

# Muscle mechanics and reflexes are not tuned for disturbance rejection

FLORIN C. POPESCU

Rehabilitation Institute, Sensory Motor Performance Program

Northwestern University

345 E. Superior Room 1406 Chicago IL 60611

USA

*Abstract:* In this paper we present some simple evidence that during movements, disturbance rejection from the human limb is by and large inertial. Despite much speculation about the ‘spring-like’ nature of muscles and reflexes, and other like characterizations of damping, the limb is predominantly inertial - the other types of forces acting upon it are not well enough behaved or strong enough to simplify control strategy. The muscles are best regarded, other than in conditions of significant co-contraction, as force generators rather than adjustable springs. Even during co-contraction, the joint’s damping properties may be more important to control than the elastic properties. Muscle studies do not tell the whole story - isolated muscle has minimal inertia, while in isometric perturbation experiments position control minimizes limb inertia effects. We present results of a study in which force perturbations were applied to the freely moving arm - inertia by itself accounted well for responses before, during and after a ‘ballistic’ movement. When compensations for a disturbance did occur, they did so after a significant delay, either because of supra-spinal reflex activity, or because of the intended time-course of ‘braking’. This result places a premium on involvement of supra-spinal circuits in accurate, dextrous motor control, and furthermore demonstrates that a deficiency of precision, repeatability and loop delay in a robotic effector can be overcome by intelligent control. Thus, the human arm is designed according to a radically different philosophy than that of current robots: smart brain and imprecise effectors, rather than a dim brain and precise effectors.

*Key-Words:* - motor control, human, impedance, reflex.

## 1 Introduction

In regards to the brain’s strategy of moving the human limbs during dextrous tasks, there are two main hypotheses [9]. One is that the desired position (trajectory) of the limb is transmitted to the spinal cord, after which the muscle and reflex properties do most of the control computation. There are a few variants of this theory - let us call it impedance control, meaning the distal levels of the CNS, plus muscles, control not only a trajectory but the resistance to disturbance around that desired trajectory. Certainly it seems ‘impedance’ may be modulated, either by co-contraction of opposing muscles, i.e. stiffening of the effector, or by varying reflex excitability. It is only a matter of attaching a central or minor role to this ability in the grand scheme of motor control. A contrasting hypothesis maintains that the motor cortex and other supraspinal areas of the CNS do not command position, though they may influence impedance around whatever position the limb happens to be in. Alternatively, commands received and processed by the spinal cord are mainly indicative of forces that

muscles are instructed to exert. As such, the upper CNS must do a fair amount of computation, if the task requires trajectory control, to determine the force profiles necessary. This computation, termed *inverse dynamics*, is made difficult by a variety of factors: changing plant and environment dynamics, redundancy of muscles, variability of output. Artificial robots used to have a lot of difficulty coping with such a scheme, which gave circumstantial support to the impedance control theory. Although both theories are somewhat vague, their ideological contrast is the role of the spinal cord, while their predictive difference comes down to the effective stiffness of the limb with respect to trajectory: if it is high, it means impedance control is probably at work - if it is low [2][3] or requires long latencies to return the limb to its desired trajectory inverse dynamics is more likely. Besides evidence of low impedance (stiffness) there is also evidence that the most important feature of a reaching movement, its endpoint, is significantly affected by small, transient forces [7][8], unless long-latency visual feedback responses are elicited.

## 2 Problem Formulation

The objective of this study was to examine the joint response to imposed perturbations during rapid movements, with the goal of identifying both plant properties as well as its controller.

### 2.1 Methods

Point to point elbow movements of one subject were unexpectedly perturbed by small force pulses applied by an attached, otherwise passive motor.

#### 2.1.1 Apparatus

The test apparatus was developed at the Rehabilitation Institute of Chicago. This setup consists of a DC brush-type motor digitally controlled by a Pentium Pro 200 PC at a sampling rate of 1000 Hz. A torque sensor mounted on the motor shaft was used to collect torque while elbow angle and velocity were recorded using a precision potentiometer and tachometer. Motor friction and inertia were compensated for using closed loop torque control, while a feed-forward inertial compensation was used to eliminate the effects of the beam used to couple the arm to the motor. This type of control strategy allowed us to study natural occurring movements, without biasing the subjects control strategy from adaptation to test apparatus.

