AN ELECTRONIC SIMULATION OF THE HUMAN HANDWRITING SYSTEM

by

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ABSTRACT

A simple model of an antagonistic muscle system is developed based on several published physiological observations and is found to be a linear first order approximation to mammalian muscle. The model response is compared to that of the human hand in various tests including impulse response, frequency response, step response and the effect of sliding friction. The results of these tests are used to select the mechanical parameters of the proposed model. The final model simulates many of the observed responses of the human hand when executing motions similar to handwriting. A control scheme is proposed for use with the mechanical model and an electronic simulation of the whole system is conducted using a digital and an analogue computer. Good matches of displacement and acceleration waveforms from human handwriting were produced by the simulation. A discussion of some physiological evidence supporting the proposed control scheme is given.
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1. INTRODUCTION

Several questions of an engineering nature come to mind when studying the neuro-muscular control of human handwriting. Is there closed loop control or does the system lack feedback? Does the brain exert a continuous control on the hand or is the control done at discrete times according to a programmed schedule? It can easily be proved that visual feedback is not necessary for legible handwriting. Sensory feedback from the limbs is also not essential for rapid accurate movements. As early as 1917 a paper by Lashley (12) found that a person could accurately control movements of the knee without sensory feedback. Although the subject was not aware of the knee's exact position due to a spinal injury, rapid movements could be made accurately. These rapid movements were the most accurate, but the time delay of nerve propagation made position feedback impossible for such rapid movements. This led to Lashley's proposal that an effector mechanism could be preset to discharge at a fixed intensity for a fixed duration without any sensory control.

More directly related to handwriting was another paper by Denier van der Gon and Thuring (6). They studied the handwriting process and found that:

1. For fast handwriting the principle of position feedback does not hold;

2. There is physiological evidence for resolving the writing movements into two more or less perpendicular directions;

3. The shape of a word is determined by the timing of the muscle contractions, and not by the magnitude of the forces used;

4. A general change of size is coupled to a
proportional change in the magnitude of
the forces.\textsuperscript{1}

Denier van der Gon and his colleagues (5) also built an electronic
simulator in which a two-valued trapezoidal signal was used to represent a
muscle force. By using two similar systems to represent the horizontal and
vertical directions they were able to obtain good copies of handwriting after
integrating the forces twice to yield a displacement signal. They achieved
control over the writing by adjusting the timing of the zero crossing of the
force waveforms.

MacDonald (13), using improved measurement instrumentation, found
that the acceleration signal from human handwriting can approximately be resolved
into a multilevel trapezoidal time function. An electronic simulator using
a multilevel trapezoidal force could duplicate handwriting very well. The
mechanical analogue used represented a point mass driven by the trapezoidal
force. Since there was no feedback inherent in this model, it was very sensitive
to slight disturbances. Because there was negligible damping, a small perturbation
in the force waveform at the beginning of a word grossly distorted the whole
word.

Both Lashley and Denier van der Gon concluded that position feedback
was not used. MacDonald however concluded that some form of feedback must be
present since small disturbances have little effect on handwriting. MacDonald
(13) proposed the following control scheme (shown in figure la) to fit the
experimental data.

A force generator was given the two inputs corresponding to the slope
and final value of a segment of a trapezoidal waveform. The force generator
output was fed to an analogue system consisting of two integrators. A comparator
sensed the output of the analogue system and a preset position. When the

\textsuperscript{1} J.J. Denier van der Gon and J.Ph. Thuring, "The Guiding of Human Handwriting
analogue system output reached the preset value the comparator sent a signal to the command generator causing three new values for final value, slope and position to be issued to the force generator. The advantages of this model are two-fold. It retains the advantages of position feedback while allowing a time delay between the command generator and the rest of the system. Figure 1b illustrates the time delay feature. If a new set of inputs is required at position A, the preset displacement can be set at B so that after a time delay d, the new set of values come into effect at point A. This model also provides the discrete control of force indicated by the previous research.

\[
md^2 \frac{x}{dt^2} = f(t)
\]

**FIGURE 1a POSITION FEEDBACK MODEL**

**FIGURE 1b TIME DELAY FEATURE**
Sensory organs, known as muscle spindles, are connected in parallel with most muscles. These provide length information from the muscle and are thought to form the sensors of the stretch reflex loop. The stretch reflex is the natural tendency of a muscle to oppose unexpected muscle stretching. The muscle spindles also provide a position signal to the higher centres of the brain.

