The role of proprioceptive information for the production of isometric forces and for handwriting tasks *

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A patient showing a total loss of all the large sensory myelinated fibers but intact peripheral motor system produced simple isometric force pulses and more complex tasks like handwriting and drawing. Overall, the patient was able to perform the isometric force task with an accuracy that approached that of normal subjects. The writing tasks, however, proved to be more challenging. In absence of vision, the different forms and cursive trajectories forming letters (morphocinetic components) were preserved but their localization within the constraints of the graphic space (topocinetic components) were severely impaired. These results demonstrate that, in absence of visual information, proprioceptive information is necessary to calibrate the hand in space.

How important peripheral feedback is for movement accuracy is still a matter of debate (see Sanes et al., 1985, for a recent historical review). For example, mass-spring models of human movement are based on the prediction that the limb moves to a position defined by an equilibrium point between opposing muscles at a joint, and that the

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movement to this position is dependent of the spring-like characteristics of
the muscular system (e.g. Bizzi et al. 1984; Flash 1989). In these models,
peripheral feedback appears to have little role in motor control. Feldman
(1966) has also proposed an equilibrium-point model. In Feldman's model,
however, the equilibrium point is specified by the position of the static
torque-angle characteristic of the tonic stretch reflex arc and the load
characteristic (Feldman 1966; Latash and Gottlieb 1991). Thus, central
commands and peripheral conditions are important for movement control;
absence of afferent information results in a loss of the positional frame of
reference for central control signals. A number of recent experiments with
deafferented humans have provided evidence for the importance of
proprioceptive inputs for the control and execution of simple voluntary
movements. Poorer control of movement trajectories and endpoint accuracy
have been observed in these patients (Forget and Lamarre 1987; Ghez et al.
1990; Gordon et al. 1987; Salles et al. 1985; Rothwell et al. 1982). Static
limb posture and isometric force production is also impaired in deafferented
humans. Overall, these patients: (a) are unable to maintain a static limb
posture in absence of visual guidance, and the positional drift is not related
to the direction of the load (Sanes 1990; Rothwell et al. 1982), (b) show
much larger variability of peak force and force rise time (Gordon et al.
1987).

Published description of more complex behaviors such as handwriting-like
movements in absence of afferent information are scarce (Forget 1986; Ghez et al. 1990). Paillard (1991) has proposed that handwriting is
regulated by morphocinetic and topocinetic components. The morphocinetic
components refer to the cursive trajectory forming letters. Morphocinetic
components are generally produced automatically and do not require the
support of visual and proprioceptive feedback. Movements generating these
forms have been shown to obey an isochrony principle (i.e. they show an
invariance of the angular velocity when curvature changes; Lacquaniti et al.
1983; Viviani and Terzuolo 1982; Viviani 1990). Research on handwriting
also suggests that letters are written by concatenating morphocinetic
components (Rosenbaum 1991). On the other hand, the topocinetic
components refer to the displacements of the hand within the constraint of a
graphic space. The continuous development of morphocinetic chains, the
spaces between letters and words, back and forth hand displacements
necessary for punctuation and accents are topocinetic components requiring
rigorous space and direction calibration (Paillard 1991). Within this framework, visual information is used to provide accurate topocinetic saccades (e.g. punctuations) and to maintain a left to right progression of the writing within the constraint of the graphic space. Therefore, in absence of vision, the handwriting of deafferented humans should be characterized by marked deficits in the topocinetic components only.

The purpose of this paper is to describe how a patient showing a total loss of all the large sensory myelinated fibers but intact peripheral mater system can produce simple isometric force pulses and more complex tasks like handwriting and drawing.

**Methods**

**Subjects**

A deafferented patient (42 years old) showing a total loss of the senses of touch, vibration, pressure and kinesthesia, as well as absent tendon reflexes in the four limbs was tested. Motor nerve conduction velocities of the muscles of the arm are normal (Cooke et al. 1985). A more detailed clinical description of the patient can be found in Forget and Lamarre (1987). Six neurologically normal subjects also participated as control subjects for the isometric task and one subject participated for the handwriting tasks.

