Support-Specific Modulation of Grip Force in Individuals With Hemiparesis

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Objective: To investigate whether use of auxiliary sensory input will result in modulated grip force.

Design: Case-control study.

Setting: Free-standing acute inpatient rehabilitation hospital.

Participants: Six people with unilateral hemiparesis due to unilateral stroke and 6 control subjects without neurologic disorders.

Interventions: Seated subjects lifted and transported the same object under 3 different conditions: with no support, with the target arm positioned on a freely moving skateboard, and with a finger from the subject's contralateral hand lightly touching the wrist of the target arm.

Main Outcome Measures: Peak grip force and temporal coupling between the grip force and lift-off of the object.

Results: All subjects were able to better regulate grip force when provided with additional sensory input. Light finger touch resulted in decreased grip force, as did skateboard use ($P<.05$). Subjects with hemiparesis showed 2 times longer latency between grip-force application and lift-off of the object ($P<.05$).

Conclusions: Statistically significant grip-force reduction was noted with both support aids. These findings could have implications in clinical and rehabilitative areas.

Key Words: Grip; Hemiparesis; Rehabilitation; Touch.

THE FUNCTIONAL AND COMMONLY used skill of grasping and lifting an object is based on successful integration of several organization strategies and coordination rules by the central nervous system. It is believed that stored programs based on previous experience,[1] as well as real-time processing of sensory information related to the actual properties of the object,[2] are used in the scaling of forces to manipulate the object.

The ability to appropriately judge the force necessary to lift an object decreases with age and disease. Research has shown that elderly persons often use excessive grip force while lifting, especially when compared with younger subjects; they also show greater delays between gripping and lifting an object.[3,4] When compared with healthy subjects, significantly higher levels of grip force were also seen in people with Parkinson's disease,[5] cerebellar dysfunction,[6,7] cerebral stroke,[8] and Huntington's disease.[9] Healthy people exposed to local anesthesia experienced a deterioration of afferent information as well, which resulted in an increase of grip forces.[10] It was determined that the functional loss of distal cutaneous mechanoreceptors was responsible for this impaired control of grip force.[11,12]

Although many everyday tasks require skilled manipulations with 2 hands, most studies examining grip-force control use a 1-hand paradigm (for reviews, see Johansson and Cole[10,13]). It is also known that people with unilateral impairment commonly use the help of a second hand for such activities as lifting a cup, using a towel, and feeding. Thus, the effect of bimanual coordination or additional support in the control of grip forces is of particular interest.

First, it was suggested that nondigital sensory input might be used for some grip control during impaired digital sensibility.[11] Second, recent postural studies[14-16] showed that additional contact cues may reduce postural sway in healthy subjects and in people with bilateral vestibular loss. In particular, contact of the index finger with a stationary surface, even at mechanically inefficient force levels, has been shown to decrease indexes of postural sway by up to 50%.[14,17,18] It was suggested that additional sensory cues help to control posture when sensory information from other systems is unavailable or is unreliable.[16] However, the effect of sensory cues on grip force has not been investigated.

The present study, which included both healthy subjects and people with hemiparesis, investigated a task of lifting and transporting an object and focused primarily on modulation of grip force, timing, and synchronization. I hypothesized that people with hemiparesis would demonstrate higher grip force and an increase in latency between the grip-force application and the lift-off of the object compared with healthy controls. I also hypothesized that additional sensory input would aid both groups of subjects to better modulate grip force.

METHODS

Participants

Six people with hemiparesis (mean age ± standard deviation [SD], 67.6±15.8y; weight, 71.4±14.5kg; height, 166.8±13.9cm) due to a unilateral cerebrovascular accident (20.8±6.6d poststroke) and 6 healthy control subjects participated in the experiment. The inclusion criteria were a recent single stroke, the ability to perform a task of grasping and lifting an object with the affected hand, and the ability to understand and follow 2-step directions. The exclusion criteria were serious or unstable medical conditions, a history of other neurologic diseases including peripheral neuropathy and aphasia, fixed contractures or deformities of the upper limbs, and any other factors that might prevent participation in the experiment. Subject characteristics are presented in table 1. Muscle strength of the affected upper extremities ranged from 3 to 4 according

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Table 1: Characteristics of All Subjects