In the human system the muscle spindle could provide the position information required for the proposed model. The force generator would be analogous to the muscle and the command generator to higher centres of the central nervous system (CNS) in the spine and brain.

The discrete nature of handwriting control is apparent from the segmented nature of the acceleration of the hand during writing. This is illustrated in figure 2a where horizontal and vertical position, velocity and acceleration of the pen point are recorded as functions of time. Figure 2b is an X-Y plot of the position signal. The discovery of the segmented acceleration implied that any model of the handwriting system should be composed of a series of segments with a minimum of control between the beginning and end of any segment. The instrumentation used to obtain figure 2a is described in Appendix I. The basic component of the measurement system is an electrolytic tank.

The object of the present work was to develop a simple electronic model of the handwriting system. It was hoped that such a model might provide a better understanding of the way a person controls and executes rapid skilled movements such as handwriting.

An electronic simulator controlled by a digital computer was built to test the model proposed by MacDonald. Details of the simulator are given in Appendix II. The simulation proved to be difficult to control in the form originally proposed.
FIGURE 2a. CHART RECORDINGS OF HANDWRITING

FIGURE 2b. X-Y PLOT OF 2a
A mechanical model consisting of a point mass with viscous and elastic damping was added and the control scheme was modified slightly to allow easier selection of the preset displacement. With these alterations the simulator could produce good copies of handwriting.

Unfortunately the simulator had a high sensitivity to small changes in initial position. A similar sensitivity in the human system is unlikely since a person is capable of writing at almost any point within the range of the fingers. The simulator also had difficulty producing acceleration waveforms to match those of human writing even though the displacement output of the simulator was a good copy of the human writing. Several other comparisons between the model and human writing revealed more discrepancies in the model's performance. A system which can match an arbitrary sample of handwriting is not necessarily analogous to the human system. An improved mechanical model appeared to be necessary since a point mass driven by two perpendicular forces is not a good representation of the human hand.

2. DEVELOPMENT OF A MECHANICAL MODEL OF MUSCLE

There are several things to be considered when attempting to model a muscle system. Since muscle is not completely rigid, some elasticity must be taken into account. Tendons also have elasticity, an important fact in the case of the human hand, where most of the muscles are located in the forearm and are connected to the fingers and wrist by long tendons. Many studies have been made of the ability of muscle to shorten against various loads when maximally (tetanically) stimulated (1,3,11,18,23,24). It has been found that the velocity of shortening is limited, and depends on muscle length and external load. Therefore some form of viscous damping must be included in the model.

As with most physical systems, the elasticity and damping are not
linear, but depend on muscle length, external force, velocity of shortening and time. Some form of angular to linear conversion is required since most muscles essentially rotate a bone about some fixed point by shortening their length. Such a conversion has been neglected in this work, since it does not effect the results of the model to any great extent. Since muscles can only exert a force while contracting, in order to achieve control of position they are arranged in antagonistic pairs. A simplified picture of a typical antagonistic muscle pair is shown in figure 3.