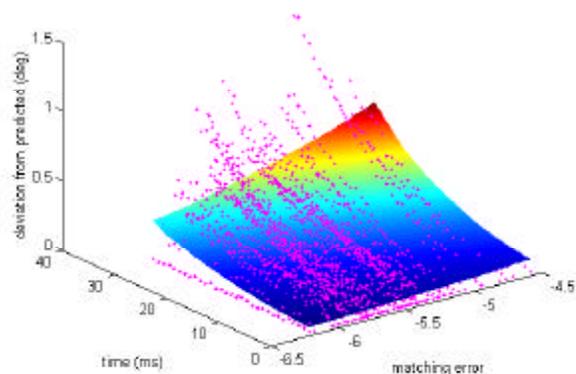
#### 2.1.1 Paradigm

The subject performed 200 movements, from visually presented starting point to target, viewing a cursor on a computer screen. He was instructed not to stiffen the arm (co-contract). The arm was required to keep the beginning position (30 deg. Flexion) and a beep instructed the subject to begin the motion to the target (30 deg. Extension). The movement time was displayed after the motion in order to train the subject to make movements of about 300 ms. Randomly shuffled amongst the 200 ms movements were 10 perturbations of 10 types (therefore 50% of movements were perturbed). The perturbations types were flexion/extension at 100 ms before the beep ('pre'), at the  $-15^\circ$  crossing ('early'),  $0^\circ$  crossing (mid-motion), the  $15^\circ$  crossing ('late') and 100 ms after motion settling ('post').

### 2.2 Results

The most difficult part of analysis of perturbed but otherwise unconstrained motion is the subtraction of 'intended' trajectory from the perturbed trace. There are two basic approaches to this problem. One is to

train some sort of function (e.g. neural network) to predict unperturbed motion given some history. The other much slower and more laborious approach is to collect a large number of trials and choose, for a given trajectory up to a time at which we apply the perturbation, the closest similar trajectory (nearest-neighbor). We do not need to train any function since we are doing our analysis off-line and speed of prediction computation is not an issue. We do, however, allow the predictor trajectory to shift and 'stretch' in both position and time, as well as pick a forgetting factor for the fit (what happened 10ms ago is more important to us than 200ms ago), which we chose as exponential with a 100ms decay time ('half-life'). Fitting unperturbed trajectories against each other in this manner provides us with a limit of elbow movement predictability (see Figure 1).



**Figure 1.** Predictability of human elbow movements Plotted is the difference between two similar trajectories vs. time (up to 30 ms in future, taken at mid-motion). The similarity criteria (matching error) is  $\log(\int \text{deviation}(t)/\exp(t/100\text{ms}), t=0..\text{inf})$ . Note that the predictability reaches  $\sim 1$  deg at 30 ms and  $\sim 1.5$  deg at 60 ms (not shown).

Given that some of our perturbations are applied before the movement, we should not have to rely on trajectory prediction in every case (intended trajectory is constant before motion). In fact it may be helpful to compare these traces to those from which predicted trajectory subtraction was necessary. Figure 2 represents the data from all 200 trials. We have placed all data on the same figure. Superimposed on the 'most predictable' trajectory (i.e. most representative) are averaged perturbed responses. Underneath we see individual force traces and position deviations with the appropriate 'intended' trajectories subtracted, where applicable. What we notice, while looking at the 'pre' and 'post' movement responses, is approximate pulses

