Neuroscience 293 (2015) 1–11

SOMATOSENSORY FEEDBACK REFINES THE PERCEPTION OF HAND SHAPE WITH RESPECT TO EXTERNAL CONSTRAINTS

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Abstract—Motor commands issued by the CNS are based upon memories of past experiences with similar objects, the current state of the hand and arm postures, and sensory input. Thus widespread somatosensory information is available to form precise representations of hand shape on which to base motor commands to match a desired posture or movement. The aim of this study was to examine the extent to which somatosensory information reflecting external influences on independent finger movement is incorporated into the perception of hand shape driving the motor command. To address this issue, a matching task was performed while pairs of fingers in the grasping hand were constrained to move in tandem when grasping familiar objects. The hypothesis was that motor commands would be driven by comparison of the online sensory information from the matching hand to a desired somatosensory state determined by the current somatosensory input from the grasping hand. The results demonstrated that multi-muscle patterns of activation and hand postures were altered with respect to the external constraint on independent finger movement. A secondary aim of this study was to examine the influence of sensory information on the structure of the multi-muscle patterns. The hypothesis was that the same synergies (patterns of activation across muscles) would be used to complete the task but would be rescaled with respect to condition. The results demonstrated that rescaling the patterns of multi-muscle activity from the unconstrained condition could not equivalently represent those from the constrained conditions. Thus it appears that external restriction of independent finger movement was signaled by somatosensory feedback and incorporated into the desired state driving the motor command resulting in selective activation of groups of muscles.

Key words: electromyography, finger, grasp, muscle synergies, sensorimotor, somatosensory.

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Abbreviations: ADM, adductor digiti minimi; APB, abductor pollicis brevis; EMGs, electromyograms; FPB, flexor pollicis brevis; PC, Principal Component; PIP, proximal interphalangeal.

http://dx.doi.org/10.1016/j.neuroscience.2015.02.047

INTRODUCTION

Grasping and manipulating objects require a sophisticated level of control needed to form specific postures and apply appropriate forces with our fingers and hands. Therefore, precise motor commands must be issued to coordinate the activation of muscles or groups of muscles to achieve appropriate positioning of the limb and points of contact with the object. These motor commands are shaped by an internal representation of the current state, sensorimotor memories of previous experiences with the object or similar objects (Gordon et al., 1993; Wolpert and Flanagan, 2001; Quaney et al., 2003; Cole et al., 2008; Parikh and Cole, 2011; Baugh et al., 2012; Lukos et al., 2013) and online sensory feedback (for review see Johansson and Flanagan, 2009). The initial commands may be based on predicting elements of fragility, weight, and surface texture of the objects being manipulated (for review see Flanagan et al., 2006). Studies of sequential hand movements by Flanders and colleagues have also supported the idea that a representation of hand shape is continuously updated and maintained by the CNS in order to provide a basis for future motor commands (Jerde et al., 2003; Flanders, 2011). Sensorimotor information acquired by grasping and lifting objects with one hand can be transferred to predictively control grip forces with the other hand (Gordon et al., 1994) although this is disrupted in cerebellar patients (Nowak et al., 2005, 2009). However, the way in which somatosensory input is incorporated into the motor command is not well understood. Matching tasks where a static grasping posture is pantomimed by the other non-grasping hand have been used to examine what somatosensory input is transferred to the opposite hemisphere and incorporated into the motor command of the non-grasping hand. Pesyna et al. (2011) found that the cutaneous and proprioceptive input specific to a gravitational reference frame, irrespective of grasping forces, was incorporated into the perception of hand shape for a matching task. Interestingly, when the gravitational reference frames of the grasping and matching hands were different, the postures of the finger and wrist joints of the matching hand were altered to keep the imagined object in its proper spatial orientation. Therefore, specific elements of somatosensory information appear to dominate the perception of hand shape while others are ignored. One reason for the difference may be that the influence of gravitational forces is inherent in motor commands and more easily transferred to the other hemisphere while grip forces are initially estimated and then modulated in response to online feedback for object manipulation.

Following this line of reasoning, somatosensory information related to other additional external constraints on movement, such as splinting of an injured finger or use of a tool whose function is related to movement of multiple digits together, i.e., scissors, might also be expected to be incorporated into the perception of hand shape.

