

Failure to disrupt the ‘sensorimotor’ memory for lifting objects with a precision grip

Kelly J. Cole · Martin Potash · Clayton Peterson

Received: 13 February 2007 / Accepted: 27 July 2007 / Published online: 24 August 2007
© Springer-Verlag 2007

Abstract When repetitively lifting an object with mechanical properties that vary from lift-to-lift, the fingertip forces for gripping and lifting are influenced strongly by the previous lift, revealing a ‘sensorimotor’ memory. Two recent reports indicate that the sensorimotor memory for grip force is easily disrupted by an unrelated task like a strong pinch or vibration, even when the lift was performed with the hand contralateral to the vibration or preceding pinch. These findings indicate that this memory may reflect sensory input or muscle contraction levels, rather than object properties or the specific task of gripping and lifting. Here we report that the predictive scaling of *lift* force was *not* disrupted by conditioning tasks that featured exerting a vertical isometric force with the upper extremity. When subjects lifted a 2 N object repetitively the peak lift force rate was 26.4 N/s. The lift force rate increased to 36.1 N/s when the 2 N object was lifted (regardless of hand) after lifting the 8 N object with the right hand, which reveals the expected ‘sensorimotor’ memory. The lift force rate did not increase (24.8 vs. 26.4 N/s for the control condition) when a bout of isometric exertion (9.8 N) in the vertical direction with the distal right forearm preceded lifts of the 2 N object. This finding was confirmed with another isometric task designed to more closely mimic lifting an object with a precision grip. This difference in the sensitivity of grip versus lift force to a preceding isometric contraction indicates

that separate sensorimotor memories contribute to the predictive scaling of the commands for gripping and lifting an object.

Keywords Hand · Prehension · Motor control · Memory

Introduction

The fingertip forces that we use to grasp and transport familiar objects are generated predictively and scale in proportion to mechanical properties of the object (Johansson and Cole 1992; Flanagan and Wing 1997). Abundant evidence supports the concept that a predictive (forward) model of object and arm dynamics scales grip force in an object-specific manner (for a review see Davidson and Wolpert 2005). Vision appears to provide important information about the object via size and shape cues (Gordon et al. 1991a, b; Jenmalm and Johansson 1997; Jenmalm et al. 2000) or via arbitrary visuomotor associations (Dubrowski et al. 1999; Cole and Rotella 2002; Sinnaeve et al. 2002). These studies indicate that implicit information about the object, obtained through experience, can be used to scale the fingertip forces.

Under certain conditions fingertip forces also are scaled through a memory of the previous lift. This has been termed a ‘sensorimotor’ memory. The effects of this memory are readily observed when the weight of the object, or friction at the grip contact patches, vary randomly from lift-to-lift with no cues to signal the change in object characteristics (Johansson and Westling 1984, 1988; Jenmalm and Johansson 1997). The forces at the hand contralateral to the previous lift can be scaled in this way and so the sensorimotor memory must be mediated centrally (Gordon et al. 1994; Quaney et al. 2003; Nowak et al. 2004). When cues

K. J. Cole · M. Potash · C. Peterson
Department of Integrative Physiology,
The University of Iowa, Iowa City, IA, USA

K. J. Cole (✉)
Department of Integrative Physiology,
S. 501 FH, The University of Iowa, Iowa City,
IA 52242, USA
e-mail: kelly-cole@uiowa.edu

about the object are available the fingertip forces scale according to these cues and not according to the previous lift. Even so, small residual effects of the previous lift are observed, indicating the independence of the sensorimotor memory from processes that generate predictive motor commands based on visual cues (Gordon et al. 1991a, 1994; Cole and Rotella 2002). Evidence from fMRI studies are consistent with roles for the right inferior parietal cortex (supramarginal cortex), cerebellum, and right inferior frontal cortex (area 44) in the process of updating sensorimotor memory representations (Schmitz et al. 2005; Jenmalm et al. 2006).