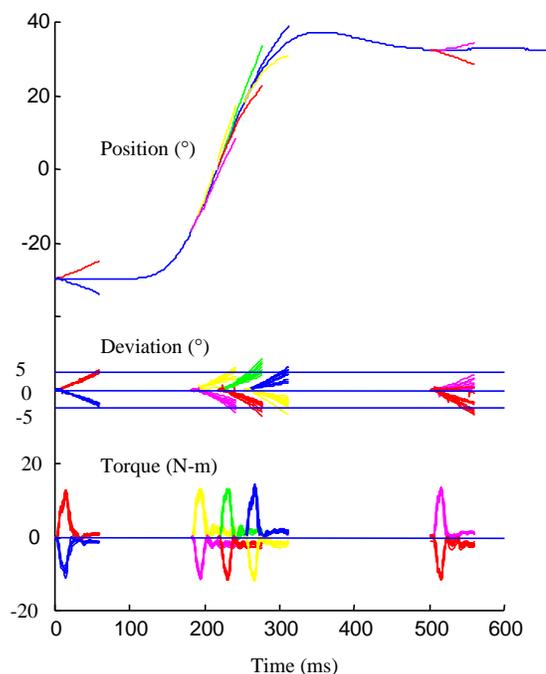
(nearly identical for each perturbation condition) followed by ramp positional responses. This type of response is easily recognizable as inertial (in the case of a spring we would see a pulse and that of a damper, a step). Since the pulse is not perfect, neither is the ramp – the near ramp scales very well with the double integral of force. As far as the magnitude of the position disturbance, measured at 60ms after perturbation onset, at which we may reasonably expect the reflex dependent force to begin its effect, we can see it averaging 5 degrees in either direction in the ‘pre’ movement (see Table 1 for the numbers). These responses are nearly identical to each other, and are quite recognizably ramps. The inertia which fits these responses (0.007 Nm/s/s) is in agreement with previous studies [1] and with anatomical data (.01 kg-m).

**Table 1.** Mean  $\pm$  s.e. trajectory deviations at 60ms

Perturbation	Assistive	Resistive
‘pre’	5.05° $\pm$ 0.15	-4.17 $\pm$ 0.33
‘early’	4.40 $\pm$ 0.16	-4.39 $\pm$ 0.22
‘mid’	6.23 $\pm$ 0.29	-4.75 $\pm$ 0.33
‘late’	4.42 $\pm$ 0.36	-3.77 $\pm$ 0.38
‘post’	1.67 $\pm$ 0.39*	-4.19 $\pm$ 0.42

Of particular interest are the responses of perturbations applied during movement. Individually taken, they are also of ramp type, albeit with varying slopes. This shape is not a trivial result - without subtraction of intended trajectory they are curved, as Figure 2 clearly shows. This can simply be interpreted as the lack of ‘intended’ movement predictability- we can see that the standard deviation of the spread of the responses (10x standard error shown in Table 1) is comparable to the predictability inferred from the unperturbed data (Figure 1). In other words, there is probably not varying response to the same pulse as much as subtraction of a varying prediction. The prediction error tends to overshoot as much as undershoot, so it probably has little net effect on the mean response. In fact the deviation at 60ms is not appreciably different (t-test, .01 significance, about 10 trials each sample) in the perturbations applied during movement as those before movement. The only condition which shows a clear difference in response is in the ‘post’ movement perturbation and to pulses which push the same direction as the movement (there is a spread in response because the arm is not always at rest, only on average). Otherwise the perturbations show the same type of ‘ramp’ response of the same magnitude.

What about stiffness (K) and damping (B)? In this paper we do not show the results of such fits (K-B-I), as they are of not much use and replete with technical difficulties. Suffice it to say that adding K and B parameters to the ‘model’ does not improve the fit appreciably. In fact, the ‘error’ curve of such an optimization is littered with local minima, and adding K and B leads to nonsensical results, despite near perfect fits. Clearly, in the case of the ‘post’ movement perturbation we mentioned, some stiffness, damping, or combination thereof ought to be considered. A change in inertia is not possible - either the stiffness, damping or both become appreciable. The type of stimulus in this study (a pulse) cannot really distinguish between them. In fact, the central problem is that, compared to inertia, the elastic (K) and viscous (B) are so insignificant that, if they remained at the level at which they were when the perturbation occurred (generally not possible), their effect on the position record, where the trace would return to the unperturbed trajectory is only to be clearly seen at about 200ms and above. Future studies must optimize the perturbation shape to focus on the physiological parameters of interest.



**Figure 3.** Perturbation Of Elbow Motion Results  
Plotted are the typical trajectory profile (with 60 ms of average deviation superimposed), the deviations from ‘intended’ trajectory for each trial, and the torque pulses applied at each trial. The time axis is

common to all plots (notice 10 perturbation types), and position scaling is same for upper 2 plots.

