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This is a personal copy of the authors. The final publication is available at Springer via http://dx.doi.org/10.1007/s00221-014-4024-8.

# Humans can integrate feedback of discrete events in their sensorimotor control of a robotic hand

*Abbreviated title: Discrete event sensory feedback control*

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Number of pages: 17

5 figures, 0 tables, 0 multimedia and 3D models.

Words for Abstract 248, Introduction 527, and Discussion 985.

Keywords: Sensorimotor control; Human; Hand; Tactile afferents; Sensory substitution; Sensory feedback

## Abstract

Providing functionally effective sensory feedback to users of prosthetics is a largely unsolved challenge. Traditional solutions require high band-widths for providing feedback for the control of manipulation and yet have been largely unsuccessful.

In this study we have explored a strategy that relies on temporally discrete sensory feedback that is technically simple to provide. According to the *Discrete Event-driven Sensory feedback Control* (DESC) policy, motor tasks in humans are organized in phases delimited by means of sensory encoded discrete mechanical events. To explore the applicability of DESC for control, we designed a paradigm in which healthy humans operated an artificial robot hand to lift and replace an instrumented object, a task that can readily be learned and mastered under visual control. Assuming that the central nervous system of humans naturally organizes motor tasks based on a strategy akin to DESC, we delivered short-lasting vibrotactile feedback related to events that are known to forcefully affect progression of the grasp-lift-and-hold task. After training, we determined if the artificial feedback had been integrated with the sensorimotor control by introducing short delays and we indeed observed that the participants significantly delayed subsequent phases of the task.

This study thus gives support to the DESC policy hypothesis. Moreover, it demonstrates that humans can integrate temporally discrete sensory feedback while controlling an artificial hand and invites further studies in which inexpensive, non-invasive technology could be used in clever ways to provide physiologically appropriate sensory feedback in upper limb prosthetics with much lower band-width requirements than with traditional solutions.

## Introduction

It stands to reason that prostheses would function better if their users could rely on sensory feedback (Childress 1980). However, despite various attempts to provide sensory feedback and closed-loop control of hand prostheses over the years, none has been proven functional and thus been deployed in clinical practice (Antfolk et al. 2013). In all previous attempts, feedback was provided in a continuous fashion, e.g., by mapping grip force to a certain vibration frequency (Mann and Reimers 1970; Chatterjee et al. 2008; Cipriani et al. 2008; Stepp et al. 2012), a mechanical stimulus (Meek et al. 1989; Antfolk et al. 2012), or an electrical current (Szeto and Saunders 1982; Sasaki et al. 2002). Yet it is known that continuous closed-loop control of dynamic motor behaviors is severely limited by neural delays and therefore impractical at frequencies above 1 Hz (Hogan et al. 1987). An alternative to continuous feedback is to rely on temporally discrete feedback such as that proposed by the *Discrete Event-driven Sensory feedback Control* (DESC) model (Johansson and Edin 1993; Flanagan et al. 2006). This model posits that motor tasks in humans, such as object manipulation, are organized in phases characterized by specific coordinated muscle activity and delimited by means of sensory encoded discrete events, e.g., object contact, lift-off, etc. Such events are often represented in a multimodal fashion but at other times they exclusively evoke activity in tactile afferents. That is, the task evolves in an open-loop fashion where the successful completion of each phase is signified by specific combinations of temporally correlated sensory signals.

Assuming that DESC is a general control policy in humans, we have investigated if artificial sensory feedback is integrated in the sensorimotor control of a task when it is represented by discrete events that are tightly correlated with pertinent mechanical events. To this end, we designed a paradigm in which healthy humans operated an artificial robot hand to lift and reposition an object, a task that can be readily learned and mastered under visual control. Our system delivered short-lasting Vibro-Tactile (VT) feedback related to events that are known to forcefully affect the progression of the grasp-lift-and-hold task, i.e., digit-object contact and release and object lift-off and repositioning (Westling and Johansson 1987). *Notably, the task could be readily completed without this feedback so the vibrotactile feedback was not only artificial but also redundant*. Nevertheless, because of the tight temporal coupling between the artificial feedback and the task-relevant mechanical events, we expected that the participants would integrate this feedback into their sensorimotor control of the robotic hand. To detect such integration, we introduced feedback delays in ‘catch’ trials after first training the participants. We hypothesized that this would delay subsequent behavioral phases. Specifically, by delaying the feedback pertaining to object contact, we expected the subsequent load phase to be delayed as previously observed in humans with anesthetized fingertips (Johansson and Westling 1984).