The aim of this study was to examine the extent to which somatosensory information reflecting external influences on independent finger movement is incorporated into the perception of hand shape driving the motor command. The external restriction of independent finger movement was accomplished by taping two different pairs of fingers together in the grasping (right) hand, requiring them to move in tandem. This constraint creates a novel situation for which sensorimotor memories would not be available to drive motor commands at the matching hand. Therefore, the working hypothesis was that motor commands would be driven by comparison of the online sensory information from the matching hand to a desired somatosensory state determined by the current somatosensory input from the grasping hand. This hypothesis would be supported by distinct differences between control (unconstrained) and tandem conditions in the intrinsic joint angles of the digits (collectively called hand posture) and multi-muscle patterns in the left (matching) hand. Specifically, differences in joint angles and muscle activity of the matching hand should include those for digits not being constrained in the grasping hand, thus demonstrating an overall change in matching hand posture reflecting the constraint at the grasping hand. The alternative to this hypothesis is that the motor commands are driven by sensorimotor memories of grasping these familiar objects under normal (unconstrained) conditions resulting in no differences in hand posture or muscle activity.

A secondary aim of this study was to examine the influence of sensory information on the structure of the multi-muscle patterns. The specific working hypothesis was that the same synergies (patterns of activation across muscles) would be used to complete the task but would be rescaled with respect to condition. If rescaling the activation patterns from the control condition cannot accurately represent the multi-muscle patterns from the tandem conditions, it would support the notion of selective activation of muscles respective of task constraints. The results are discussed with respect to the role of somatosensory input in the motor command and the potential role of sensory input in the flexible activation/coordination of groups of muscles or synergies.

EXPERIMENTAL PROCEDURES

Six healthy human subjects (five right handed, one ambidextrous, three male, 23 ± 5 years, 1.69 ± 0.13 m) with no known neurological disorders or significant hand injuries were recruited for the study. The experimental protocol was approved by the University of Minnesota's Institutional Review Board and all subjects gave informed consent prior to the experiment.

Task

Subjects were asked to grasp 13 objects common to daily use (Fig. 1, left) with their right hand and match this hand posture with their left hand. The objects were selected to provide a wide range of hand shapes and were known to represent distinct areas in Principal Component (PC) space (Santello et al., 1998; Weiss and Flanders, 2004; Pesyna et al., 2011). Familiar objects were chosen based on the assumption that an internal memory of the hand shape for grasping familiar objects was already formed and would be reliable and useful (Deshpande et al., 2010) for comparing small differences in somatosensory information (Nowak et al., 2004) related to adjustments in hand shape required by constraining pairs of fingers to move in tandem. For consistency of hand posture for a particular object, subjects were instructed to grasp each object the same way throughout the experiment. For each trial, the participant grasped the object presented by the experimenter with their right hand, then closed their eyes and matched the grasping posture with their left hand. Subjects indicated when they had reached a matched hand posture and held that static hand posture for ~3 s.

The experimental procedure consisted of ten blocks of trials for each grasp condition during which each object (n = 13) was presented in pseudorandom order so that each object was grasped ten times for a total of 130 trials performed in each of the three grasp conditions. Rest was given throughout the experiment to prevent fatigue. Subjects grasped the objects freely in the control condition, while two other experimental conditions consisted of constraining independent movement of either the index-middle or middle-ring finger pairs of the right hand such that both fingers moved in tandem (IM-tandem and MR-tandem, respectively). Independent finger movement was constrained by taping the paired fingers around the proximal interphalangeal (PIP) joints which still allowed for tandem movement at the paired PIP joints. Both the index and ring fingers were paired with the middle finger since the pairs move together relatively easily but the index and ring finger differ in their function during object manipulation. While the index finger often opposes the thumb without the use of the other fingers, the ring finger is more coordinated with additional fingers for object manipulation.

Data acquisition

A custom LabView Virtual Instrument was used to record muscle activity and posture from the left hand for one second while remaining static in the matching posture. Muscle activity was recorded as surface electromyograms (EMGs) using 2-mm diameter bipolar Ag/AgCl surface electrodes (Discount Disposables, St. Albans, VT, USA) placed 10 mm apart (see Fig. 2 of Winges et al., 2007). Custom-made, electrically shielded wire leads were permanently soldered to these electrodes and connected to standard laboratory amplifiers. The ground electrode was placed on the participant's