### 3 Discussion

To most familiar with the literature on human motor control, the results outlined herein, though simple, must be somewhat puzzling. What happened to the spring-like properties of muscle, to the elasticity which was to be the trademark of the arm's design? A careful look at the literature suggests all is not clear. We must not focus on isolated muscle preparations - generally the naturally coupled inertia has been already removed. We must also not be swayed by certain types of perturbation protocols: positional (inertia is accounted for by limiting acceleration) and step force (in which case the deviations get large and elastic response becomes significant, not to mention reflex responses). Furthermore, some studies employ non-transient, frequent perturbations which may alter behavior (co-contraction, elevated reflex excitability). Beginning with [3] where pseudorandom pulse trains were applied to elbow movement, similarly to the current experiment except with many more perturbations, the moving arm was found to be very compliant, more so than during posture even, with a natural frequency of about 3Hz. This finding is quite consistent with this study - a 3 Hz natural frequency K-B-I response would depend on the most part on I in the first 60 ms – see last paragraph of Results. In fact, the nature of the perturbation (continuous train of pulses), for the reasons outlined above, would tend to be an overestimate of stiffness. The results of this pulse train study as well as those of other isolated pulse studies [2], show the mechanical state of muscle to be very compliant and the time required for a return to the nominal trajectory to be very long (comparable to the length of movement). What about spinal reflexes?

There is an upper limit to the gain of reflexes, due to their instability-causing delay [4]. There is even some evidence that the higher frequency gain of the reflex during movement is higher than it should be (wrong half of the Nyquist plane) [5], while at its maximum (towards the end of movement) it was still less than the intrinsic stiffness, which we already know to be quite low. The untold part of the story, as far as the current study is concerned, is that extending the time window of interest from 60 ms to 120 ms (the latter would include reflex-mediated changes in position, base on conduction delay estimates) does not change the picture qualitatively. A quantitative analysis is more complicated, since

time variation of mechanical parameters and some non-linearities make the estimation of reflex-dependent response contribution quite difficult. Future studies will address this question. Overall, the time course of adjustment to a small transient perturbation takes a comparable amount of time to the duration of the intended movement, which is very slow compared to spinal reflex delay (hundreds of milliseconds vs. tens). Pure inertia models fit well up to 100ms or so.

There is a class of studies - unexpected transient perturbations which occur during 'natural' point-to-point movement which are quite consistent with this physiological picture, as in Sanes [6] in which an unexpected viscosity was presented to a neuropathy patient (no reflex without vision), which resulted in a large undershoot in the endpoint of the intended wrist movement - this points to considerable compliance. There is also unexpected Coriolis force insertions (which is velocity dependent), and which shift endpoints of a planar pointing movement [7]. A similar study [8] applied single pulses during such a movement, with similar results, except for eliminating supra-spinal voluntary reactions from the list of reasons for the observed endpoint shift (all of these studies block vision otherwise the subject would eventually reach the target). So small forces can change the underlying movement, along with its endpoint, significantly, due to a compliant plant - however, vision or some other feedback can, via cerebral control, compensate for disturbances.

Finally, we noticed that at the end of the movement there is some increase of impedance - we did not decide whether this added mechanical disturbance rejection ability was predominantly stiffness or damping. The literature is equivocal - both stiffness and damping increase at the end of a movement. The shape of movements near the endpoint (overshoot and damped oscillation) might point to both being significant. The oscillations might be due to activation 'pulses' due to feedback control of endpoint [9] rather than inherent elasticity, while damping is near certain [10]. A picture of the human limb as a large inertial load, controllable by force generators (thrusters) and a programmable damper (brake) is not unimaginable. It may well be that the elastic properties of muscle are significant during walking and standing, while reflexes modify impedance in catching, falling, etc. - but this is not necessarily so for the majority of manipulation tasks. The spinal cord may still be counted upon to coordinate motor units, to prevent injury etc., as it does for all mammals – dexterous manual control might not be among its responsibilities.

## 4 Conclusion

Preliminary evidence shows that the intrinsic mechanics of muscle, and to some extent the segmental reflexes, are not significant contributors to disturbance rejection in the moving arm. Mass, a.k.a inertia as well as long latency feedback loops seem to account for disturbance rejection at rest and while moving. The possible exception of this case may be the end of motion and immediately thereafter, which is not surprising since the limb is in the process of braking, a process which long latency feedback cannot efficiently accomplish.

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