Our results showed that the participants clearly delayed their load force onset when the VT feedback was delayed, demonstrating that humans can integrate temporally discrete sensory feedback while controlling an artificial hand, and gives support to the DESC policy hypothesis (i.e. the central nervous system of humans naturally organizes motor tasks based on a strategy akin to DESC). Accordingly, this invites further studies in which inexpensive, non-invasive technology could be used in clever ways to provide physiologically appropriate sensory feedback in upper limb prosthetics with much lower band-width requirements than with traditional solutions.

## Materials and Methods

Nine healthy participants participated in the study (age range 22-31; 5 females; three left-handed). Informed consent according to the Declaration of Helsinki was obtained before conducting the experiments.

The experimental platform consisted of a robot hand, a rotary potentiometer that measured the thumb-index tip-to-tip distance, a PC, a test-object instrumented with force sensors, an object stand with embedded load cells and vibrotactile units that conveyed sensory feedback (Fig. 1a).

The robotic hand was a left-handed version of the SmartHand (Cipriani et al. 2011; Prensilia Srl, Italy). It consists of four fingers and a thumb actuated by five motors. In the present work, movements were limited to allow only flexion-extension of the index finger and thumb. The hand included encoders on the motors which were under position control based on commands sent over a serial bus from the PC.

The participants controlled the robot hand by moving their own thumb and index fingers in a thumb-index pinch grip. The thumb-index distance was measured with a resolution of ~0.1 mm and a sampling frequency of 66 Hz. A signal proportional to the thumb-index distance was computed using custom software and continuously sent to the robot hand as a position command to the thumb and index motors (the relationship between the human and the resulting distance between the robot digits distance was not fixed, as described in more detail below). The maximum speed of the robot fingertips was ~200 mm/s. Once the robot digits touched the test-object, they could no longer move due to the interaction with the object and forces normal to its surfaces (termed *grip forces*, GF) were generated to levels that depended on the distance between the participant's digits (0.25 N/mm). The maximum rate of change in the grip force delivered by the robot hand was 38 N/s.

The same test object as used by Panarese et al. (2008), was used in this experiment. The test object consisted of a rigid plastic block (55×40×50 mm; 105 g) covered by plastic plates, equipped with piezo-resistive force sensors (FSG series, Honeywell Sensotec; 0-15 N; 0-2 kHz) able to measure the GF (Fig. 1a). The mechanical compliance of the test object was essentially zero. The minimum grip force ($GF_{MIN}$) required to lift the test object with the robot hand without slippage was ~0.5 N. As long as the test object was in contact with the stand, the vertical *load force* (LF) applied by the participants to the object was calculated from the readings of a piezo-resistive force sensor that measured the force applied by the test object to the support stand (as in Gordon et al, 1993). GF and LF were both acquired with 16-bit resolution (USB-6211, National Instruments Corp.).

A sensory feedback system comprising three miniaturized vibrators conveyed tactile feedback to the participants. The miniature vibration motors (Precision Microdrives, UK; 6 mm diameter, 12 mm length cylinders) were driven by a custom microcontroller board in order to vibrate at a frequency of 150 Hz with a peak-to-peak force amplitude of about 0.32 N (Cipriani et al. 2012). The microcontroller board was able to control the duration of the vibration by receiving commands from the host PC over a serial bus. The three vibrators were taped to the fingertips of the human thumb, index and ring fingers. The vibrators on the thumb and index provided feedback when the robotic thumb and index finger, respectively, contacted or released the test object. The vibrator on the ring finger was activated at the moment of object lift-off and when it was replaced on the stand.

### *Experimental protocol*

Participants were instructed to repeatedly grip, lift, replace, and release the test object at a self-selected speed. Specifically, their task consisted of (i) moving their left arm to reach the object with the robot hand mounted on the splint (Fig. 1a); (ii) moving their own thumb and index finger to control the robot hand so that it eventually grasped the object; (iii) lifting the test object a few centimeters above the stand, (iv) putting the test object back on the stand and, finally, (v) releasing the object by opening their grasp. During the experiment participants were seated with their elbows bent at a 90 degree angle. The splint setup connecting the robot hand to the participants' forearms effectively masked object vibrations at contact and lift-off.

