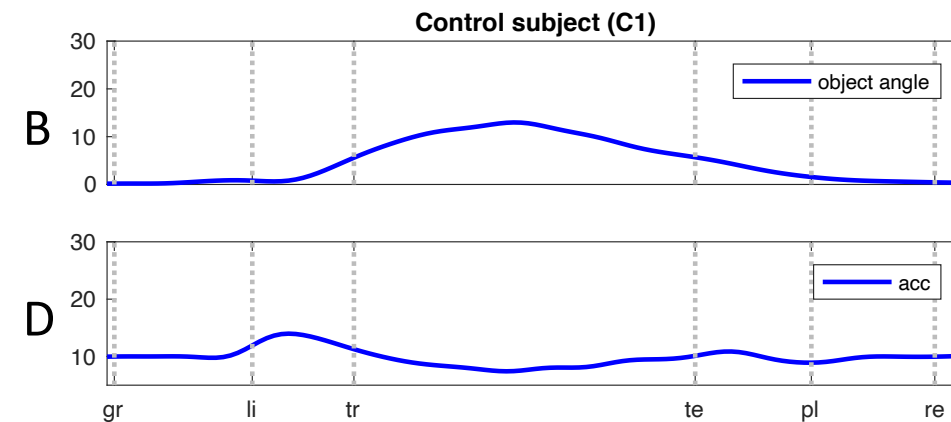
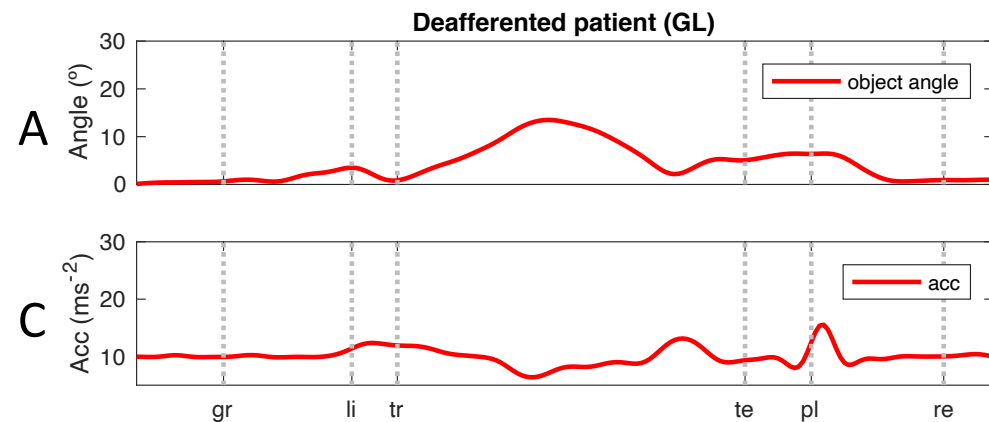