Recently we reported that the sensorimotor memory may reflect the previous action rather than the mechanical properties of the object (Quaney et al. 2003). We observed that the grip force used to grasp and lift a familiar object increased when the lift followed a strong pinch (without lift) against an unrelated object. This inappropriately large grip force also occurred when the object was lifted with the hand contralateral to the preceding pinch. Nowak and colleagues (2004) extended these observations by demonstrating inappropriately large grip forces when subjects lifted a familiar object after experiencing vibration of their intrinsic hand muscles. The grip force was elevated also when the hand contralateral to the vibrated hand performed the lift. These studies demonstrate that the sensorimotor memory for grip force can be influenced by seemingly unrelated motor tasks or sensory signals. It appears that the sensorimotor memory used for grasp stability (when object identity or size/shape cues are unavailable or unreliable) may represent elementary characteristics of the grasp action without regard to task or the object.

In the experiments of Quaney and colleagues (2003), and Nowak and colleagues (2004), the *lifting* forces applied to the object remained scaled to the object while the grip forces increased in response to the unrelated pinch and muscle vibration, respectively. This specificity indicates independent sensorimotor memories for scaling the grip force versus the lift forces. It is unknown whether or not the sensorimotor memory that produces lift force also can be influenced by unrelated motor tasks, such as a voluntary vertical isometric force at the forearm. The experiments reported here addressed this question, and the results support suggestions that the mechanisms for scaling arm transport commands during prehension function independently of those that scale grip force.

Materials and methods

Twenty healthy young adults participated in the experiments (9 females, 11 males, age 20–25 years). All professed to prefer their right hands for skills of daily living

and were free of nervous system disease and injury. Subjects were unaware of the specific purpose of the experiment and had not previously participated in experiments conducted by the laboratory. The University of Iowa Human Subject Internal Review Board approved the experiment and informed consent was obtained from all subjects according to the Declaration of Helsinki.

Apparatus and procedures

The novel test object that was gripped and lifted (Fig. 1) has been described previously (Forssberg et al. 1991; Quaney et al. 2003). Subjects gripped the object with the thumb and index finger at two parallel, vertical surfaces (35×35 mm; 2.2 cm separation) that were covered with black #320 grit sandpaper. Load cells imbedded in the object transduced the force normal to the plane of each grip surface (grip force), and the vertical tangential force at each surface (lift force). The test object's weight was varied between 2 N and 8 N by inserting different masses into a cavity in the object that was shrouded from the subject's view. An accelerometer (SenSym SXL010G; Sunnyvale, CA, USA) was mounted on the object to transduce vertical acceleration.

Two experiments used different isometric tasks of the upper extremity. The first experiment involved 12 healthy, young adult subjects (age 20–25 years; 6 females and 6 males). The isometric task required the subjects to attempt to lift their forearm in the vertical plane against a rigid restraint, so as to mimic the object lifts that were performed primarily with elbow flexion. The subject's forearm was restrained by a stiff wire connected to a padded yoke, which was positioned over the right styloid process. The yoke was constructed of a thermoplastic material that had been heated and shaped to conform to the shape of the distal

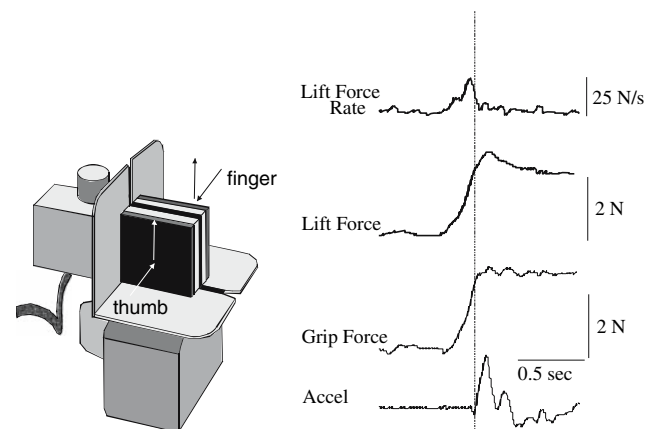


Fig. 1 A cartoon of the test object that was lifted, and examples of the force, force rate, and object acceleration signals that were transduced during a single lift of the object. The vertical line indicates object lift-off from the support surface