**Procedures**

**Isometric task**

The right forearm of the subjects were secured on a table with the hand in a supine position and the elbow at 90 degrees. A load cell was placed between the index and the thumb. The forearm and the hand were hidden with a mask to prevent subjects from using any visual cues from the muscular contraction. For all trials and conditions, the instructions were to: (a) produce a single impulse whose peak reaches the required target force, (b) be as accurate as possible, and (c) relax back to the baseline once the peak is achieved. For all conditions, the subjects had no visual feedback of their performance and were simply instructed to produce a force that was a percentage of their maximum. After a brief familiarization with the apparatus, the subjects were asked to produce five maximum forces (mean patient = 20.3 N, mean controls = 52.9 N). In a first manipulation, 5 trials at each of 10, 20, 30, 50, and 70% of the maximum were recorded. The different target forces were randomly presented and no verbal feedback was given. In a second manipulation, 20 trials at each of 10, 20, 30, 50, and 70% of the subject's maximum force were recorded. Verbal feedback about the accuracy was given after each trial for the first 10 trials of each force level. The last 10 trials for each target force level were produced without any feedback.
The force signals were sampled at 250 Hz (12-bit A/D conversion). Filtering and first and second derivatives were computed with optimally regularized Fourier series (Hatze 1981). Unless otherwise mentioned the results obtained for the normals were submitted to a one-way ANOVA (target force level) with repeated measures.

**Handwriting tasks**
While holding a pen, the patient and a normal subject were asked to write simple words or to draw continuous ellipses with and without vision. They adopted a normal seated position and wrote on a regular height table. Some of these movements were recorded with the help of a three-dimensional digitizing system (Selspot II).

After collection (100 Hz), the data from two cameras were transformed in a set of 3-D coordinates. The coordinates were then filtered (Butterworth second-order dual-pass with a 6 Hz cut-off frequency) and differentiated (finite difference technique) to obtain the velocity-time profiles.

**Results**

**Isometric task**

The relationship between the target force and the attained peak force was evaluated to determine whether the patient has an internal model of the different forces. For this first experiment, the subjects had no feedback (verbal or visual) regarding the accuracy of their force production and no experience with the task (except for a few no-feedback familiarization trials). The slopes and intercepts for the target force-attained peak force relationships are presented in table 1.

<table>
<thead>
<tr>
<th>Normals</th>
<th>Intercept</th>
<th>Slope</th>
<th>$R$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.54</td>
<td>0.81</td>
<td>0.844</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>12.10</td>
<td>0.75</td>
<td>0.843</td>
<td>0.71</td>
</tr>
<tr>
<td>3</td>
<td>10.72</td>
<td>0.75</td>
<td>0.879</td>
<td>0.77</td>
</tr>
<tr>
<td>4</td>
<td>7.43</td>
<td>1.00</td>
<td>0.816</td>
<td>0.66</td>
</tr>
<tr>
<td>5</td>
<td>14.61</td>
<td>0.59</td>
<td>0.835</td>
<td>0.70</td>
</tr>
<tr>
<td>6</td>
<td>11.07</td>
<td>0.73</td>
<td>0.887</td>
<td>0.78</td>
</tr>
<tr>
<td>$\bar{X}$</td>
<td>11.39</td>
<td>0.78</td>
<td>0.851</td>
<td>0.72</td>
</tr>
<tr>
<td>Patient</td>
<td>0.15</td>
<td>0.78</td>
<td>0.855</td>
<td>0.73</td>
</tr>
</tbody>
</table>
Further, the relationships for the patient and one subject are presented in fig.1. Clearly, the patient has an accurate internal force model. The correlation obtained between peak force and the target force were statistically significant for the deafferented patient and all normal subjects ($t_{18}, p<0.01$). For both the patient and normals, more than 70% of the variance observed in peak force was explained by the target force. A Student $t$-test showed that the slope of the target force-peak force relationship obtained for the patient was similar to that of the normals ($t_{0.05 (5)} = 0.069$). While normal subjects tended to overestimate the different target forces (as indicated by the positive intercepts, on average, 11.39) the patient had an intercept that approached zero (0.15). This difference was statistically significant ($t_{0.05 (5)} = - 4.38$).