Four discrete mechanical events were detected online (Fig. 1b): (i) that the individual robot digits made contact with the test object, (ii) that the object lifted off from the stand, (iii) that the object again made contact with the stand and (iv) that the digits released the object. These mechanical events, crucial for the grasp-and-lift task according to the DESC sensorimotor control hypothesis, were used as triggers for sensory feedback to the participants through the vibrators (VT units). In particular, when either of the robot digits contacted or released the object, a vibration on the corresponding digit of the participant was delivered; when the object was either lifted off or put back on the stand, a vibration to the ring finger was delivered (the ring finger was preferred to the middle since being more distant from the index finger it reduced issues with the wires; it was preferred to the little finger because it made it easier to stably fix the vibrator). Contact and lift-off events were identified by detecting when GF and LF or when their first time derivatives surpassed their respective thresholds defined in pilot experiments. The duration of the vibration was 50 ms, easily perceived and initiated practically synchronously with the corresponding mechanical event.

The protocol included eight series of 100 trials for a total of 800 trials for each participant with 5-10 minutes break between the series. From pilot experiments we learned that about five series were required to train participants to perform the task smoothly. In the last three series, participants performed 240 trials with synchronized feedback (as in the previous five series) and 60 interleaved catch trials with delayed feedback: 30 *contact catch* trials and 30 *lift-off catch* trials. In the catch trials, the vibrotactile sensory feedback signals were delayed 100 ms with respect to each digit in contact catch trials and 150 ms in lift-off catch trials (in pilot experiments we observed little effects with 100 ms delay in lift-off catch trials and therefore decided to use 150 ms). While participants were aware that they received feedback related to the task on their fingertips, they received no information about its relevance or how to use it, nor were they informed about the existence of catch trials.

Precautions were taken to enforce that the participants paid close attention to the task. First, to prevent them adopting a strategy in which they grasped the object by simply closing the robot digits as much as possible, the hand was reopened and the trial was aborted if GF was larger than ~1.6 N. Second, to make it impossible to rely on learned digit positions (thus mimicking a realistic prosthetic application) and thus to enforce the subjects' reliance on VT feedback, the distance between the participant's digits ($D_N$) and the robot digits ($D_R$) was $D_R = Offset + k \cdot D_N$ where *Offset* was changed trial-by-trial with a random value ranging ±1 cm (with a uniform probability distribution). Accordingly, different distances between the human index finger and thumb were required in each trial to successfully grasp the object and to generate appropriate GF. The scaling factor between $D_N$ and $D_R$, $k$ was fixed across all subjects so that the robot digits moved with the same speed as the subject's digits. Throughout the experiments participants could see the test object but importantly not the actual contact between the robot digits and test object (Fig. 1a): when grasping the object, the distal part of the robot index finger was hidden behind the test object and the robot thumb itself covered its contact with the test object. Headphones masked all auditory cues from the motors driving the robotic hand.

### *Data analysis*

All data was digitized and stored for off-line analysis. Each trial was defined as successful or not. Unsuccessful trials were those in which the participant failed to lift the object or applied excessive grip forces.

For each participant we analyzed the data from the last four series of 100 trials ($5^{th}$–$8^{th}$), i.e. the performance at the end of the training process and throughout the catch series. The time between the moments of the first digit and second digit contact and the time between the first digit contact and the onset of LF increase were determined. The *preload phase* was defined as the period from the moment of first digit contact to the onset of the LF increase and the *load phase* was defined as the period from the onset of LF increase until the moment of lift-off, i.e., when the contact between the test object and the stand was first broken (Fig. 1b).

For each participant we compared the data from normal and catch trials. Intra-participant data analysis was performed using an unpaired two-sample t-test, while a paired two-sample t-test was used for inter-participant analyses. In both cases a p-value less than 0.05 was considered statistically significant.

## Results

### *Trained behavior*

During the 5$^{th}$ series, the participants were able to reach for the object and lift it with the robot hand without slippage and without applying excessive GF in practically every single trial. Once the participants had established contact with the object there was typically a short delay before the LF rapidly increased in parallel with the GF and eventually the object was lifted from the support.

The force coordination showed a consistent pattern across participants (Fig. 2): each participant established the grasp by making contact with the object and applying GF to the object during the preload phase and then increased the GF and LF roughly in parallel until liftoff. Once the object was replaced on the stand, LF and GF decreased in parallel until the object was released (Fig. 1b).