Subject	Sex	Interval Between Event and Admission to Study (d)	Localization of the Lesion	Side Hemiplegia	Sensation	Muscle Strength
1	F	20	Subcortical infarct	R	Intact	4–
2	M	13	Brainstem lacunar infarct	L	Mild	4–
3	M	33	Ischemic infarct in the frontal and parietal lobes	L	Mild	3
4	F	21	Right subcortical ischemic infarct	L	Intact	3
5	F	19	Left basal ganglia ischemic infarct	R	Moderate	4
6	F	19	Left brainstem infarct	R	Intact	3+
Patients		20.8				
SD		6.6				

Abbreviations: F, female; L, left; M, male; R, right.

to the conventional grading scale.[19] Spasticity of the paretic upper extremity was quantified with a modified Ashworth Scale[20]; on average, the Ashworth score ± SD was 1.25±0.41. The control subjects were matched in sex and age (4 women, 2 men; mean age, 64.7±18.8y; weight, 74.2±15.0kg; height, 172.0±11.6cm) with the patients. All control subjects were recruited from a pool of hospital volunteers; they were free of any known neurologic or muscle disorders. All the subjects signed an informed consent form approved by the Institutional Review Board of Marianjoy Rehabilitation Hospital before the experiment.

Apparatus

A cylindrical plastic cup (diameter, 8cm; height, 12cm; total weight with load cells, 240g) was held in the subjects' hand using a cylindrical grasp involving opposition of the thumb and all fingers. A load of 340g was placed into the cup for all the trials, so the total weight of the cup in the experiments was 580g.

The cup was instrumented with 2 unidirectional strain gauges (model 208C03[a]). The first strain gauge was located on the side 8cm from the bottom of the cup and extended out 2mm from the cup's side. The second strain gauge was set in the base of the cup.[21] The first gauge was used to measure the force applied by the thumb of the hand; the second gauge was used to measure the force between the cup and the top of the desk. The sensitivity of the transducers was 2.25mV/N; its linearity was better than 1%. The entire system was operating in a direct current–coupled mode, using the sensor's discharge time constant as established by a built-in microelectronic circuit within the sensors. The cup's center of mass was located at the level of the side strain gauge, which ensured that torques about the grip axis were minimized.

A personal computer with customized software based on the LabView, version 4.1,[b] was used to control the experiment, collect the data, and perform most of the analyses. The signals were sampled at 100Hz with a 16-bit resolution.

Procedure

Before the study, each arm was appropriately labeled as "dominant," "nondominant," "unaffected," or "hemiparetic arm." Hand dominance of the control subjects determined which arm would be classified as dominant or nondominant. In subjects with hemiparesis, arms were classified as "unaffected" or "hemiparetic."

For the study, each subject was comfortably seated on a chair, with feet flat on the floor and the subject's back upright against the back of the chair. The shoulders were in a neutral position. The initial target elbow was flexed to 90°, and the wrist and forearm were in neutral positions (fig 1). Chair and table height were adjusted until the forearm barely touched the table; these heights were kept constant for each subject throughout the experiments. The cup was positioned on the tabletop in front of the target arm. Each subject was instructed to grasp the cup and move it from its initial position to its final position, which was at a distance of .25m. Each subject used both the unaffected and the hemiparetic (or dominant and nondominant) arms in 3 different lifting and transporting tasks. For the first 3 tasks, the unaffected (or dominant) arm was used; then the same 3 tasks were repeated with the other arm. For statistical purposes, each of the 6 tasks was completed 6 times (trials).

For the first task, subjects were instructed to use their target arm to grab the cup and to transfer it to the final position. In the second task, and before lifting the cup, the subjects applied a light touch of the index finger of their contralateral arm to the wrist of the target arm. A foam-padded arm skateboard (.3×.15×.025m) on low-friction ball-bearing casters was used in the third experimental series. The arm was fastened with self-adhesive straps, allowing manipulations in the wrist joints to grab the cup while accepting the load of the extremity and the cup. No assistance from the contralateral arm was permitted.

Before data collection, subjects wiped their hands with the alcohol pads to remove sweat and excess oil from the skin and were given up to 4 practice trials to become familiar with each task.

At a computer-generated signal, each subject was instructed to grab the cup, lift the cup, and move it to the final position. Each subject was told that he/she had up to 10 seconds to perform the task in a self-paced manner after hearing the tone signal. Before the execution of each task, the experimenter ensured that the trunk was kept straight. Trials with apparent trunk movements were discarded from data analysis.