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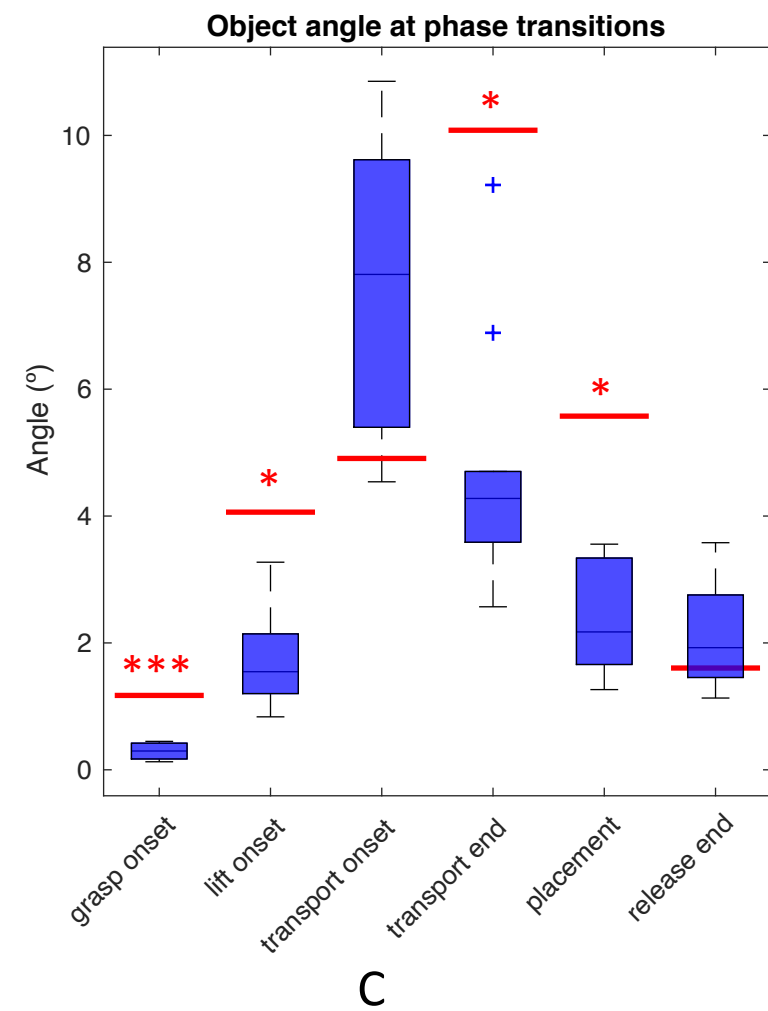