The majority of the participants (6/9) typically contacted the object with the robot thumb first (Fig. 3a), i.e., the digit that was in full view throughout the task. The absolute median time difference between robot thumb and index contact times varied across participants (45–130 ms).

Unless the robot fingers have established contact with the object it is, of course, inappropriate to apply any vertical force. In normal lifting, the delay from the initial digit contact and the onset of load force increase, i.e., the preload phase, is typically <100 ms (Johansson and Westling 1984). When lifting with the robotic hand, the median preload phase duration across the participants was slightly longer and ranged 80-272 ms (Fig. 3c). The median GF at the end of the preload phase ranged 0.44–0.70 N (Fig. 3b), i.e., lower than what is typically observed when humans use their own hands.

The median load phase duration ranged 224–479 ms across the participants (Fig. 3d), i.e., close to what is observed during normal lifting. The median GF at the end of the load phase ranged 0.69–1.14 N.

### *Effect of delayed VT feedback*

It was predicted that if the participants had integrated the VT stimuli in their sensorimotor control of the grasp-and-lift task they would delay the load phase when activation of the VT units associated with digit-object contact and release was delayed. This was analyzed by measuring the time it took to reach the LF halfway to lift the object. For all participants, the LF was indeed delayed by on average 68 ms when the digit contact VT feedback was delayed by 100 ms ($p<0.01$; Fig. 4; Fig. 5a).

Representative data from a single participant (S9) are shown in Fig. 4. The time series corresponding to the GF and LF were synchronized on various contact events i.e., when the index or the thumb made first contact or when the first or the last digit made contact. Irrespective of the method of synchronization, the LF was clearly and significantly delayed when the VT feedback was delayed.

While practically all participants showed evidence of integrating the VT feedback into their control of the initial phases of the grasp-and-lift task, the effect of delaying the VT feedback corresponding to object lift-off was not significant (Fig. 5b).

### *Inter-participant variability*

The participants clearly varied a great deal in how quickly they learned to execute the task smoothly. While we have no objective measures of this, the distinct impression was that the participants that were less able to carry out the task also seemed to associate poorly the VT feedback with specific mechanical events.

The participant with the lowest GF at lift-off (S5) adopted a unique strategy. She applied LF already at very low GF levels and for any sign of slipping she would adjust the GF during the load phase. Moreover, she stopped the increase of the GF promptly at lift-off evidently relying on the VT feedback because she was the only participant that showed a significant difference between normal and lift-off catch trials ($p=0.01$).

## Discussion

In this work healthy participants learned to operate an artificial apparatus to perform the apparently simple manipulative task of grasping, lifting, holding and replacing an object using a precision grip of a robot hand. We partially replaced the biological event-driven afferent flow (Johansson and Edin 1993; Flanagan et al. 2006) with an artificial feedback stimulus pertaining to tactile events. Participants received discrete VT stimuli synchronously with mechanical events that marked the transitions from one phase of the manipulative task to the next. We hypothesized that participants would integrate this sensory feedback into their sensorimotor control of the task and, if so, predicted that any disturbance in the timing of this feedback stimulus would result in detectable changes in their behaviours, i.e., they would no longer rely solely on vision. As we indeed observed such effects, we conclude that our hypothesis was corroborated.

Our results are compatible with the DESC model which hypothesizes that the central nervous system (CNS) monitors specific peripheral sensory events marking the transitions between phases of the manipulative task and uses these events to apply control signals that are appropriate for the task and the current phase. To our knowledge this is the first time that such effects have been shown with an apparatus in which both the motor and sensory flows were substituted. Indeed, previous studies that supported the DESC model involved participants using their own hands: phase transitions were, for instance, shown to be considerably delayed (0.5-1 s) during local anaesthesia of the digits or fingertips in contact with the object (Johansson and Westling 1984, 1991).