forearm in intermediate pronosupination. The restraining wire from the yoke was attached to a piezoresistive force transducer. The transducer was rigidly mounted to the table. In the second experiment, eight additional subjects (age 20–22 years; three females and five males) performed an isometric task in which they lifted their hand against a rigid restraint while simultaneously pinching a force transducer to produce a grip force. The grip force on the pinch transducer was independent of the vertical hand force exerted against the rigid hand restraint. A padded yoke similar to that used in the first experiment was positioned over the metacarpophalangeal joints (to more closely simulate the combined wrist and elbow joint loading that occurs when lifting a grasped object). As before, the forearm was oriented in intermediate pronosupination. The force transducer that was pinched was mounted rigidly and positioned so that subjects could pinch the transducer while exerting the isometric lifting force at the hand restraint. When performing this task, subjects first exerted the target vertical force against the restraint, and then pinched the transducer to produce a target pinch force while maintaining the target vertical force. As such, the fingers did not exert vertical force against the pinch transducer.

In both experiments subjects washed their hands with soap and water and were seated in front of the test table. The test object for the gripping and lifting trials was positioned so that reaching for the object required minimal shoulder flexion without internal rotation, external rotation, or abduction. The lifts were performed primarily with elbow flexion. Subjects were instructed to lift the object 5 in. (to a marker) and hold the object statically for seven seconds. The inter-trial interval was less than 10 s. The isometric contraction condition was performed with the right upper extremity in the same configuration. In the first experiment subjects performed the isometric contraction by attempting to raise their upper extremity against the padded yoke until an oscilloscopic display indicated 9.8 N (8 N for the second experiment). The subjects were given visual feedback of the vertical force via an oscilloscope in order to sustain this target force for seven seconds. The lift of the 2 N object was performed within 10 seconds of the end of the isometric action. In the second experiment subjects observed two traces on the oscilloscope, which provided visual feedback of the vertical force and pinch force. Their goal was to superimpose the traces upon a reference cursor, at which point the vertical and pinch forces each would be 8 N. No visual feedback of force was provided when subjects lifted the novel object in the two experiments.

Data collection and analysis

Force and acceleration signals were digitized at 500 samples/s with 16-bit resolution. Grip force was calculated as the

mean of the normal force measured at the index finger and thumb. The vertical tangential force at each digit was summed to yield the lift force. Force rates were calculated using symmetrical time differentiation of the digitized signals (10 ms window).

In each experiment each subject produced 174 trials, including lifts and isometric contractions that were distributed across the Test Tasks (lifts of the 2 N object) and Conditioning Actions, as shown in Fig. 2. The Conditioning Actions are the types of trials that preceded, or ‘conditioned’ each test lift (viz., lift of 8 N object, isometric ‘lift’, lift of 2 N object). The Test Tasks (lifts of the 2 N object with the right or left hand) provided the trials that were measured to address the aims of the experiment. These Test Tasks were grouped into six categories for measurement and analysis (three preceding actions \times two hands). The first 85 trials consisted of *lifts* that were pseudorandomly ordered between the two hands and object weights. Isometric Conditioning Actions were not performed in these first 85 trials. The remaining trials were lifts of the 2 N object with either hand, which were interspersed with isometric Conditioning Actions. For each trial of a Test Task, the peak lift force rate and peak grip force rate were measured prior to lift-off of the object from the support surface, with lift-off determined from the vertical acceleration signal. These measurements were averaged within subject for each Test Task. The averages were tested for difference using 2-way analysis of variance (ANOVA) for the factors ‘Hand (right or left)’ \times ‘Conditioning Action’, with repeated measures within subject. Specific comparisons within the factor

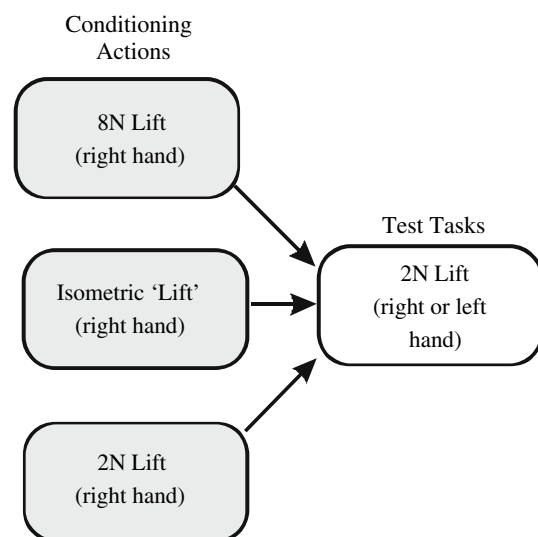


Fig. 2 A diagram showing the three Conditioning Actions (lifting the test object at a weight of either 8 N or 2 N) with the right hand that preceded the test tasks (lifting the test object at a weight of 2 N with either the right or left hand) during experiments one and two. Data were measured separately for the Test Tasks under the 6 different conditions (2 test tasks each preceded by 3 Conditioning Actions)

