# TASK-DEPENDENT VARIABILITY IN HUMAN HAND EMG: EVIDENCE FOR OPTIMAL FEEDBACK CONTROL AT THE MUSCLE LEVEL

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## INTRODUCTION

How the central nervous system (CNS) coordinates redundant actuators is a central problem in motor control. We have shown that the CNS can simplify the control of redundant muscles by selecting task-specific coordination patterns and scaling them to modulate the magnitude of the force output (Valero-Cuevas 2000). Moreover, we have recently argued (Todorov and Jordan 2002) that the CNS does not eliminate redundancy in a planning stage, but instead takes advantage of redundancy—by using a feedback control law to choose (online) the best motor pattern under the circumstances. We have found (Todorov and Jordan 2002) that such optimal feedback controllers obey a "minimal intervention" principle, which states that task-irrelevant deviations away from the average behavior should not be corrected. Such a controller allows variability to accumulate in dimensions that are redundant (task-irrelevant), and selectively constrains variability in task-relevant dimensions. This phenomenon has been repeatedly observed since Bernstein, and recently quantified via the "uncontrolled manifold" method (Scholz and Schoner 1999). However, existing observations are restricted to the levels of kinematics and kinetics. An important open question is whether muscle activity (the true output of the CNS) also exhibits such task-dependent variability. Here we ask that question, and answer it affirmatively.

## EXPERIMENTAL METHODS

The data used in the analysis have been described previously (Valero-Cuevas 2000). We recorded fine-wire EMG signals from the seven muscles of the index finger and the 3D components of the fingertip force vector. The task consisted of producing isometric force plateaus at 50% and 100% maximal voluntary force. We studied five orthogonal directions of force, each in three finger postures. Eight unimpaired young adults wore a custom-molded thimble that defined a point-contact with the 3D force sensor that required well-directed forces and no fingertip torque to prevent slipping or rotation about the contact point (Fig 1). Filtered EMGs and force measurements were sampled at 100Hz. Each EMG was normalized so that its maximal observed activation was 1.

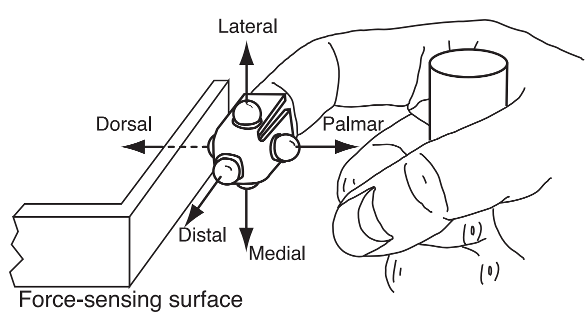


**Figure 1:** Producing isometric fingertip force in one of five directions (the "dorsal" direction). 3D force is produced across a point-contact defined between a polished force-sensing surface and a metallic bead embedded in the thimble.

## DATA ANALYSIS

The usable dataset consisted of 1209 plateau periods (about 1.3 sec each), which were grouped so that all periods from the same subject and finger posture belonged to the same set (23 sets total). Within each set, we found the 3x7 matrix $A$ that best relates the instantaneous 7D muscle activations $\mathbf{m}$ to the instantaneous 3D fingertip forces $\mathbf{f}$. The linear model $\mathbf{f}(t) = A * \mathbf{m}(t)$ accounted for about 85% of the force variance. We then decomposed the 7D muscle space into a 3D subspace R which is task-relevant, and a 4D subspace N which is task-irrelevant or redundant. R and N are computed as the range and null-space of the matrix $A$. The redundant subspace N has the property that if a vector $\mathbf{v}$ belongs to N, then $A * \mathbf{v} = 0$, and therefore $A * (\mathbf{m}+\mathbf{v}) = A * \mathbf{m}$. So if the 7D vector of muscle activations $\mathbf{m}$ is perturbed by adding the vector $\mathbf{v}$ to it, the new vector of muscle activations $\mathbf{m}+\mathbf{v}$ will generate exactly the same fingertip force. Such a perturbation is task-irrelevant, and according to the minimal intervention principle should not be corrected. Thus the minimal intervention principle predicts higher variability in subspace N compared to subspace R. To test this, we projected the 7D muscle activation vectors in the two (complementary) subspaces N and R, computed the corresponding variances V(N) and V(R), and compared them. Note that V(N) and V(R) are not scalars, but 4x4 and 3x3 covariance matrices, repectively. To obtain scalars $v$(N) and $v$(R) that represent overall variance, we computed the average variance per dimension: $v = \mathrm{trace}(V)/\mathrm{dim}(V)$ for each subspace (Scholz and Schoner 1999). Although the coordinate systems of R and N are defined up to an arbitrary rotation, rotations do not affect the trace of V, and so $v$ are independent of the choice of coordinates.

## RESULTS AND DISCUSSION

The results are illustrated in Fig 2, which shows the average standard deviation per subspace dimension. We plot sqrt($v$(R)) vs. sqrt($v$(N)), and each data point corresponds to one of the 23 sets of plateau periods. The fact that 87% of points lie below the diagonal indicates that EMG variability in redundant dimensions is indeed higher than EMG variability in task-relevant dimensions. The ratio $v$(N)/$v$(R), averaged over the 23 sets, was 3 (Fig 2 shows statistics for the ratio of standard deviations). These results strongly suggest that the CNS regulates muscle activity in a manner equivalent to that of optimal feedback controllers.

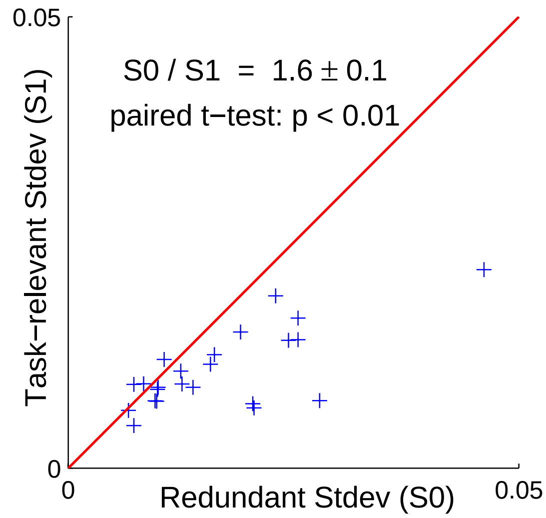


**Figure 2:** Comparison of EMG average standard deviations in the redundant (abscissa) and task-relevant (ordinate) subspaces.

## REFERENCES

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