After the 6 tasks had been completed, 2 more series were performed, to record maximal grip force applied to the gauge. Subjects were instructed to place the thumb on the load cell and the rest of the fingers on the cup as described earlier, lift it, and then apply as much pressure as possible to the load cell. Subjects were asked to maintain that pressure for approximately 1 to 3 seconds. The order of the experimental series was randomized among the subjects. Short breaks (≈10s) were given between single trials. The interval between tasks was about 2 minutes, to allow the subjects' full recovery.

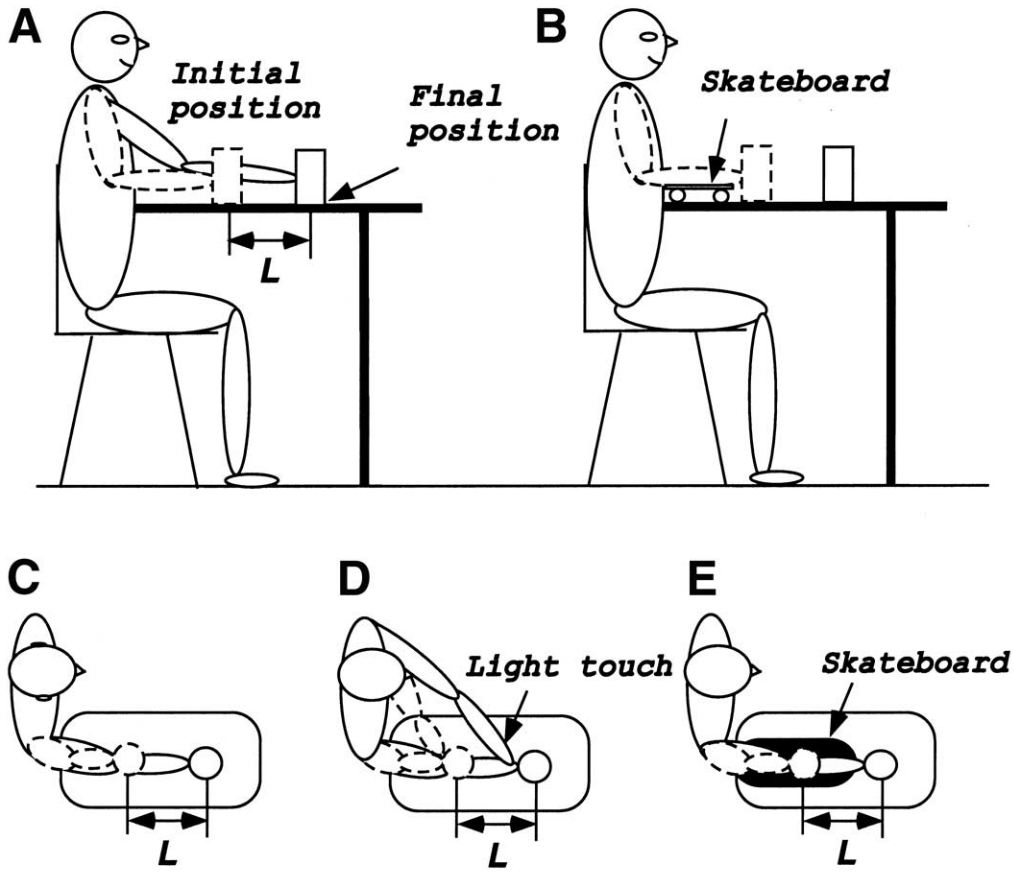

Fig 1. Experimental procedures. (A) The subject performs grasping and transporting the cup with 1 arm. (B) The subject performs grasping and transporting the cup while the arm is positioned on a skateboard. (C, E) Same as A and B, view from above. (D) The subject performs grasping and transporting the cup while a light touch of the contralateral arm is provided. Broken lines show the initial position of the arms and the cup; solid lines show the final positions. Abbreviation: *L*, distance between the initial and final positions.