'Conditioning Action' were tested using Tukey's honestly significant difference test.

Values that appear in text and figures are group means (standard errors of the mean).

Results

Previous studies of the sensorimotor memory have demonstrated that the effects of this memory transfer to the contralateral hand. This was true for the present results. The effects of the conditioning tasks on subsequent lifts of the 2 N object did not depend on whether the same hand was used. The main effect of 'hand' in the 2-way ANOVA was not significant for the lift force rate in the first experiment ($F_{(1,11)} = 0.73$; $P > 0.41$) or second experiment. We combined the data across hands for the remaining analyses of data from the first two experiments.

Experiment one

The peak lift force rate that subjects used to lift the 2 N object was significantly affected by the preceding action (Fig. 3; $F_{(2,22)} = 16.9$; $P < 0.00004$ for the main effect of 'Conditioning Task'). The lift force rate for the 2 N object was 26.4 N/s when preceded by another lift of the 2 N object, but increased to 36.1 N/s when preceded by a lift of the 8 N object ($P < 0.0005$). This effect demonstrates the often-reported sensorimotor memory and was manifest in 11 of the 12 subjects. In contrast, the exertion of a vertically directed isometric force of 9.8 N with the forearm did *not* affect the lift force rate on the subsequent lift of the 2 N object (24.8 N/s; $P > 0.72$). Only one subject demonstrated a greater grip force rate when the 2 N lift followed the isometric action (but only for lifts with the left hand).

Likewise, the peak *grip* force rate prior to object lift-off was increased by the preceding action of lifting a heavier object but was not affected by the preceding action of exerting a vertical isometric force with the forearm. A 2-way repeated-measures ANOVA was significant for the main effect of 'Conditioning Task' on peak grip force rate ($F_{(2,22)} = 7.29$; $P < 0.004$) while the main effect of 'Hand' was not significant ($F_{(1,11)} = 0.58$; $P > 0.46$). A prior lift of the 8 N object significantly increased the peak grip rate compared to repeated lifts of the 2 N object (41 vs. 33 N/s; $P < 0.025$) while a prior bout of isometric exertion at the forearm did not affect the peak grip force rate (31 vs. 33 N/s; $P > 0.72$).

Experiment two

In this experiment the isometric conditioning task was a simultaneous pinch (without vertically loading the grip