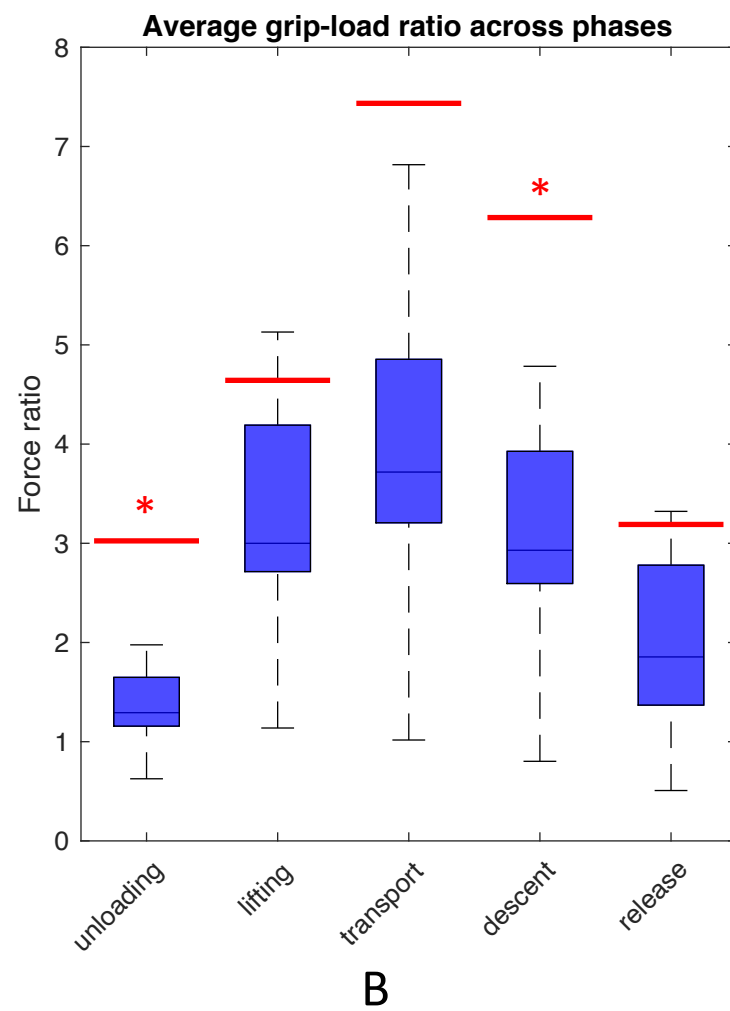
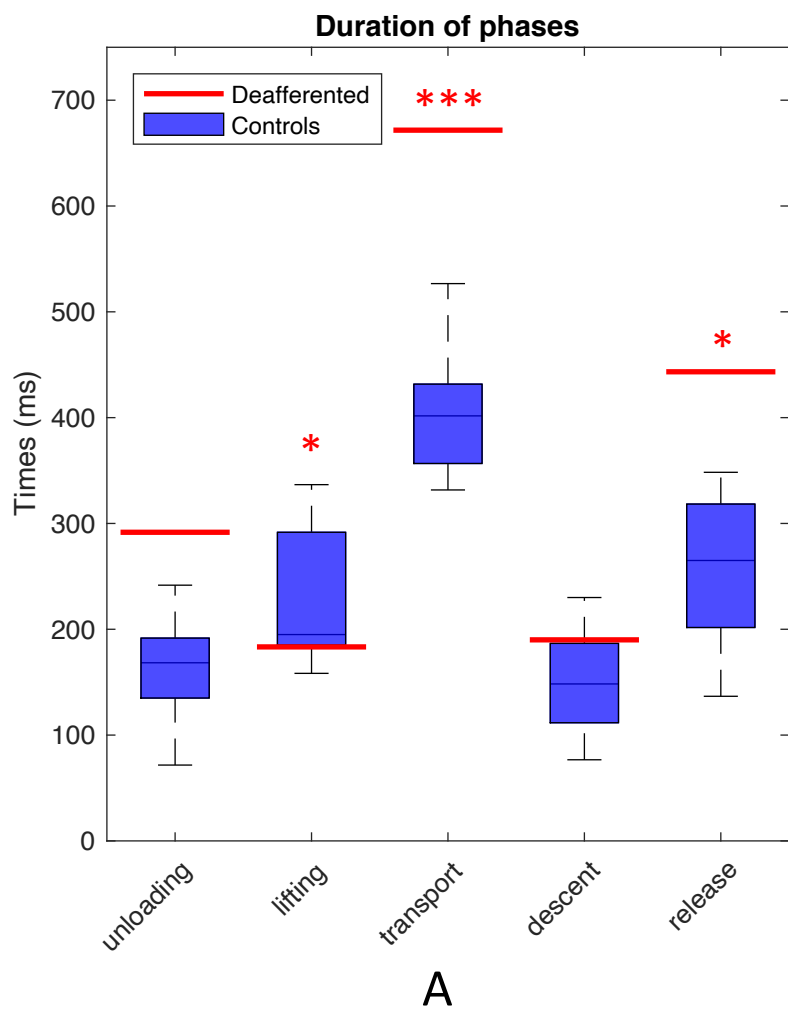
Grip-load time delay