Data Collection and Analysis

The trials were viewed offline on a monitor screen (resolution, 1ms) by an experienced research assistant (who was blinded to the information related to a particular subject) and aligned according to the first visible deflection of the force signal from the strain gauge in the base of the cup that was associated with the start of the lift of the cup. In cases where no clear onset of the force signal could be determined, the trial was rejected; this occurred 7 times across all subjects. The following measurements were made in each single trial:

1. The grip force was measured as the peak force applied to the strain gauge by the thumb during load lifts in newtons.
2. Time to peak of grip force was measured from the start of unloading the cup to the peak of grip force in seconds.
3. Latency (in seconds) was measured as the time between the onset of the grip force (first visible deflection of the force signal applied to the strain gauge by the thumb) and the lift-off of the object (first visible deflection of the force signal from the strain gauge installed to the base of the cup). This parameter may be considered to measure the coordination between fingers gripping the cup and more proximal arm muscles responsible for the actual lifting of the cup.
4. Movement time was measured as the time in seconds between the lift-off of the cup and returning it to the table. The first (unloading) and second (loading) visible deflections of the force signal from the strain gauge installed to the base of the cup were used.

In addition, maximum grip force achieved in the best of 6 trials was measured when the subjects pressed the strain gauge by the thumb and the rest of the fingers as hard as possible. Peak grip-force values were divided by the magnitude of the maximal grip force for the unaffected (dominant) or hemiparetic (nondominant) arms, respectively, and multiplied by 100. Thus, the magnitudes of peak grip force would be presented as a percentage of the maximal grip force as well.

Group differences were assessed using an analysis of variance (ANOVA) to evaluate the effect of the support (no support, light touch, skateboard) and side (hemiparetic, unaffected) on the maximal grip force, time to peak force, movement time, and latency between the onset of the grip force and the lift-off. Post hoc comparisons were performed using the Tukey honestly significant difference routines ($P<.05$). Statistical analyses were performed using Statistica, version 5.1.[c]

RESULTS

The experimental task is composed of 2 consecutive phases: a premovement phase, during which a grip force is applied while the object remains in a stationary position, and a movement phase, during which the cup is lifted and transferred to the

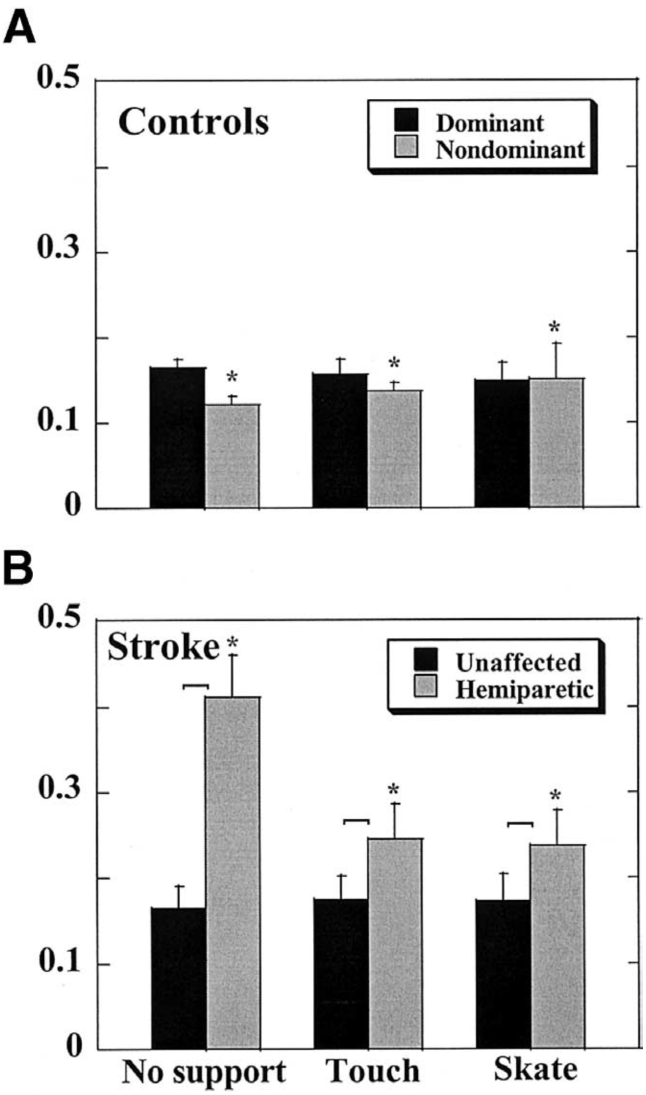

Fig 2. The average latency between the onset of the grip force and the lift-off of the object across (A) control subjects and (B) subjects with hemiparesis. NOTE. The vertical scale shows time in seconds; each bar represents the group mean ± SE. ****P*<.001 **(significant differences between the groups); ⌐¬ *P*<.01 **(significant differences between the hemiparetic and unaffected arm).**

final position until the mechanical contact with the ground stops the movement.