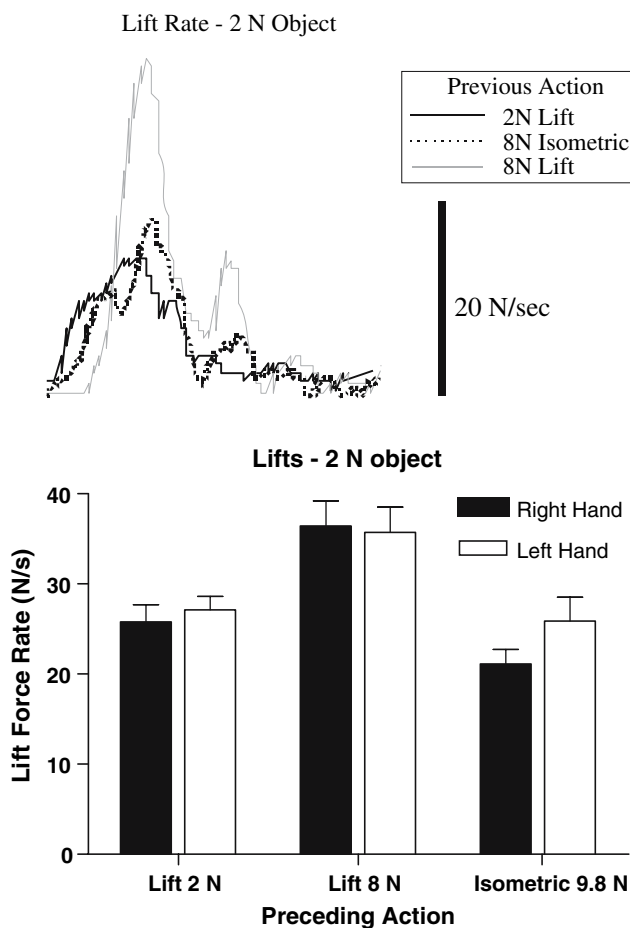


Fig. 3 Upper panel an example of the lift force rate signals from a single subject who lifted the 2 N object after each of the three conditioning tasks. The peak force rate was affected only when the previous action involved lifting the 8 N object, and not when the previous action was exerting an 9.8 N vertical isometric force at the forearm. Lower panel Bar graphs averaged across all subjects (mean \pm 1 SEM) of the peak lift force rate for lifts of the 2 N test object in experiment one categorized according to the preceding (conditioning) action

contact patches) and vertically directed isometric hand force. Our purpose was to examine whether an isometric conditioning action would influence sensorimotor memory if the action more closely mimicked the combined grip and transport actions that occur when lifting a grasped, freely moveable object. The isometric task in this second experiment included tactile signals from the pulps of the digits as subjects pinched (without attempting to lift) a force transducer while exerting an isometric vertical force with the arm.

The results of this second experiment replicated those of the first (Fig. 4; main effect of 'Conditioning Task'; $F_{(2,14)} = 12.34$; $P < 0.0008$). The lift force rate when lifting the 2 N object averaged 26 N/s when the preceding action was lifting the 2 N object and increased to 34.6 N/s when the preceding action was lifting the 8 N object ($P < 0.0009$). The lift force rate was 27.9 N/s when the

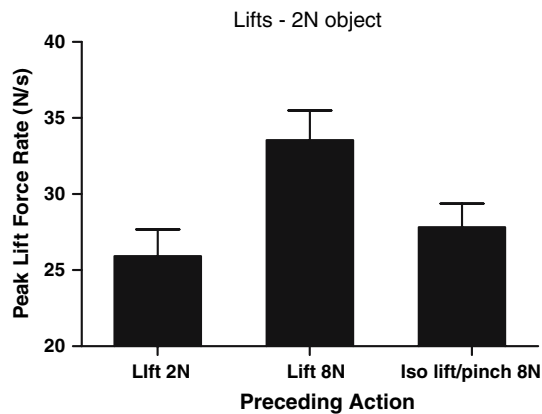


Fig. 4 Bar graph averaged across all subjects (mean \pm 1 SEM) of the peak lift force rate for lifts of the 2 N test object from Experiment Two categorized according to the preceding (conditioning) action. The peak force rate was affected only when the previous action involved lifting the 8 N object, and not when the previous action was exerting an 9.8 N vertical isometric force at the wrist while simultaneously exerting a 9.8 N pinch on a force transducer

preceding action was the combined isometric lift/pinch, which was not significantly different from lifts of the 2 N object ($P > 0.48$). Conversely, the grip force increased in magnitude when the preceding action was the isometric conditioning task compared to lifting the 2 N object, consistent with the previous report (Quaney et al. 2003). The main effect of condition on peak grip force was significant ($F_{(2,14)} = 6.09$; $P < 0.012$). Peak grip force prior to lift-off was 7.5 N (0.6 N) for repeated lifts of the 2 N object. Grip force increased to 9.7 N (0.8 N) when the previous lift was the 8 N object ($P < 0.02$) and to 8.6 N (0.6 N) when the previous task was the combined isometric lift/pinch ($P < 0.008$). The grip forces did not differ significantly when the previous condition was lifting the 8 N object versus the isometric lift/pinch ($P = 0.12$)

