Sensorimotor Learning in Virtual Environments

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1 Introduction & Aims

Movement is nothing but the quality of our being.

— Sunryu Suzuki, *Zen Mind, Beginner's Mind*

Hans Moravec's eponymous paradox states that it is easier to generate artificially intelligent performance on tasks we think of as intellectually challenging, such as chess, than to provide a machine with faculties we take for granted, such as movement. For example, Moravec's Paradox encourages us to not look past the stunningly complex computations generated by the human motor apparatus. Following Moravec's suggestion, this work focuses on the human motor system, the most advanced control apparatus in the known universe.

A recent review corroborates this perspective and provides a clear call to action:

> The processes by which biological control solutions spanning large and continuous state spaces are constructed remain relatively unexplored. Future investigations may need to embed rich dynamical interactions between object dynamics and task goals in novel and complex movements.[1]

Over the last few decades, there has been considerable amount of work done to untangle the abilities of the motor system to flexibly control the body including through optimal control theory[2], reinforcement learning in continuous action space[3], and detailed physiological studies[4]. However, as the quote above suggests, a holistic understanding of the computations underlying the generation of skilled movement remains an open problem. The aim of this thesis is to progress our understanding of skilled movement by studying the solutions produced by human subjects to motor tasks in dynamically rich, yet controlled, virtual environments. Our goal is to reverse-engineer the ability to acquire and perform novel motor skills. First we define what we mean by the terms *skill*, and *task*.

Humans produce a great variety of movements every day, often without conscious thought. For example, movements like bringing a cup of coffee to our lips for a sip are generally out of reach for state-of-the-art robotic systems. We claim that this "motor gap" between biological and artificial motor systems is due to a lack of *dexterity* in the latter. Soviet neuroscientist Nikolai Bernstein defined dexterity as the ability to "find a motor solution in any situation and in any condition."[5] The crux of this definition is the flexibility of such solutions. This flexibility, or robustness[1 6], is the ability to optimize internal parameters in response to external perturbations and adapt to new information to achieve the goals of an ongoing plan.

While a robot may be able to move a cup of coffee to a precise location in space, its solution is often found to be brittle in a new context, or unable to generalize to the movement of new objects. We define a skill as a behavior that involves dexterity in Bernstein's sense. The use of a tool such as a screwdriver is an example of a motor skill. We define a task as the production of skilled movement in a particular context. Driving a screw in a particular posture using a particular screwdriver is an example of a task. These concepts will be further formalized in later chapters.

[1]Kitano defines robustness as "the maintenance of specific functionalities of the system against perturbations, and it often requires the system to change its mode of operation in a flexible way." He claims that robustness requires control, alternative mechanisms, modularity and decoupling between high and low level variability.

Human movement is ultimately the result of the activation and contraction of muscle fibers, and movements lie on a spectrum between reflexive and volitional. The supramuscular circuitry which determines the degree of volition we ascribe to movement, where volitional movement relies on supraspinal (though not necessarily conscious) processes. The human hand is a unique evolutionary invention that underlies our ability to perform various skills in a range of tasks– movements that are decidedly volitional[2]. The hand is the pinnacle of dexterity and, as such, it is a fruitful testbed for studying the computations and circuitry that drive dexterous movement. A detailed physiological review of the hand and it's relation to skilled movement is described in Section 2.

We are more interested in the leveraging the hand as a readout of flexible motor behavior than we are in the kinematics of hand movement itself. For this reason, we chose to develop an experimental setup that is capable of recording directly from muscle activations. We achieve this through surface electromyography recordings taken from the forearms controlling subjects' dominant hands. This allows us to track the sequential selection of muscle these contractions during skill acquisition and subsequent goal-oriented muscle activations. As we are interested in subjects' abilities to acquire new skills, we design tasks that require subjects to use available, but uncommon, motor activations. We then track the selection and execution of these activation during virtual tasks. The details of how this is achieved are described in **??**.

how are value computations connected to action and policy selection how are feedback controllers adapted to motor errors, new environments, how are they learned as well as combined?

Using data from our experimental setup, we hope to gain an understanding of how the structure of muscle activation variability in evolves during skill acquisition and how the motor system constructs skilled movement through the composition of component muscle coactivations. We believe that to make progress on these two lines of enquiry we should work to reconcile the language of the experimental sensorimotor control and learning community with the language of the control theory and reinforcement learning community, as each of these communities shares a common goal of understanding the computation underlying the production of skilled movement. Here we develop several models in this direction, as described in **??**.

2 Physiology of the Motor System

> *Even a simple movement is a global body event.*
>
> — Bizzi & Ajemian, *2020*

As our hope is to make progress engineering naturalistic artificial movement, it will be beneficial to review what is known about the biological movement system. Beginning with the architecture of the motor system and it's relation to dexterity will provide a scaffold on which we can hang our experimental and theoretical investigations. Specifically, we can use results from prior physiological investigations to ground our perspective on the computations relevant to skilled hand movements. The dexterous solutions produced by the human motor system rely on a incredibly complex architecture. Specifically, we believe that this system's spectrum of modularity paired with its redundancy in the space of feedback controllers are crucial for its dexterity.

2.1 Motor Units to Muscles

Muscles are composed of fibers which contract due to chemical gradients produced at the neuromuscular junction by action potentials emanating from alpha-motoneurons (AMN) in the ventral horn of the spinal cord. The quantum of motor output is the motor unit (MU), which is defined as a single motoneuron axon and the set of junctions its axon branches form with one or more muscle fibers. The innervation ratio of a particular muscle unit is the number of junctions it innervates. The number of MUs and their innervation ratios each range from tens to thousands per muscle.