The average latency (mean ± standard error [SE]) between the onset of the grip force and the lift-off of the object across control subjects in the no-support condition was .16±.01 seconds for the dominant and .12±.01 seconds for the nondominant arm (fig 2). In the series with touch support, this time was .16±.01 and .14±.02 seconds for the dominant and nondominant arms, respectively. When a skateboard was used, the time for the dominant arm was .15±.02 seconds and for the nondominant arm .15±.04 seconds. The differences in latency between the onset of the grip force and the lift-off of the object in control subjects while using their dominant compared with their nondominant arms were statistically insignificant. Conversely, subjects with hemiparesis had a statistically significant longer time between the onset of the grip force and the lift-off of the object when using their hemiparetic arm compared with their unaffected arm ($P<.01$) or with the nondominant arm of control subjects ($P<.001$). In the no-support condition, it was .16±.02 seconds for the unaffected arm and .41±.05 seconds for the hemiparetic arm. Similarly, when a touch was provided, the time between the onset of the grip force and the lift-off of the object for unaffected and hemiparetic arms was, respectively, .17±.03 and .24±.04 seconds. When a skateboard was used, the time was .18±.05 seconds for unaffected arm and .28±.06 seconds for the hemiparetic arm. ANOVA showed the effect of group ($F_{1,10}=8.66$, $P<.05$) and side ($F_{1,10}=13.73$, $P<.01$). Additionally, a significant interaction for group and side was observed ($F_{1,10}=24.28$, $P<.001$), showing that greater latencies were observed in subjects with hemiparesis on the affected side.

The time needed to perform the unloading and loading of the cup for all the conditions is presented in table 2. Note that both groups of subjects required more time to perform the task while the upper extremity was positioned on a skateboard. ANOVA showed a significant main effect of support ($F_{2,20}=5.17$, $P<.005$).

Figure 3 shows changes in the peak grip force in each of 3 lifting conditions. The peak grip force for control subjects in the no-support condition was 19.38±1.49N and 17.65±1.38N for the dominant and nondominant arms, respectively. A smaller force was observed in the series with touch support: 14.33±1.29N and 14.16±1.15N for the dominant and nondominant arms, respectively. When a skateboard was used, the peak grip force for the dominant arm was 14.85±1.36N and it was 13.46±0.94N for nondominant arm. Subjects with hemiparesis in the no-support condition had peak grip force of 17.58±1.30N for the unaffected arm and 17.37±1.38N for the hemiparetic arm. When a touch was provided, the peak grip force for the unaffected and hemiparetic arms was, respectively, 14.15±1.20N and 13.97±0.92N. When a skateboard was used, the peak grip force was 16.02±1.24N for unaffected arm and 14.90±1.3N for the hemiparetic arm. ANOVA showed a significant main effect of support ($F_{2,20}=10.84$, $P<.01$) and was just below the level of statistical significance for side ($F_{1,10}=4.70$, $P=.055$).

The maximal grip force achieved in the best of 6 trials while applying force to the cup by control subjects on average was 51.00±8.51N and 52.75±8.50N, for the dominant and nondominant hands, respectively. In subjects with hemiparesis, it reached 46.86±11.68N and 29.46±7.89N for the unaffected

Table 2: Movement Time

	Patients		Controls	
Conditions	Unaffected	Hemiparetic	Dominant	Nondominant
No support	1.61±0.18	1.66±0.14	1.72±0.11	1.66±0.11
Touch	1.59±0.18	1.47±0.14	1.76±0.14	1.75±0.16
Skateboard	1.74±0.12	1.88±1.69	2.01±0.25	1.96±0.23

NOTE. Values are mean seconds ± SE.