Discussion

In the present experiments we observed that isometric ‘lift’ actions of the upper extremity did not interfere with the scaling of lift forces used subsequently to grip and lift a 2 N object. This lack of interference on lift force was true even when the prior task included a simultaneous isometric lift and pinch intended to mimic the actions of gripping and transporting an object. These observations contrast with our previous report that pinching a force transducer (without lifting) substantially increased the grip force used to lift a familiar 2 N object (Quaney et al. 2003). In that study the increased grip force occurred regardless of whether the hand ipsi- or contralateral to the conditioning pinch lifted the object, which indicates a central origin for this

interference. A subsequent report by Nowak et al. (2004) demonstrated that vibration over the muscle bellies of two intrinsic hand muscles disrupted (increased) grip force scaling. These findings may indicate that the sensorimotor memory for grip force depends upon recent sensory feedback from the upper extremity, without regard to the specific task. Thus, the scaling of *grip* force via the *sensorimotor memory* may not rely upon an internal representation of a specific object or action and instead may be a simple sensory memory of the pinch action. A common finding in both of these recent reports was that the disrupted sensorimotor memory for grip did not affect the subsequent lifting forces. Hence, the sensorimotor memories for scaling grip force versus transport (lift) forces appear to operate independently. This concept is reinforced by the present observations that the forces used to lift an object are not sensitive to the disturbing influences of a prior, unrelated isometric action of the upper limb.

The sensorimotor memory studied here appears to be a separate process compared to *object-specific* predictive scaling (for a review see Davidson and Wolpert 2005). Object-specific scaling via internal models of object dynamics is apparent when handling common objects (Gordon et al. 1993), when implicit size–weight information is available (Gordon et al. 1991a, b), or when color–mass relationships are available to form arbitrary visuomotor associations (Cole and Rotella 2002; Sinnaeve et al. 2002). When object identity or size–weight information is available the fingertip forces are scaled mostly in relation to these cues, however the residual effects of the previous lift (that is, the sensorimotor memory), though greatly diminished, are still observed (Gordon et al. 1991a, 1994; Cole and Rotella 2002). Hence, there does not appear to be a single process for predictively scaling fingertip forces when gripping and transporting objects, although object-specific mechanisms may dominate the scaling process when sufficient cues about object physical properties are present.

Why does gripping without lift confound the sensorimotor memory for the grip force subsequently applied to an object, while isometric ‘lifting’ (even while pinching) does not interfere with lifting the object? It may be argued that a ‘sensorimotor’ memory exists for grip force only. That is, the limb forces for transporting a hand-held object may be generated only by an internal model, such as an inverse model of the object dynamics (see Davidson and Wolpert 2005). However, it seems unlikely that the transport forces are generated from an internal model without a sensorimotor memory. As noted previously there are several reports that the prior effects of lifting a different object are observed as small residual effects in the lift force even when reliable information about the object exists from size–weight cues or when the object can be reliably identified. This residual effect would appear to reveal a sensorimotor memory for

the lift/transport action despite reasonably accurate force scaling based size cues or reliable object identification.

Another possible explanation for the insensitivity of the lift sensorimotor memory to the conditioning tasks used in the present experiments is that the sensorimotor memories for scaling grip and lift force are specific for force and motion, respectively. The effects of the conditioning tasks of the previous studies (pinch and hand muscle vibration) directly affected sensory information about grip force, which is highly relevant to the task of gripping. In both cases grip force was produced during the conditioning task and during the test task (gripping with lifting). Perhaps the relevant information for memory-based scaling of object *transport* is the kinematic outcome of the limb and/or object (e.g., vertical acceleration) rather than the forces or torques at the fingers or joints of the upper extremity. Along these lines, the contextual cues may have been more similar between the conditioning and test tasks of the previous experiments (grip, in both cases) compared to the isometric ‘lift’ and actual object lifting in the present experiment. A recent report indicates that object and limb dynamics are acquired in distinct neural representations (Cothros et al. 2006). Cothros and colleagues suggested that grasping an object with the hand may constitute a contextual cue that promotes the acquisition of a distinct model of object dynamics, and allows the switch from the arm dynamic model alone to that of the arm and object together. The conditioning tasks in the previous studies (Quaney et al. 2003; Nowak et al. 2004) may have provided contextual cues so similar so as to confound the neural representation of the grip force for the subsequent lift of the test object. Following this logic and because nothing was actually lifted during the isometric conditioning tasks in the present experiment, perhaps the contextual cues during the conditioning and test tasks were not sufficiently similar for the acquisition of, or interference with, the neural representations that scaled the lift action.