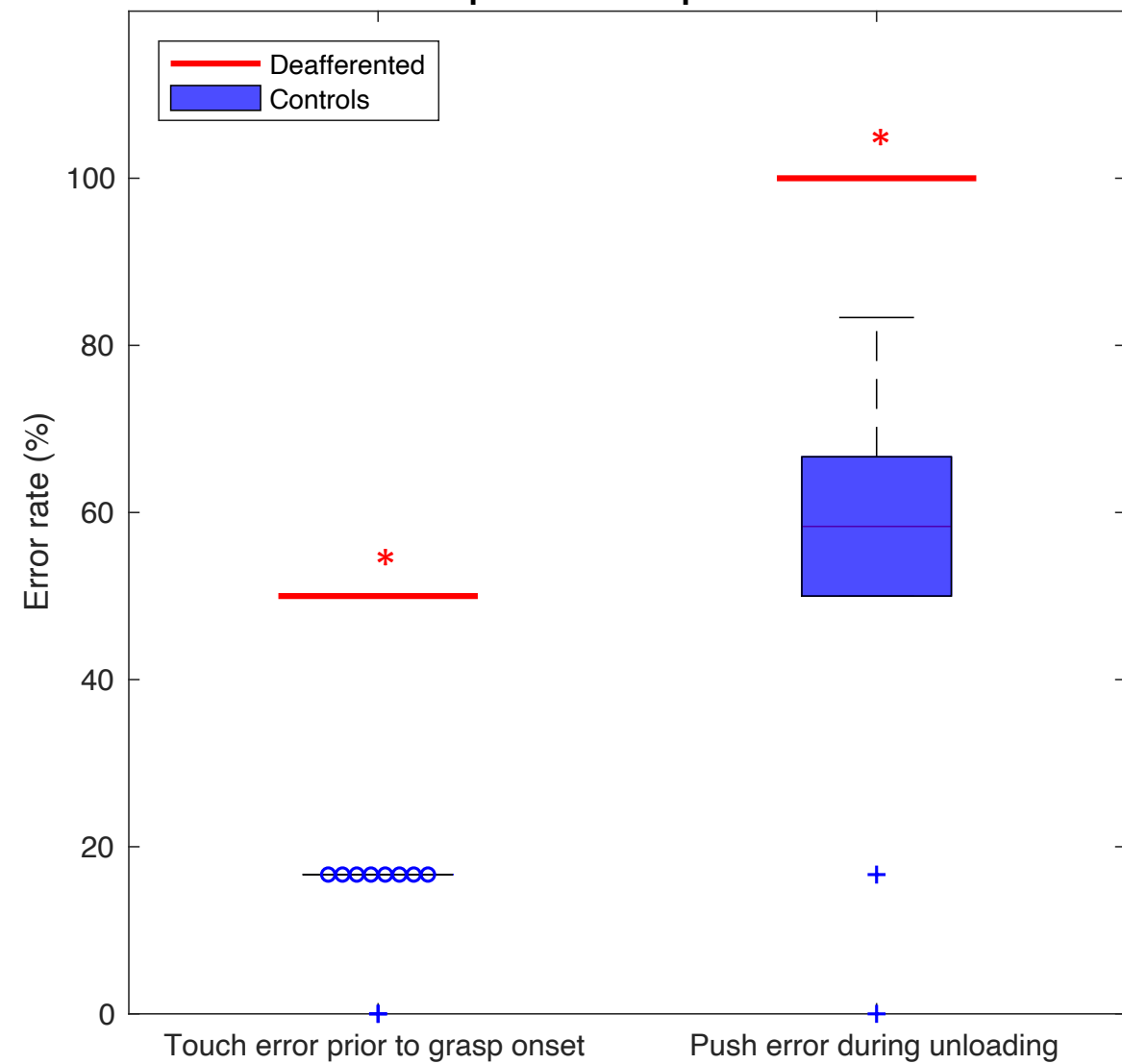
C



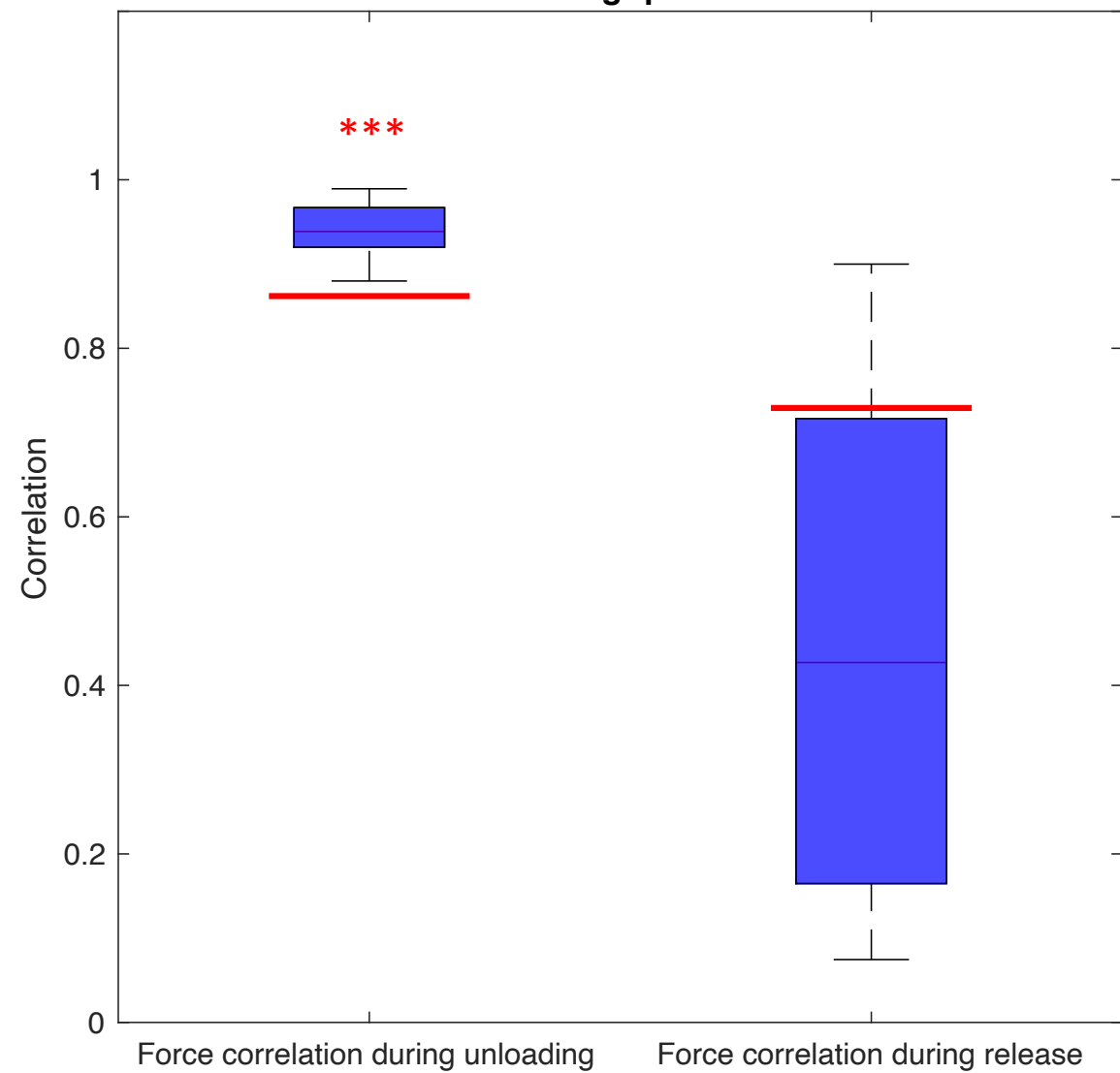


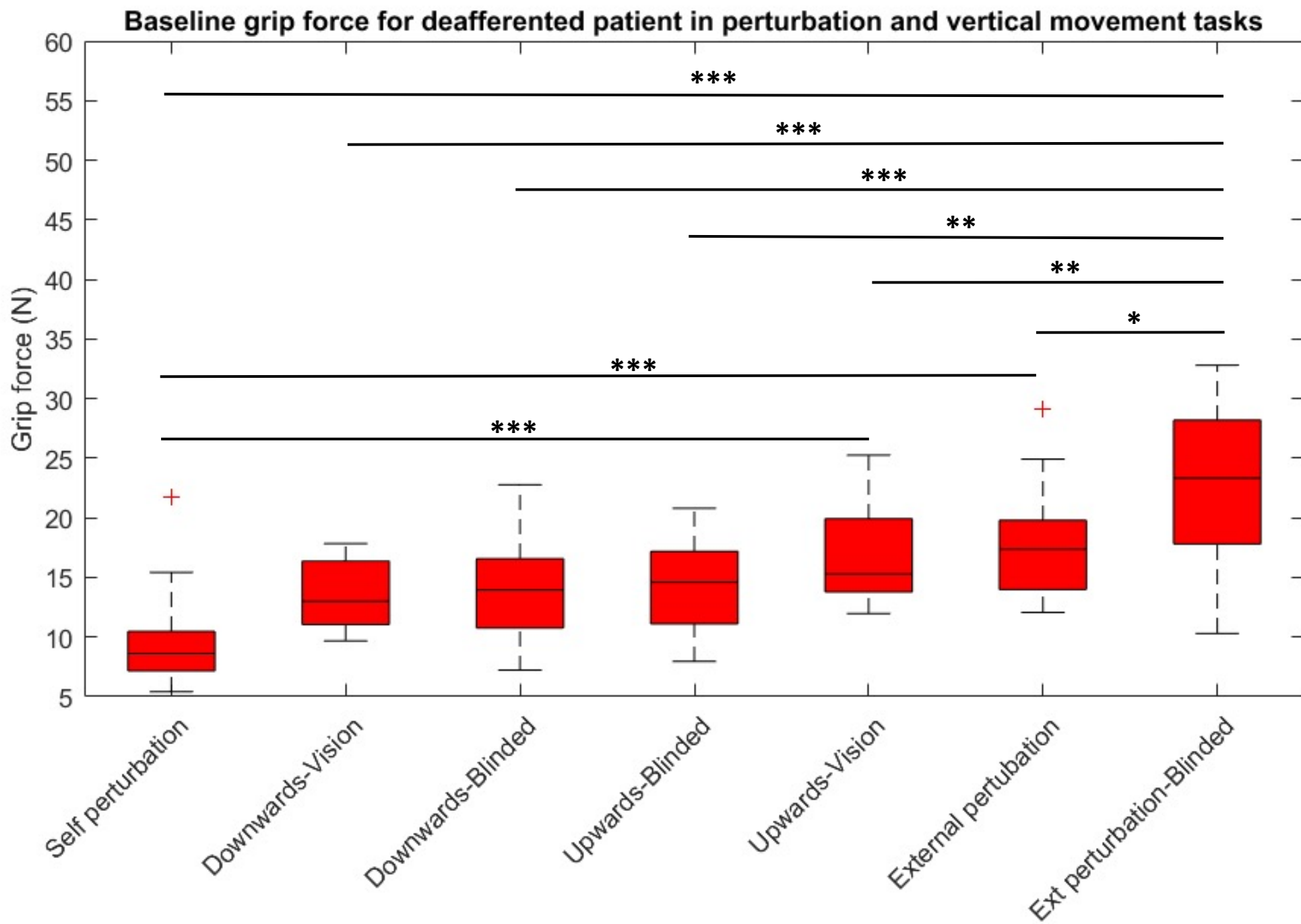


Touch and push errors upon task initiation



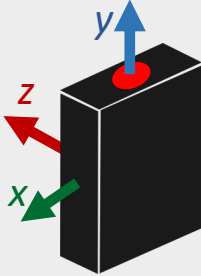
Time series correlation of grip force and base load cell