The phase transitions were all conveyed by vibrotactile stimuli containing only temporal information about 'events' the nature of which could only be interpreted by the human *given the behavioural context*. This is actually similar to what happens during normal grasping, e.g., the burst of activity in the skin afferents are similar at object contact and release (Westling and Johansson 1987). Thus, practically identical sensory stimuli can evoke specific motor responses based on the phase of the evolving task. The VT units obviously did not evoke the patterns of afferent discharges normally associated with either touch or lift-off. The fact that the participants nevertheless after a short training relied on the VT feedback suggests that the synchronization of the tactile stimulus is more important than its exact temporal pattern. Therefore, as long as the vibration is synchronous with the mechanical event and thus, as long as the CNS can integrate the visuo-tactile stimuli into a single sensory event (Tsakiris and Haggard 2005), it may be unimportant where the stimulus is delivered. We posit that the DESC policy could improve the controllability of a closed-loop prosthesis in real-life conditions, because it may allow an individual to rely on artificial tactile feedback whether visual information is available or not.

Feedback for prosthetic hands has traditionally been provided in a continuous fashion and with limited success, whether at body sites normally not involved in the motor task (Mann and Reimers 1970; Chatterjee et al. 2008; Cipriani et al. 2008; Saunders and Vijayakumar 2011; Stepp et al. 2012) or by interfacing directly to neural structures normally involved in the control (i.e. afferent nerve fibers; Dhillon et al. 2005; Rossini et al. 2010; Horch et al. 2011). For instance, Saunders and Vijayakumar (2011) provided continuous vibrotactile feedback related to grip force of a robot hand in an experimental setup similar to ours but failed to demonstrate any improved performance above that observed with visual feedback alone. Although it is possible that continuous feedback may cause sensory adaptation, the saliency of the feedback as such seems not to be the issue because even when continuous feedback is easily discriminated by patients and delivered to physiological channels (Dhillon and Horch 2005; Sensinger et al. 2009; Antfolk et al. 2012; Tan et al. 2013), it is a challenging task for an individual to learn how to actually take advantage of it in daily activities. Indeed, even after re-sutured accidentally severed nerves and subsequent significant re-innervation of *biological* sensors—that reasonably should be vastly superior to any artificial intraneural sensory feedback—functional results are unsatisfactory unless the patient is in the early teens or younger (Lundborg 2003). This implies that even under 'ideal' conditions, the limiting factor in sensory relearning is the patients' ability to reinterpret sensory information (Rosén et al. 1994). Using sensory systems that are not normally engaged in the task further taxes the cognitive system of the patient (Chatterjee et al. 2008; Cipriani et al. 2008).

Feedback based on a DESC policy would not only simplify learning—what is needed is essentially to learn the association between specific mechanical events and temporally discrete sensory stimuli—but the amount of sensory information to be transferred would be substantially less than with the solutions considered so far. However, the results achieved in this work invite studies of a number of questions related to the DESC policy. For practical reasons, we provided touch feedback related to the robot digits on the homologous human digits, while lift-off and object replacement feedback was somewhat arbitrarily delivered to the ring finger. It remains to be shown if the time-discrete feedback works also when delivered to arbitrary body sites. Similarly, it needs to be clarified if other short-lasting stimuli (like electrotactile pulses or piezoelectrically delivered taps) would work as well as vibrotactile stimuli. Neither do we know how many input channels a human can manage, nor do we know how many would be required to support complex prosthetic arm behaviours (consider, as a simple example, the need to detect incipient slips to ensure grasp stability). Finally, the DESC policy hypothesis was developed in the context of manipulation but it is unknown to what extent it applies to behavioral tasks not involving physical object-interaction.

## Acknowledgements

This work was supported by the European Commission under the WAY project (FP7-ICT-228844), the Swedish Research Council (VR 2011-3128), the Italian Ministry of Education University and Research under the FIRB-2010 MY-HAND Project [RBFR10VCLD], by the Fulbright Program and by the Department of Veterans Affairs, Rehabilitation Research and Development Service administered through VA Eastern Colorado Healthcare System - Denver VAMC.

## Conflict of Interest

CC hold shares in Prensilia S.R.L., the company that manufactures robotic hands as the one used in this work, under the license to Scuola Superiore Sant'Anna.