The present findings may indicate that pinching (without lift) has greater access to brain areas involved in updating sensorimotor memories than lifting (without pinch). There is evidence, though weak, to support this notion. The neural substrate involved in precision gripping and lifting is not understood well but appears to involve complex frontoparietal circuits along with the cerebellum (Espinoza and Smith 1990; Dugas and Smith 1992; Salimi et al. 1999a, b, c; Ehrsson et al. 2000a, b, 2001, 2003; Kinoshita et al. 2000; Boudreau et al. 2001; Kutz-Bushbeck et al. 2001; Monzee and Smith 2004; Schmitz et al. 2005; Jenmalm et al. 2006; Mason et al. 2006). In a recent fMRI study the right supramarginal gyrus in the inferior parietal lobule was identified as a possible ‘node’ for detecting the mismatch between expected and actual weights of objects and for updating sensorimotor memories for upcoming manipulative

tasks (Jenmalm et al. 2006). This area of cortex also is active when subjects pinch without lifting (Ehrsson et al. 2000b, 2001). Information about whether or not the supramarginal gyrus becomes more active during the application of vertical loads at the hand or shear forces at the fingertips apparently is lacking. However, load forces (shear force at the fingertips) do *not* appear to drive the nearby cortex in the intraparietal sulcus (unpublished results cited in Ehrsson et al. 2003), an area which becomes more active during grip-load coordination tasks compared to grip only tasks or lift-only tasks (Ehrsson et al. 2003).

We conclude that the sensorimotor memory for lifting is not easily disturbed by joint or skin loading in a task unrelated to lifting, unlike the powerful effect of unrelated tasks on the sensorimotor memory for grip force. Our findings may reflect differences in the task specificity of the sensorimotor memories for grip and lifting, or the untested possibility that the sensorimotor memory for lift force depends upon sensory signals related to the kinematic outcomes of lifting, rather than force.

References

- Boudreau M, Brochier T, Pare M, Smith A (2001) Activity in ventral and dorsal premotor cortex in response to predictable force-pulse perturbations in a precision grip task. *J Neurophysiol* 86:1067–1078
- Cole K, Rotella D (2002) Old age impairs the use of arbitrary visual cues for predictive control of fingertip forces during grasp. *Exp Brain Res* 143:35–41
- Cothros N, Wong J, Gribble P (2006) Are there distinct neural representations of object and limb dynamics? *Exp Brain Res* 173:689–697
- Davidson P, Wolpert D (2005) Widespread access to predictive models in the motor system: a short review. *J Neural Eng* 2:S313–S319
- Dubrowski A, Proteau L, Carnahan H (1999) Practice influences the coordination of visual and haptic inputs during grasping. *Soc Neurosci Abstr* 25:1913
- Dugas C, Smith AM (1992) Responses of cerebellar purkinje cells to slip of a hand-held object. *J Neurophysiol* 67:483–495
- Ehrsson H, Fagergren A, Forssberg H (2001) Differential fronto-parietal activation depending on force used in a precision grip task: an fMRI study. *J Neurophysiol* 85:2613–2623
- Ehrsson H, Fagergren A, Gulyas B, Johansson R, Forssberg H (2000a) Cortical areas activated during manipulation: grasp actions, spatial actions and grasp stability actions. *Soc Neurosci Abstr* 26:1577
- Ehrsson H, Fagergren A, Jonsson T, Westling G, Johansson R, Forssberg H (2000b) Cortical activity in precision versus power-grip tasks: an fMRI study. *J Neurophysiol* 83:528–536
- Ehrsson H, Fagergren A, Johansson R, Forssberg H (2003) Evidence for the involvement of the posterior parietal cortex in coordination of fingertip forces for grasp stability in manipulation. *J Neurophysiol* 90:2978–2986
- Espinoza E, Smith AM (1990) Purkinje cell simple spike activity during grasping and lifting objects of different textures and weights. *J Neurophysiol* 64:698–714
- Flanagan JR, Wing AM (1997) The role of internal models in motion planning and control: evidence from grip force adjustments during movements of hand-held loads. *J Neurosci* 17:1519–1528