![Antagonistic Muscle System](image)

**FIGURE 3 ANTAGONISTIC MUSCLE SYSTEM**

The following model was based on the above considerations and on models used in other papers (3,11,16,23,24). However, the exact arrangement of the mechanical components was somewhat intuitive. The model is shown in figure 4. The various mechanical components are actually distributed parameters in the human system, but they have been lumped for ease of modelling. Non-linearities have been neglected since this is only an approximate model and
data on the nonlinearities are not available. The angular to linear conversion has been neglected as previously mentioned.

\[ k_m = \text{muscle elasticity} \]
\[ k_t = \text{tendon elasticity} \]
\[ k_v = \text{viscous damping} \]
\[ CE = \text{contractile element} \]

**FIGURE 4 PROPOSED MECHANICAL MODEL**

It is assumed that the contractile element represents an idealized muscle which will shorten when stimulated. If the antagonistic muscle is stimulated the unstimulated muscle will completely relax and offer no resistance. In the human case this is approximately true. One difference between this and other models is that the contractile element is a controlled length, not a controlled force. The variable to be controlled is assumed to be the position...
of the mass. A control signal from the brain tells the appropriate contractile element to shorten to a length $L$. In figure 4 if $\frac{dL}{dt} \leq 0$ contractile element 1 is controlled and contractile element 2 is relaxed. If $\frac{dL}{dt} > 0$ the situation is reversed. The final position of the mass will be equal to the length $L$. Since it is not possible for a physical element to shorten instantaneously the contractile element will shorten at a particular rate until the correct value is reached.

In this scheme it is assumed that the CNS issues a slope or velocity of movement and a final value for the desired position of the mass. Depending on the sign of the derivative of the desired position the CNS also decides which muscle must shorten. Expressed mathematically, the whole system becomes three coupled differential equations with two constraints.

$$\frac{dw}{dt} + \frac{k_m + k_t}{k_v} v = \frac{k_m}{k_v} z + \frac{k_t}{k_v} x$$

$L$ represents the desired value of $x$

$$\frac{d^2 x}{dt^2} + \frac{2k_t}{m} x = \frac{k_t}{m} (w + v)$$

if $\frac{dL}{dt} \leq 0$ $z = w$ CE #1 is pulling

$$\frac{dv}{dt} + \frac{k_m + k_t}{k_v} v = \frac{k_m}{k_v} y + \frac{k_t}{k_v} x$$

if $\frac{dL}{dt} > 0$ $z = L$ CE #2 is pulling

It is assumed that the springs have zero initial length, and there is no residual tension in the system. The residual tension would correspond to muscle tone. These effects could have been included but would have only added constants to the equations.

Due to the difficulties previously mentioned, there is little data available on the mechanical parameters of the human muscle. There is, however, extensive data available for animal muscle (3,11,17,18). A paper by Bahler in the IEEE Transactions on Bio Medical Engineering (3) offers a good analysis of mammalian skeletal muscle; specifically, the right gracilis anticus muscle
of the rat. The muscle was removed from the rat and attached to a mechanical apparatus. It was bathed in a solution to prolong its response to electrical stimuli. The force, velocity and position produced by the muscle were measured. The mechanical apparatus could also be used to stretch the muscle in a known way. The results of the paper can be summarized by a quotation from the paper's abstract:

"...for lengths less than 120 percent of rest length, mammalian skeletal muscle can be modeled as a non-linear force generator, a function of length and time, bridged by a nonlinear viscous-like element, a function of time, length and velocity, in series with a non-linear elastic element, a function of length."2

Figure 5 is taken from Bahler's paper. It represents the dynamic length-force-velocity phase space of the contractile element during a tetanic contraction. (Bahler's "contractile element" includes the force generator and the viscous element but not the series elastic element). The length and force have been normalized to the rest length and maximum tetanic tension. These experiments were for tetanic stimulation only and it must be assumed that the muscle behaves linearly for lesser amounts of stimulation.

In order to compare the model of figure 4 with Bahler's results it must be reduced to the form shown in figure 6a since Bahler was working with only one isolated muscle. The differential equation for this configuration is shown below.

\[
\frac{dw}{dt} + \frac{k_m}{k_v} w = \frac{F}{k_v}
\]

The equation is plotted in figure 6b in the same phase space as Bahler used.