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## Figures

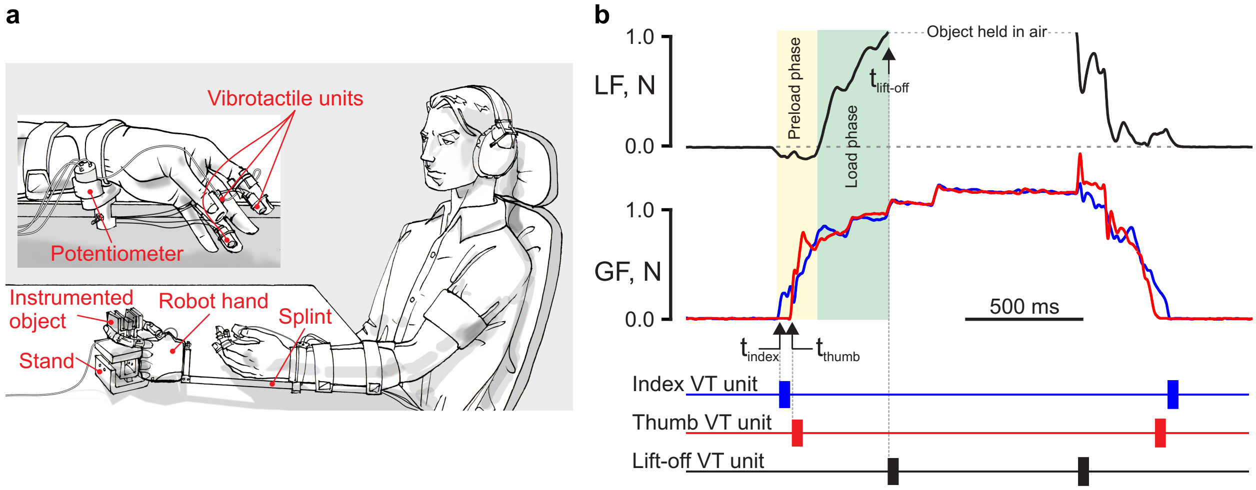


**Fig. 1** *Experimental materials and methods*. *A*. The participants controlled the movements and force generation of a robot hand by moving their own index finger and thumb. The robot hand was attached to the participant's forearm by means of a splint. *B*. Sample trial during which the participant grasped the instrumented test object. Vibrotactile (VT) units attached to the participants' index and thumb vibrated for 50 ms when the corresponding robot digits made contact with ($t_{index}$ and $t_{thumb}$) or released the object. Likewise, at lift-off and replacement of the object, a third VT was activated. Each trial was divided in a *preload phase* from the initial object contact until load force was applied, a *load phase* during which the grip force (GF) and load force (LF) increase roughly in parallel and the period during which the object was held in the air (data did not allow subdivisions into *lifting* and *hold phases*)

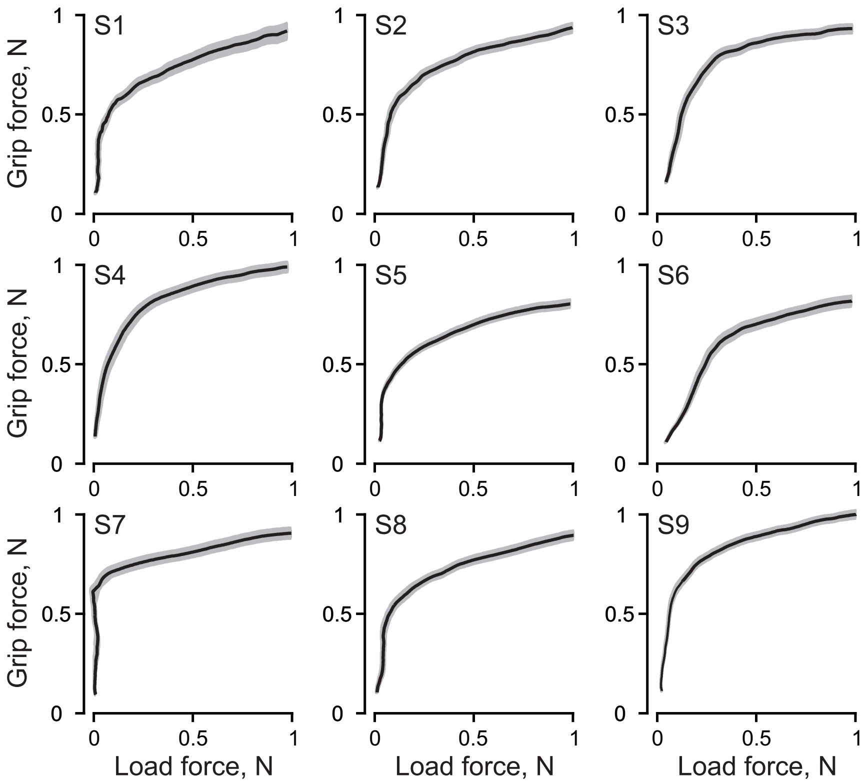


**Fig. 2** *Coordination of grip and load forces*. The mean grip force (GF) and load force (LF) for normal trials across the nine participants. As when humans lift objects with their hands, all participants made an initial contact with the object and typically reached a GF>0.5 N before they initiated the load phase and applied LF in parallel with the GF. Note that the weight of the object was smaller than what has been used in previous grasp-and-lift studies in humans. Gray areas correspond to 95% confidence areas