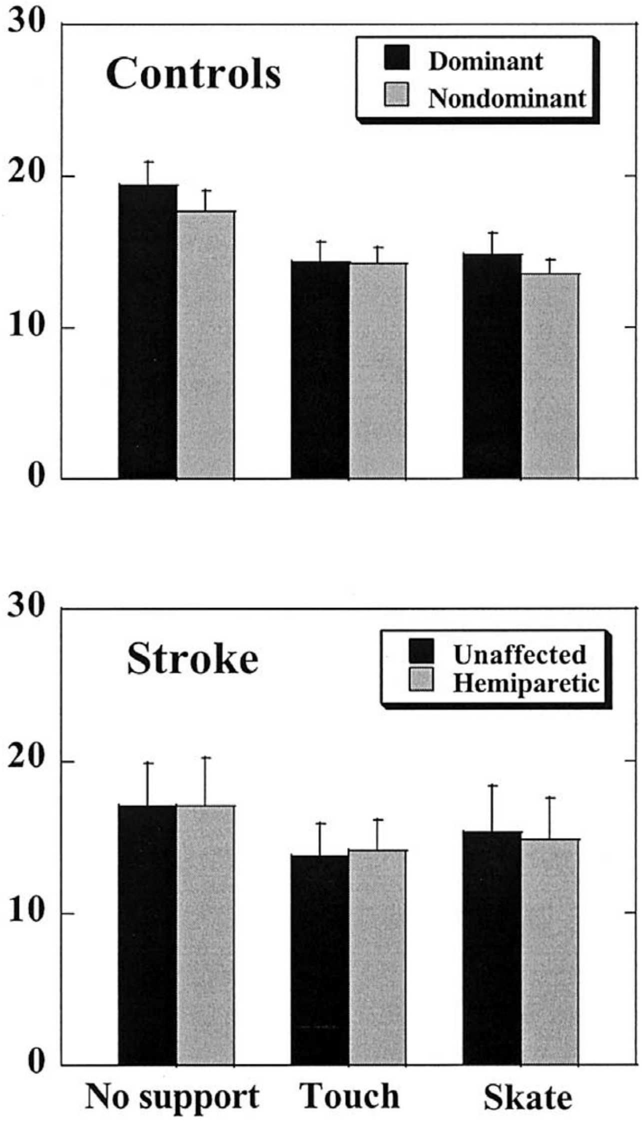

Fig 3. Quantitative data for peak grip forces used under each of the 3 support conditions. NOTE. The vertical scale shows grip force in newtons; each bar represents the group mean ± SE.

and hemiparetic hands, respectively. Figure 4 shows the magnitude of peak grip force divided by the magnitude of the maximal grip force for the unaffected (dominant) or hemiparetic (nondominant) arms, respectively, and multiplied by 100. The average percentage of the maximal force that control subjects applied to the object in the no-support condition was 37.36%±6.67% for the dominant arm and 34.6%±6.16% for the nondominant arm. Subjects with hemiparesis used similar grip force when performing the task with the unaffected hand (34.37±5.49N); however, they used a larger percentage of the maximal force (57.41%±10.40%) while using the hemiparetic hand. Both groups used reduced grip force in conditions with additional support (touch or skateboard). ANOVA showed a significant main effect of support ($F_{2,20}=11.21$, $P<.001$) and significant interaction for group by side ($F_{1,10}=6.39$, $P<.05$).

The average time to peak of maximum grip force for all the experimental conditions calculated for subjects with hemiparesis and controls is presented in table 3. ANOVA showed a significant main effect of side ($F_{1,10}=5.14$, $P<.05$) and significant interaction for group, side, and support ($F_{2,20}=5.15$, $P<.05$).

DISCUSSION

There are 3 findings of note in the present study: (1) subjects with hemiparesis showed significantly longer latency between grip-force application and lift-off of the object; (2) when using their hemiparetic arm, subjects with hemiparesis used higher levels of normalized grip force than they did when using their unaffected arm or than did the control subjects; and (3) both groups of subjects were able to reduce grip force when provided with additional sensory input.