From figure 6b it can be seen that Bahler's results and the model agree to some extent. It is apparent that the model is a linear first order approximation to an actual muscle. To produce the results Bahler observed would require the introduction of the nonlinearities previously mentioned thus complicating the model considerably. The wisdom of using a more accurate model may be questioned when it is remembered that the model will be used to simulate either the vertical or horizontal component of actual handwriting. There are more than fifty muscles in the hand and forearm and to produce an accurate model of these would be extremely difficult considering the many parameters involved. Even if a reasonable model could be found it would be
necessary to develop a control philosophy involving all these muscles working synergistically.

It was decided to test this simple linear first order model in situations similar to those which could be produced for actual handwriting in the electrolytic tank. Although the model does not simulate all of the characteristics of antagonistic muscles, it represents a considerable improvement over the point mass model used by Denier van der Gon (5) and MacDonald (13).

**FIGURE 6a** ISOLATED MUSCLE MODEL

**FIGURE 6b** LENGTH-FORCE-VELOCITY PHASE SPACE FOR MUSCLE MODEL
3. **ANALOGUE SIMULATION AND TESTING OF MODEL**

The differential equations for the model were simulated on a EAI 231-R PACE analogue computer. Comparators and relays were used to switch the control input taking into account the polarity of the input's derivative. There were four mechanical parameters \( k_t, k_v, k_m \) and \( m \) to be determined and it was also convenient to time scale the problem so that the model was analogous to the human system. The parameters were selected on an iterative basis using the response of the model to the tests discussed below.

a) Comparison with the impulse response of human muscle

It is difficult to make any mechanical measurements on a human subject since there can be no direct control over the inputs to the human system. Any voluntary movement must come from the CNS which may override or modify a voluntary muscle command. Resolving any motion into particular actions by particular muscles is difficult because of the large number of muscles in the hand and forearm. Denier van der Gon (6) gives some physiological basis for resolving all motions into movements in two perpendicular directions and since previous work had resolved all motions into their projections on two perpendicular axis this strategy was continued.

It would be convenient, however, to get some indication of the mechanical properties of a typical hand or forearm muscle. A common physiological technique is to simulate small numbers of muscle fibres by means of electrical pulses fed to the muscle or nerves through needle electrodes. Such work is usually restricted to animals, or is carried out on humans under very closely controlled conditions. It is possible, however, to stimulate muscles by using external skin electrodes, although the control of individual muscles is not as precise as with needle electrodes.

Some research into the requirements of external stimulation led to
the design and construction of a constant current stimulator described in Appendix III. Small (3/8 inch diameter) gold plated electrodes were attached to the skin with adhesive tape after being covered with a jelly containing sodium chloride to decrease skin resistance. The location of the electrodes controlled which muscle was stimulated. It was hoped that a single pulse of current could be used to obtain a mechanical response analogous to the impulse response of an electrical system.

The electrodes were attached to the forearm or hand. One muscle "twitch" which was convenient used the positive electrode about two inches from the elbow on the underside of the forearm. The negative electrode was positioned on the underside of the wrist so that the thumb twitched inwards toward the palm. With the negative electrode in slightly different locations, other fingers could be made to execute a similar motion, although it was often difficult to stimulate only one finger. The current was usually between 1 and 10 milliamperes with a pulse width of about 5 milliseconds. It is interesting to note that the correct polarity is required. If the polarity was reversed a considerable increase in stimulating current was required to obtain the same muscle movement.

When a satisfactory twitch was obtained, permanent records were made by taping a stiff wire to the moving finger. The wire was put into the water of the electrolytic tank and the hand supported by the remaining fingers. The hand was oriented so that the twitch was along either the vertical or horizontal directions. A Polaroid picture of the displacement, velocity and acceleration of the finger during the twitch was made using an oscilloscope. A typical picture is shown in figure 7a. The oscilloscope was triggered on the leading edge of a 5 milliamper, 3 millisecond pulse. Ten twitches of the thumb are superimposed in this example. The slight displacement undershoot
FIGURE 7a HUMAN TWITCH RESPONSE

FIGURE 7b SIMULATOR RESPONSE TO AN IMPULSE INPUT
at the end of the twitch is not completely shown because of the choice of
time scale.