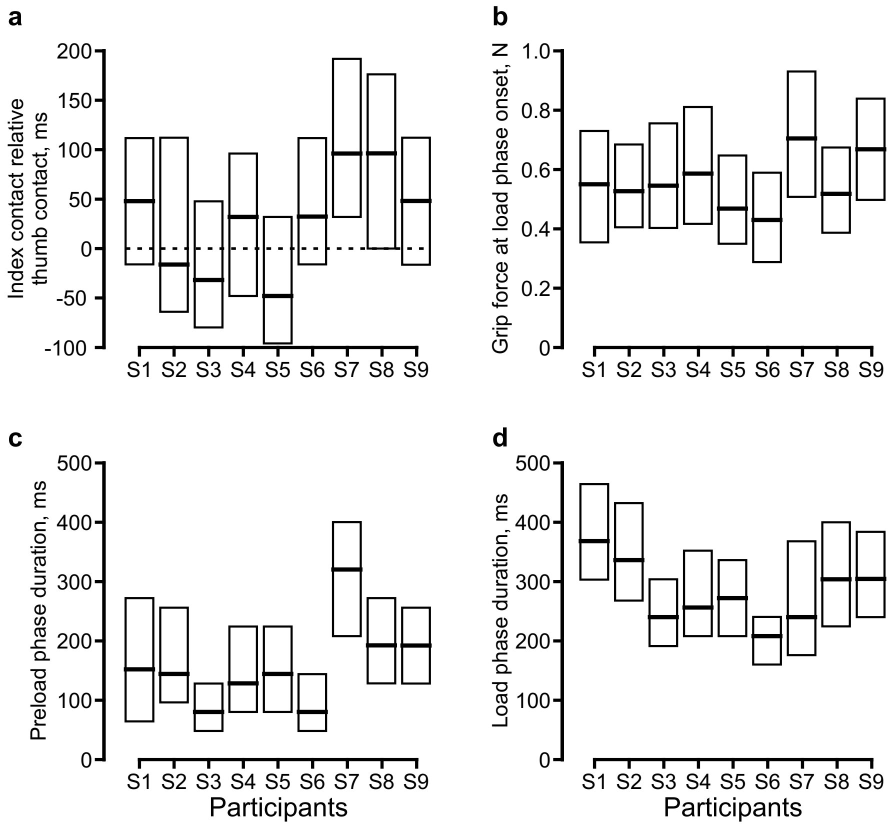


**Fig. 3** *Trained lifting behaviors*. *A*. Three participants most often made the initial contact with the unseen index finger whereas the remaining six typically first made contact with the thumb. *B*. The grip force at the onset of the load phase was fairly consistent within each participant with a median ranging 0.44–0.70 N. *C*. The preload phase duration, i.e., the time from the first contact with the object and the subsequent onset of load force increase, was typically lower than 200 ms. *D*. The load phase (cf., Fig. 1) was typically below 400 ms. Horizontal lines represent the median and the boxes the range from the 1$^{st}$ to the 3$^{rd}$ quartile