For the second experiment, the first 10 trials with verbal feedback are not included in the analyses as they served the purpose of building a more accurate force model. The trials without feedback indicate if the patient was able to build and maintain the force model. The overall relationship between peak force and target force is presented in fig. 2. Overall, normals and the patient improved their force model; regression analyses showed that the percentage of variance in peak force explained by target force was higher than 90% for all subjects (on average, 96% for the normals and 95% for the patient).

Representative force-time curves for the patient and a normal subject at three of the five target levels are presented in fig. 3. Again, the patient showed remarkable consistency and accuracy in attaining a given target force.

The force rise time needed to attain the different peak forces obtained are presented in fig. 4. The ANOVA on the force rise time showed a main effect...
Fig. 2. Peak force-target force relationship (in percent of maximum) for the normal subjects and the deafferented patient after trials with verbal feedback.

force \( (F(4,20) = 8.70, p < 0.01) \). A decomposition of the main effect into its orthogonal components showed a significant linear trend \( (F(1,5) = 12.32, p < 0.01) \) suggesting that force rise time increased linearly with increasing peak force (162, 178, 187, 196, and 212 ms, respectively for the 10, 20, 30, 50, and 70% target force levels). A similar trend was observed for the patient (181, 184, 173, 208, and 228 ms for the 10, 20, 30, 50, and 70% target force levels).

Fig. 3. Representative force-time profiles for one normal subject and the deafferented patient at the 10%, 30%, and 70%-target force.
target force levels, respectively). For the smaller and the larger target forces, the patient exhibited more temporal variability than normals. This result is shown in the embedded histogram of fig. 4. These results show that both, normals and the patient, produced the different peak forces by varying the rate of rise of force and the rise time.

In order to determine whether the patient was more variable at attaining a given target force than normals, relative peak force variability (i.e. ratio of the standard deviation of peak force to the maximum peak force, expressed in percentage) was used as a measure of dispersion. For normals, fig. 5 shows that peak force variability increased in a negatively accelerating fashion with increasing peak force. The ANOVA showed a main effect of target force \((F(4,20) = 5.08, p < 0.05)\) and the decomposition of the effect into its orthogonal components showed a significant quadratic trend \((F(1,5) = 14.57, p < 0.05)\). The variability for the patient was also similar to that observed for normals except at the 20%-target force. The departure from normals at this force level is the consequence of a single trial for which the peak force produced was more than three times as large as the mean of the remaining trials for this force level. The patient reported no overshoot for this trial. However, this trial was at the very end of the experiment and it is possible that the overshoot was caused by a lack or a loss of attention. It was not the result of a loss of calibration, however, since the following three trials (last trials of the experiment) were all within 5% of the target force.

![Fig. 4. Force rise time (ms) as a function of target force for the normals and the deafferented patient. The error bars for the line represent the between-subject variability for the normals. The embedded histogram represents the within-subject variability. Note the larger variability for the patient at the 10% and 70%-target force.](image)
Fig. 5. Peak force variability (in percent of maximum) as a function of target force. The larger variability observed at the 20%-target force is the consequence of a single trial for which peak force was more than three times as large the mean of the remaining trials. The patient did not report any overshoot on this specific trial.

Handwriting

When the patient was asked to write, whether it was a simple sentence or to sign her name with vision, both the morphocinetic and the topocinetic components of the movement were preserved. Fig. 6 has an example of this observation when the patient wrote the French “Il fait tiède” with vision.
Without vision (bottom of fig. 6), it can be noted that all the morphocinetic components are preserved but the topocinetic components are much degraded; for example, the $l$ is superimposed on the $i$ of $il$, the bar of the $t$ of the word $faii$ is located on the $f$, the bar of the $t$ and the dot from the $i$ of the word $tiède$ are too high.