To compare the model with the twitch responses of human muscles,
a short trapezoidal pulse was fed to the simulator. This pulse was approxi­
mately 25 milliseconds long. With the parameters of the model optimized the
shape of the displacement, velocity and acceleration waveforms agreed well
with the responses observed from human muscles. Some differences in the time
scale could be expected since the twitch responses from the tank were either
the thumb or single fingers while the model had been adjusted to match the
response of the whole hand. Figure 7b shows the simulator response to a
single trapezoidal pulse.

b) Response to sliding friction disturbances

By subjecting both the model and human writing to some controlled
disturbance a convincing test of the model's validity can be made. Sliding
friction is a good example of such a disturbance and was first used by Denier
van der Gon and his co-workers (6) in their research. They used an iron rod
wrapped with many turns of wire to form an electromagnet. Writing was done
on an iron plate and when the coil was energized, extra sliding friction was
added to the human system. Unfortunately, in the case of the present
equipment, the electrolytic tank's teflon insulation limited the magnetic
attraction and there was not enough friction to disturb the writing.

To overcome this problem a large electromagnet and a plastic tank
were constructed as described in Appendix I. Writing was carried out with an
iron rod. Since the size of the magnet was no longer limited, it was possible
to get sufficient attraction. There was a 1/16 inch acrylic sheet over the
magnet which acted as the writing surface and prevented the magnet from
upsetting the electric field patterns in the electrolytic tank.
When the magnet was used it was difficult to get reproducible results with ordinary handwriting. If the magnet was energized at slightly different times during different trials using the same word, the results were not consistent. Occasionally the iron "pencil" would stall completely when the magnet was turned on. Simulating sliding friction in two dimensions on the computer model is also difficult. The friction force must be directed in the opposite direction to the velocity so that analogue sine and cosine generators are required to determine the appropriate correction to the input forces.

To overcome these problems the magnet tests were restricted to experiments in one dimension. The effect of the added friction was consistent for each trial if unidirectional strokes were used. It was found that the amplitude of the strokes was reduced almost immediately after the magnet came on but the timing of the strokes remained remarkably constant even over intervals as short as 100 to 200 milliseconds. This measurement was made by finding the time between zero crossings immediately before and after the friction was applied. Denier van der Gon (6) had observed this decrease in amplitude and had said that the timing of handwriting appeared to remain constant but his instrumentation was not extensive and he had no way of checking the timing of the waveforms over such short intervals.

It would appear that there is no adaption by the CNS to the increased friction caused by the magnet. Any such adaption would have been delayed by the nerve propagation time which is greater than 100 milliseconds. Because the frequency of the strokes remained constant over both short (100 milliseconds) and long periods of friction (more than 1 second) there appears to be no unconscious CNS "interference" with the timing of the strokes.

Sliding friction disturbance tests were responsible for one of the
major contradictions between the model proposed by MacDonald (13) and human writing. That model responded to sliding friction by decreasing the amplitude of the strokes and by increasing the period of the strokes. This is a direct contradiction to the observed response of human writing, which maintained the frequency of the strokes.

Sliding friction was simulated on the improved mechanical model by adding a constant force to the moving mass. The polarity of the friction force was opposite to the velocity's polarity. Figure 8a shows the model's response to a sudden increase in sliding friction and figure 8b is a recording from the electrolytic tank for vertical strokes of approximately the same frequency as the model. It should be noted that static friction is also present in the tank. This is believed to account for the impulse-like shape of the acceleration from the tank. Static friction was not simulated in the model. There is some sliding friction between the iron "pencil" and the tank bottom before the magnet is energized. A small sliding friction force was added to the simulator to duplicate this effect.

c) Frequency and step response comparison

From the experiments done in the electrolytic tank it was known that for certain frequencies, the acceleration of the hand while executing unidirectional strokes was roughly trapezoidal. At lower frequencies the acceleration tended toward an impulse-like shape and at higher frequencies it tended to become triangular. At the transition from trapezoidal to triangular there was an increase in the amplitude of the acceleration. Previous mechanical models had failed to show all three types of response.