[2]It could be argued that the hand is in fact a crucial aspect of humanness. It is thought that the human cerebellar and neocortices evolved reciprocally to expand and support the computational burden of increasingly complex motor tasks such as tool-making and language production. REF?

The motor unit provides the motor system with spatial redundancy at the muscle level: multiple muscle fibers contract due to a single AMN spike, and multiple AMNs may overlap in their innervations. The forces produced by motor units span several orders of magnitude, though most units produce very small forces. Here we find temporal redundancy: in order to produce movements motor units combine to generate a range of forces[7]. Since the innervation ratios of muscles in the forearm and hand are relatively small, the logarithmic recruitment and redundancy of motor units enables the hand to produce movements with very fine spatiotemporal resolution. Paradoxically, however, the well-known signal-dependent noise in models of motor output is higher for hand muscles than for more proximal muscles, likely due to small numbers of motor units compare to larger muscles[7,8].

Muscle fibers are contained within muscle compartments, and each muscle may have one or more compartments. The fingers of the hand are extended by the extensor digitorum (ED) which contains four compartments, one for each of the tendons the muscle produces. Each tendon connects to the three joints of each digit. The fingers are flexed by two muscles, the flexor digitorum superficialis (FDS) and the flexor digitorum profundus (FDP). Like the ED, these muscles produce four tendons, one to each finger from each of their four compartments. Thus, one must coactivate these agonist and antagonist muscles in order to move only a single finger in isolation[7].

In total, the human hand, thumb, and forearm system contains more than 30 muscles and at least 20 degrees of freedom are theoretically able to be actuated. Nineteen of these muscles are intrinsic, having their origin and insertion points within the hand itself[9]. Due to biomechanical coupling, the effective degrees of freedom is less 20, though an exact count is difficult due to the complexity of the anatomical structure of the hand's tendon network. One study showed that tendons of the fingers are arranged in such a way as to perform a kind of logical computation which expands the mechanical capabilities of the appendage by sharing force across its tendons[10].

Studies have attempted to quantify the number of effective degrees of freedom of the hand with various methods. This has primarily been taken to mean the number of linear features which contain a desired level of the original signal variance, where the signal is the joint angles of the hand engaged in various behaviors[11,12]. These methods have resulted in various interpretations between 2 and 8 fundamental hand features. Overall, however, there is agreement in the literally that the effective number of degrees of freedom is markedly less than the theoretical maximum number. Whether this is due to hardwired upstream constraints or evidence of a motor control strategy remains debated.

From our brief tour of the anatomy, we have seen how the motor system is highly distributed. We believe this structure exists in order to facilitate the adaptation and learning of new movements in a range of contexts. We don't take the fact that there are a small number of linear features of joint angles and velocities across behaviors to mean that humans are not capable of learning a wide range of motor outputs given the requisite feedback and training. The production of this variety lies in the motor system's ability to wield muscle coactivations, hardwired or not, as well as its ability to individuate movements in specific instances which require it.

For example, skilled piano performers have been found to exhibit a higher degree of independent movement among the fingers compared to control participants. Control groups displayed a hierarchical, presumably low-dimensional, organization of finger movement patterns, while pianists showed distinct but individuated movement patterns[13] These results are imply that with skilled practice humans can produce finer and more independent movements of the fingers, and construct bespoke coactivations to solve specific goals. Similarly, studies have found that coherence between the index finger and thumb is greater on the dominant hand. Of course, this could imply a development lateralization, but use-dependent plasticity due to greater precision grip behavior of the dominant hand is a viable explanation[7].

Overall, we are interested in investigating. . .

2.2 The Redundancy Problem

Just as many fibers may be innervated by a single AMN, many supraspinal neurons act on single AMNs, either directly through corticomotoneuronal connections or through a variety of spinal interneuron circuits.

The spinal cord's neuronal organization is based on relatively rigid muscular synergies, and a mechanism to fractionate this is of particular importance for the muscles of the hands and digits which may need to be employed in a variety of flexible associations during voluntary movements. Corticomotoneuronal connections offers the primate motor system a method of such fractionating.

Rathelot and Strick have found subdivisions of primary motor cortex

2.2.1 Synergies

> We have some idea as to the intricate design of the puppet and the puppet strings, but we lack insight into the mind of the puppeteer. (Bizzi and Ajemian 2020)

A considerable amount of research has focused on the existence of synergies as a simplifying structure in the motor system. While we do not deny the existence of synergistic muscle coactivation and constraints existent in the architecture of the hand and its control system, we believe that the concept of synergies is often attributed to the process of motor control as opposed to a straightforward structural constraint.

In one study, "synergies" changed over the course of the experiment as subjects adapted to the novel perturbation. This is very promising.

Our definition of synergy is simply a sequence of coordinated muscle activations. It has been shown that this arises spontaneously through an optimal feeback control system which contains redundancy.

2.2.2 Motor Maps

A traditional view of the neuronal machinery of movement control is that activity at a site in motor cortex propagates down a fixed pathway through the spinal cord, activating a set of muscles. Based on our stimulation results, however, the underlying mechanism seems to be less of a simple feed-forward pathway and more of a network. The effect of the network is to create a specific class of mapping from the cortex to the muscles, a mapping that can change continuously on the basis of feedback about the state of the periphery. If the periphery is relatively still, the mapping from cortex to muscles appears fixed and resembles the traditional view. But once the state of the periphery is allowed to vary as in natural movement, the mapping from cortex to muscles becomes somewhat fluid in a manner that facilitates complex movement control. (Graziano 2010)

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