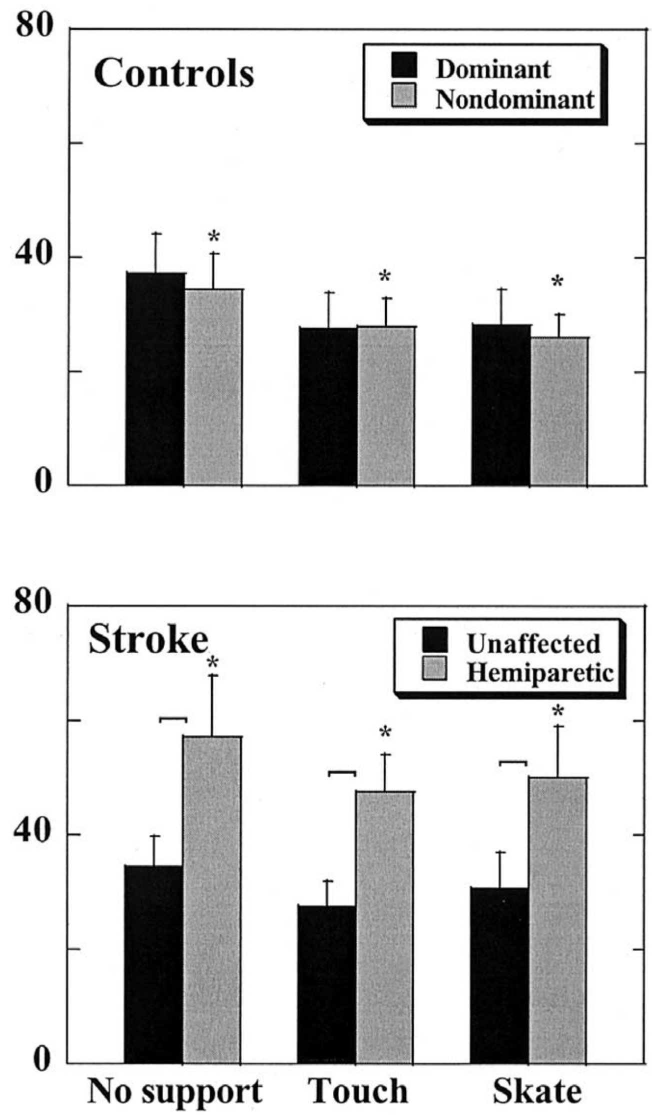

Fig 4. Peak grip forces as a percentage of the maximal force measured in each of the 3 support conditions. NOTE. The vertical scale shows peak grip force as a percentage of the maximal force. *$P<.05$ (significant differences between the groups); ⌐¬ $P<.05$ (significant differences between unaffected and hemiparetic arms).

Table 3: Time to Peak of Maximal Grip Force

Conditions	Patients		Controls	
	Unaffected	Hemiparetic	Dominant	Nondominant
No support	.38±.07	.56±.12	.29±.04	.34±.02
Touch	.42±.07	.45±.05	.29±.02	.40±.04
Skateboard	.35±.08	.54±.07	.34±.03	.26±.02

NOTE. Values are mean seconds ± SE.

Temporal Coupling Between the Grip Force and the Lift-Off of the Object

There is a difference in hand and arm muscle function when lifting and transporting an object. Hand muscles produce the grip force, whereas more proximal arm muscles create the force for lifting or transporting the object. A close temporal coupling between the grip force applied by the fingers on an object and the load force exerted by more proximal muscles to lift or hold the object has been described in the literature.[22,23] In the current experiments, temporal coupling was observed in control subjects but not in the affected arms of subjects with hemiparesis, who showed significant delay between the grip-force application and the lift-off of the object. Similar delay has been observed in subjects with Parkinson's disease[5] and subjects with cerebellar disorders.[24] A disruption of the temporal coordination between the proximal arm muscles (lifting the object) and the fingers (gripping the object) was also observed recently in patients with cerebellar disorders.[7] Thus, it may be cautiously concluded that longer latency between the onset of the grip force development and the lift-off of the object seen in subjects with hemiparesis represents a breakdown of the temporal coordination between the fingers and the more proximal arm muscles. An alternative explanation could be that a delay in the coordination between finger and arm muscles of people with hemiparesis observed in the current experiments is due to disruption of interjoint coordination[25] and disruptions in the recruitment and derecruitment of agonist and antagonist muscles in the forearm.[26-29] Registration of the onsets of electromyographic activity of the proximal arm muscles responsible for lifting the objects and the finger muscles used to grip it would provide additional evidence of such temporal coupling in subjects with hemiparesis.