The model was driven with a trapezoidal input for the frequency response tests with unidirectional strokes. This seemed logical since the contractile element of the model could not be expected to shorten instantaneously. Figure 9 shows the results of the final model and results from the tank. The dis-
**FIGURE 8a** MODEL RESPONSE TO SLIDING FRICTION

**FIGURE 8b** HUMAN RESPONSE TO SLIDING FRICTION
FIGURE 9 COMPARISON OF MODEL AND HUMAN RESPONSE
placement and acceleration waveforms show good agreement over the full frequency range.

Another test used to compare the model with the human system involved a voluntary rapid wrist movement from one position to another. The object was to simulate a step response. It was found that the human overshoot was about 10 to 20 percent. The final model overshoot was similar to the human response.

The four tests described above were used to evaluate the values of the mechanical elements of the model. They were adjusted to give the best agreement with human responses to the same stimuli. The values for the mechanical elements were chosen to be;

\[
\begin{align*}
    k_m &= 1.0 \\
    k_t &= 1.0 \\
    k_v &= 0.5 \\
    m &= 1.0
\end{align*}
\]

The analogue simulation time constant was chosen to be 30 milliseconds. The proposed model performed well in the comparisons with human response and had some physiological credibility since it was in agreement with Bahler's results. The model was now considered sufficiently accurate for use with digital computer control in an attempt to simulate actual handwriting.

4. RESULTS OF ELECTRONIC HANDWRITING SIMULATION

The system used for controlling the mechanical model was similar to that of MacDonald (13) and Denier van der Gon (5) in that the time each segment was in effect was preset. The mechanical model required a trapezoidal signal (L) corresponding to the desired position of the mass. Three parameters were used to specify each segment; a slope or velocity of shortening term, a final value for the position and a term proportional to the length of time the segment was in effect. By using a preset time for each segment the model agreed well with the human response in the sliding friction tests since the
human response to sliding friction was to maintain the frequency of the writing. A description of the electronic simulator is given in Appendix II.

After some experience was gained with the new system, it was observed that the slope of the control signal \( L \) was now much more important than in previous models. The control signals to the analogue computer tended to be almost triangular at times, implying that with this model the muscle's velocity of shortening is very important. The horizontal and vertical displacements as functions of time were matched to samples of handwriting from the tank. When the horizontal and vertical accelerations of the model were compared to those from the tank, some general agreement in shape was found. This was contrary to previous models where the acceleration waveforms never matched the results from the tank even if the displacements were matched very closely.

Figure 10a shows the results of matching the displacements as time functions. The horizontal and vertical accelerations are also shown compared to the tank results. (The tank results are the darker traces). Figure 10b is an X-Y plot of the simulator output compared to the original handwriting and figures 10c and 10d are the same waveforms for a different word. Some differences in the waveforms are caused by noise introduced by the two differentiations in the measurement electronics. Also, beyond a certain point, a long time spent matching the waveforms produced little improvement.

Another source of acceleration disturbances is the static friction of the pen against the tank bottom. If the pen stops on the tank bottom even for an instant, the acceleration waveform will show a large spike when the pen suddenly overcomes the friction and begins to move again. Since it does not simulate static friction, the acceleration signal from the simulator is much smoother. The small spikes in the simulator acceleration waveform are
FIGURE 10a DISPLACEMENT AND ACCELERATION MATCHING

FIGURE 10b X-Y PLOT OF FIGURE 10a

FIGURE 10c DISPLACEMENT AND ACCELERATION MATCHING

FIGURE 10d X-Y PLOT OF FIGURE 10b
due to comparator relay switching in the analogue computer and should be ignored.

If it is assumed that muscle can shorten at a fixed velocity, the control scheme does not require any direct feedback. Minor perturbations in the control signal L do not cause disastrous changes in the output writing because there is heavy local feedback in the mechanical model. The local feedback is the result of the elastic and viscous elements and of the antagonistic muscle action. The possibility of feedback control of muscle shortening velocity is discussed in the next chapter.