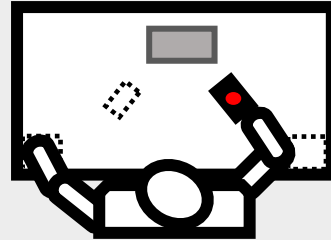
Anticipation and compensation for somatosensory deficits in object handling: Evidence from a patient with large fibre sensory neuropathy

Instrumented object with load cells, IMU



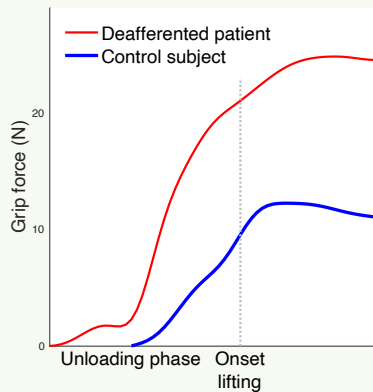
→ grip force, acceleration, orientation

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

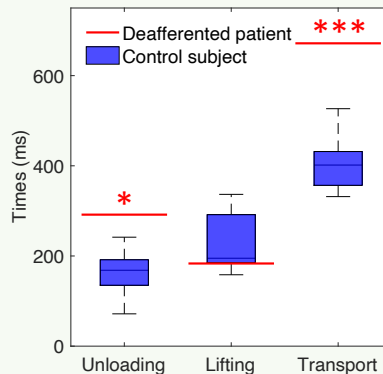


→ comparison of deafferented patient and healthy controls

Increased grip forces on object



Changes in phase duration



Object deviation at phase transitions