Differences in Grip Force

An abnormally high level of grip force has been observed in patients with a range of basal ganglia conditions, including Parkinson's disease,[5] in patients with Huntington's disease,[9,30] focal dystonia,[31] and cerebellar disorders,[7] and in the elderly.[4] An elevation in grip force was also seen in healthy subjects whose cutaneous afferents of the fingers and lower arm were subjected to local anesthesia.[32] In the current experiment, I expected subjects with hemiparesis to use increased levels of absolute grip force compared with control subjects. However, the grip force that subjects with hemiparesis applied did not differ between the affected and unaffected arms, nor did the force applied by the dominant and nondominant arms of the control subjects differ. This could be due to the fact that the level of impairment of the subjects with hemiparesis was relatively mild and that they were required to lift and transfer objects of a relatively small weight (580g, see Methods). If the subjects with hemiparesis had been required to lift and transport objects of a larger weight, they would have needed to apply a higher level of absolute grip force to prevent object slippage. However, because of weakness of the muscles of the hemiparetic upper extremity,[20,33] this would require them to use a greater percentage of their maximal grip force. The results of the calculation of the normalized grip force corroborate this suggestion: subjects with hemiparesis applied almost 60% of the maximal grip force of the affected arm to lift and transport a 580-g object, whereas less than 40% of maximal grip force was needed to lift the same object with the unaffected arm.

Grip-Force Scaling to the Anticipated Support Condition

There are similarities in control of grip while manipulating an object and in control of postural equilibrium while standing. For both grip and stance stability, the necessary stabilizing commands are issued in advance of potentially destabilizing perturbations by adaptive feedforward controllers based on internal models of the action that are tuned to the initial mechanical conditions.[13,34] Thus, it is well known that commands to leg and trunk muscles, whose goal is to preserve equilibrium, precede the commands to the voluntary arm movements.[34-37] Similarly, it is well documented that manipulative activities, such as lifting and transporting objects, are accompanied by the anticipatory modulation of grip force.[21,32,38] It is believed that anticipatory grip-force adjustments are based on "memory" from immediate prior experience that includes information on the object's weight, size, and frictional characteristics,[32,39,40] as well as information on the kinematics of a planned movement.[6]

In the current experiment, I observed anticipatory modulation of grip force with the changes in the provision of support. A freely moving skateboard provided a mechanical support and additional sensory information, whereas a light finger touch of the contralateral arm provided only additional sensory information. When a light finger touch of the contralateral arm was available, both subject groups reduced the amount of applied grip force. Thus, provision of sensory information with a touch of the finger of the contralateral arm, even touch not associated with increase of stability of the hand lifting the object, could be used for grip-force adjustment.

It is probable that, through contact with the contralateral arm, subjects were able to derive enough additional sensory information to better evaluate the physical properties of the object to be lifted, as well as to ensure that the grip force was not too high to avoid fatigue and not too low to prevent slippage of the object. Corroboration of this conclusion comes from postural studies involving contact cues from the fingertip leading to reduced postural sway in healthy subjects and in subjects with bilateral vestibular loss.[14-16] A mechanical support provided with the skateboard could be associated with changes in the initial conditions of the task, because lifting is more secure when the arm is supported. Another possible explanation is associated with stabilization of the kinematic chain connecting the hand to the external structure, which consequently leads to an increased sense of security while lifting an object.

Thus, based on the usefulness of active touch for the reduction in postural sway,[15,16,41] it is tempting to suggest that a light finger touch of the contralateral arm could be helpful while manipulating objects. Because many pathologic changes in grip-force control have been linked to deficits in sensorimotor processing, additional sensory input provided with a touch could benefit people with impairment of grip-force control. This could be especially important when weakness of the arm muscles limits performance of simple daily tasks, such as pouring a drink or feeding. In addition, the temporal coordination between the onset of the grip force and the lift-off of the object was faster in the hemiparetic arm with provision of light touch.

CONCLUSIONS

The study has examined the modulation of grip force while lifting and transporting an object both in individuals with hemiparesis and in healthy controls. All subjects were able to better regulate grip force when provided with additional sensory input. Subjects with hemiparesis showed significantly longer latency between grip-force application and the lift-off of the object, which indicates possible changes of the temporal coordination between the fingers and the more proximal arm muscles. This study examined only a limited number of subjects with mild hemiparesis due to a recent stroke. Hence, future research is needed to evaluate the benefits of light touch for people with hemiparesis in clinical and in rehabilitative settings.

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Suppliers

a. PCB Piezotronics Inc, 3425 Walden Ave, Depew, NY 14043.
b. National Instruments Corp, 11500 N Mopac Expwy, Austin, TX 78759-3504.
c. StatSoft Inc, 2300 E 14th St, Tulsa, OK 74104.