The handwriting capabilities of the patient were further studied by requiring the production of simple ellipses with and without vision. Fig. 7 has representative ellipses drawn with and without vision for the patient and the normal subject. Note the regularity and consistency with which the patient and the normal subject were able to draw ellipses with vision. Without vision, the normal subject was still able to produce consistent and regular ellipses. The patient, on the other hand, drew ellipses of consistent shape but the spatial locations of the ellipses always drifted within the constraint of the graphics space. The orientation of the drift varied across trials. With vision, this drift was absent since the patient used a visual-tracking mode characterized by a slower drawing speed. Thus, it is the topocinetic components, that is the locations of the ellipses within the constraints of the graphic space, that are impaired in the patient.
Discussion

The force experiment showed that afferent information is not necessary for the production of simple isometric force pulses. Our patient was able to produce force pulses that approached the accuracy and consistency observed for normals. The peak force variability observed was similar to that reported for normals (Newell and Carlton 1988; Newell et al. 1984; Sherwood et al. 1988). For all normal subjects and the patient, force rise time increased with an increasing peak force, suggesting systematic shifts in rate of force production with changing task constraints (Newell et al. 1984). The impairments were seen in a larger force rise time variability at the lower and higher force levels and in a larger peak force variability at the 20%-force level. This larger force variability at the 20%-force level was the consequence of a single 'outlier' trial. Using a psychophysical paradigm, Sanes (1990) recently observed that deafferented humans have marked abnormalities in detecting low force level changes in applied loads. He suggested that a mechanism of corollary discharge could operate at high levels of motor output but that somesthetic information is critical for detection of changes in motor commands for muscle activity at low levels of motor output. Our results do not support this suggestion since our patient behaved similarly to normals at the low and high force levels.

Our patient was much better at producing different target forces than Gordon et al.'s patients (1987). It is important to note, however, that Gordon et al. had an elbow flexion force production task while, in the present experiment, we used a thumb-index force production task. Our patient, over the years, has adapted to the disease and has learned to accomplish, albeit more slowly and more clumsily than normals, a number of regular daily tasks. It is possible that this increased practice in reaching and grasping objects has provided her with better ways to monitor the force output in order to grasp adequately different objects. Alternatively, it is also possible that the larger cortical representation of the distal segments could allow for a more accurate programming than for the more proximal segments. In absence of vision and contrary to our results obtained for the isometric force task, the programing and control of multi-joint movements is critically dependent on proprioceptive information from the limb. For the handwriting tasks, the absence of vision resulted in marked deficits in the topocinetic
components, that is in the displacements of the hand within the constraints of the graphic space. Nevertheless, the morphocinetic components were generally well preserved. This result is in variance with earlier reports by Laszlo and Bairstow (1971). Using a compression block technique, they observed that subjects had (1) difficulties starting a letter production, (2) repeated parts of letters many times, and (3) produced movements unrelated to the shape of the letter they were attempting to write. In their experiment, only 20 trials were observed and it is possible that subjects could improve their performance with extensive practice. This possibility is supported by earlier samples of our patient's handwriting (Forget 1986) showing legs well defined morphocinetic components. Alternatively, it is also possible that, in Laszlo and Bairstow, the cuff technique yielded some motor impairments.

Without vision, the shape of the ellipses was conserved across the different loops but the spatial position of the ellipse within the graphic space drifted within the constraint of the graphic space. This drift is consistent with Paillard's suggestion that topocinetic saccades are necessary for precise space and direction calibration. In absence of vision, proprioceptive feedback can provide this spatial calibration; the patient, however, has no proprioceptive map to match the topocinetic dimension of handwriting. The drift observed is also in agreement with Gordon et al. (1987) and Ghez et al. (1990) who showed that, without vision, the consistency and stereotypy of trajectory configuration for deafferented patients was seriously degraded. They suggested that deafferented humans do not adapt the amplitudes and directions of applied forces to the actual mechanical properties of their limb. Thus, for the ellipse task, the absence of information from the limb could have prevented the patient to compensate for the non-uniform inertial properties of the limbs.

Overall, our results show that afferent information is not essential for the production of simple thumb-index isometric force pulses. On the other hand, in absence of vision, more complex movements like handwriting required spatial calibration feeded by proprioceptive information. In absence of such information, the different forms and cursive trajectories forming letters (morphocinetic components) were preserved but their localization within the constraints of the graphic space (topocinetic components) was severely impaired. These observations are also reminiscent of Marsden's (1982)
suggestion that the concatenation of simple motor programs into a fully formed motor plan requires afferent information.

References