- Forsberg H, Eliasson AC, Kinoshita H, Johansson RS, Westling G (1991) Development of human precision grip. I: Basic coordination of force. *Exp Brain Res* 85:451–457
- Gordon AM, Forssberg H, Johansson RS, Westling G (1991a) Integration of sensory information during the programming of precision grip: comments on the contributions of size cues. *Exp Brain Res* 85:226–229
- Gordon AM, Forssberg H, Johansson RS, Westling G (1991b) Visual size cues in the programming of manipulative forces during precision grip. *Exp Brain Res* 83:477–482
- Gordon AM, Westling G, Cole KJ, Johansson RS (1993) Memory representations underlying motor commands used during manipulation of common and novel objects. *J Neurophys* 69:1789–1796
- Gordon AM, Forssberg H, Iwasaki N (1994) Formation and lateralization of internal representations underlying motor commands during precision grip. *Neuropsychologia* 32:555–568
- Jenmalm P, Johansson RS (1997) Visual and somatosensory information about object shape control manipulative fingertip forces. *J Neurosci* 17:4486–4499
- Jenmalm P, Dahlstedt S, Johansson R (2000) Visual and tactile information about object-curvature control fingertip forces and grasp kinematics in human dexterous manipulation. *J Neurophys* 84:2984–2997
- Jenmalm P, Schmitz C, Forssberg H, Ehrsson H (2006) Lighter or heavier than predicted: neural correlates of corrective mechanisms during erroneously programmed lifts. *J Neurosci* 26:9015–9021
- Johansson RS, Cole KJ (1992) Sensory-motor coordination during grasping and manipulative actions. *Curr Opin Neurobiol* 2:815–823
- Johansson RS, Westling G (1984) Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Exp Brain Res* 56:550–554
- Johansson RS, Westling G (1988) Coordinated isometric muscle commands adequately and erroneously programmed for weight during lifting task with precision grip. *Exp Brain Res* 71:59–71
- Kinoshita H, Oku N, Hashikawa K, Nishimura T (2000) Functional brain areas used for the lifting of objects using a precision grip: a PET study. *Brain Res* 857:119–130
- Kuhtz-Bushbeck J, Ehrsson H, Forssberg H (2001) Human brain activity in the control of fine static precision grip forces: an fMRI study. *Eur J Neurosci* 14:382–390
- Mason C, Hendrix C, Ebner T (2006) Purkinje cells signal hand shape and grasp force during reach-to-grasp in the monkey. *J Neurophysiol* 95:144–158
- Monzee J, Smith A (2004) Responses of cerebellar interpositus neurons to predictable perturbations applied to an object held in a precision grip. *J Neurophysiol* 91:1230–1239
- Nowak D, Rosenkranz K, Hermsdorfer J, Rothwell J (2004) Memory for fingertip forces: passive hand muscle vibration interferes with predictive grip force scaling. *Exp Brain Res* 156:444–450
- Quaney B, Rotella D, Cole K (2003) Sensorimotor memory for fingertip forces: evidence for a task-independent motor memory. *J Neurosci* 23:1981–1986
- Salimi I, Brochier T, Smith AM (1999a) Neuronal activity in somatosensory cortex of monkeys using a precision grip. I. Receptive fields and discharge patterns. *J Neurophysiol* 81:825–834
- Salimi I, Brochier T, Smith AM (1999b) Neuronal activity in somatosensory cortex of monkeys using a precision grip. II. Responses to object texture and weights. *J Neurophysiol* 81:835–844
- Salimi I, Brochier T, Smith AM (1999c) Neuronal activity in somatosensory cortex of monkeys using a precision grip. III. Responses to altered friction perturbations. *J Neurophysiol* 81:845–857
- Schmitz C, Jenmalm P, Ehrsson H, Forssberg H (2005) Brain activity during predictable and unpredictable weight changes when lifting objects. *J Neurophysiol* 93:1498–1509
- Sinnaeve A, Dubrowski A, Carnahan H (2002) Evidence for the use of both iconic and long-term memory systems for friction when grasping. *Soc Neurosci Abstr* 28:2684