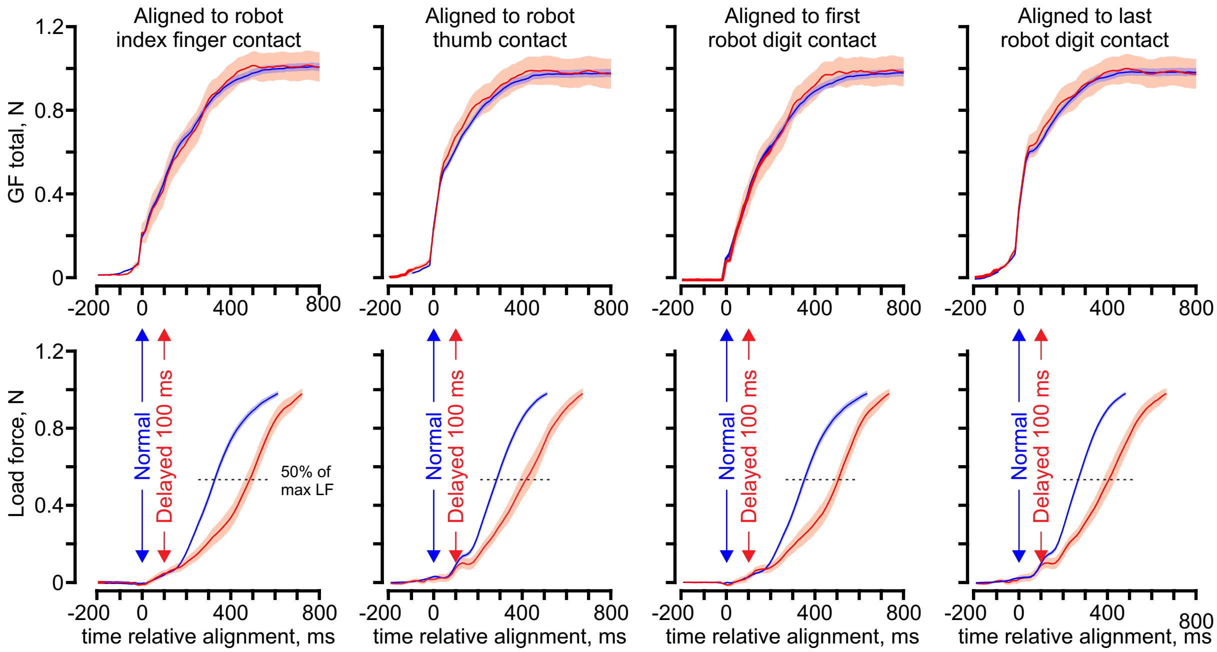


**Fig. 4** *Delayed load phase with delayed vibrotactile feedback*. Irrespective of if data was synchronized to the contact with the object of the index finger, the thumb, the first or the last digit making contact, the load force developed significantly slower when the vibrotactile feedback was delayed. Data from participant S9; solid lines represent means and the filled areas 95% confidence intervals of the means

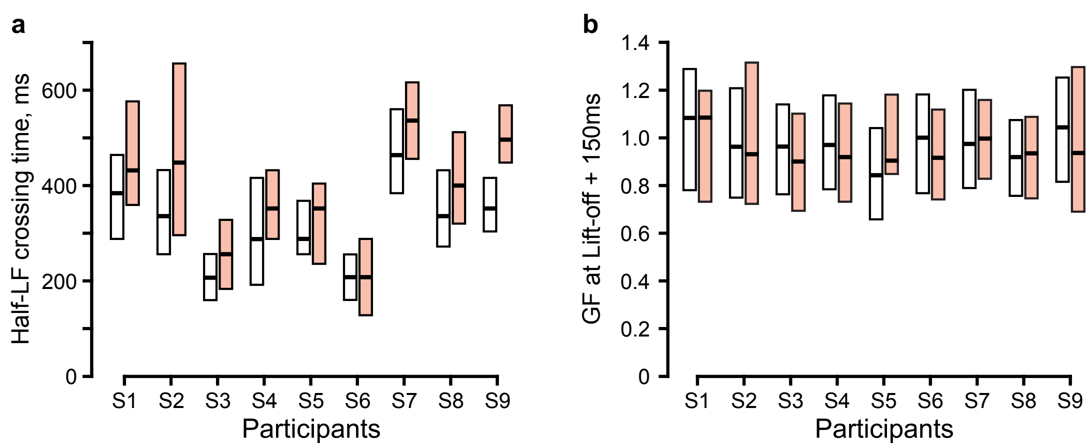


**Fig. 5** *Effect of delayed vibrotactile feedback*. *A*. All participants showed a delay of the load force development when the vibrotactile (VT) feedback of digit contact was delayed by 100 ms (albeit that the difference was small for S6). *B*. Delaying the VT feedback of lift-off (by 150 ms) did not affect the grip force at lift-off. Solid lines represent median values and the rectangles the

range from the 1st to the 3rd quartile; clear rectangles represent data from normal trials and the filled rectangles data from trials when the VT feedback of digit contact was delayed