5. DISCUSSION OF RESULTS

It was observed that an X-Y plot of the L function was a rough match of the desired writing. This implies that the dynamics of the muscles merely serve to smooth out the writing. In other words, the contractile elements of the muscles follow the writing to a linearized first order approximation and the dynamics of the muscles smooth the writing into its characteristic shape. This is demonstrated in figure 11a where the top trace is the X-Y plot of the displacement while the bottom trace is the X-Y plot of the control signal L. It should be remembered that the model uses a digital method for generating the control signal and this produces the discrete dots of the lower trace. The control L and the displacement as functions of time are shown in figure 11b.

In order to gain physiological support for the type of control system proposed, some results of neuromuscular research will be presented. Most of the segments used by the simulator to copy human handwriting were longer than 100 milliseconds with some as long as 300 milliseconds. If any feedback is used by the nervous system for the handwriting process, the latency
or delay due to propagation time in the nerves and decision making must be less than 100 milliseconds. It is possible that feedback control of muscle shortening velocity would not include the brain in the loop. Some routine muscle control, such as maintaining muscle tone and maintaining posture, is done at the spinal level. The stretch reflex is also controlled from the spine. Control of muscle velocity may be done at this level of the CNS, implying a shorter latency in any feedback loop.

FIGURE 11a
COMPARISON OF DISPLACEMENT AND CONTROL SIGNALS

FIGURE 11b
TIME PLOT OF FIGURE 11a
Vposition
Vcontrol
Hposition
Hcontrol
(0.2 sec/div)
It is commonly accepted that the latency for a hand-spine-hand nerve path is about 30 milliseconds and for a hand-brain-hand nerve path, about 100 milliseconds. From this it would appear that velocity feedback control is possible with a feedback loop including the spine.

To explore this possibility it is necessary to know the various nerve paths which are used for muscle control. A review paper on muscle spindles by P.B.C. Matthews (14) forms the basis for this discussion. In a typical muscle there is one large motor nerve path (known as the alpha path) which directly controls the muscle. The adjective 'large' refers to the diameter of the nerve fibre which is proportional to its velocity of propagation. One or more muscle spindles are attached approximately in parallel with the muscle fibres. The muscle spindle is supplied with two sets of small motor

\begin{figure}
\centering
\includegraphics[width=\textwidth]{muscle_innervation.png}
\caption{Simplified Muscle Innervation}
\end{figure}
nerve fibres (gamma fibres). The spindle has two output fibres which are fed by the primary and secondary nerve endings. These fibres are coupled to the spine and are then projected into the cerebellum of the brain which is responsible for the precision of voluntary movements. Figure 12 is a highly simplified drawing of the arrangement described above.

If the gamma fibres are not stimulated, the primary ending of the muscle spindle responds to dynamic changes in the muscle length, that is, it is a velocity sensor. The secondary ending is mainly a position sensor. However if one of the gamma fibres is stimulated the primary ending can be made to behave as a position sensor with almost no dynamic response. If the other gamma fibre is stimulated the dynamic response of the primary ending can be increased. (A classification of gamma fibres into gamma 1 and gamma 2 is based on anatomical observations of the area of the spindle where each fibre ends. It has not been resolved which fibre produces the static response or which enhances the dynamic response of the primary ending.) It is known that the CNS has control over all three motor nerves (alpha, gamma 1 and gamma 2). It appears then that the CNS has a controllable muscle sensor which can respond to muscle lengths or various rates of muscle shortening depending on the CNS control of the gamma fibres. This evidence indicates that a velocity feedback loop is possible.

There is a problem however. Most papers dealing with the response of muscle spindles (2,4,14,17,22) only report a spindle sensitivity to muscle stretching with no response to muscle shortening. For feedback control of muscle shortening the antagonistic muscle spindle would have to be used. This would not be stretching at the same rate as the active muscle was shortening, due to the mechanical components between the two muscles. It would appear however, that sufficient gamma activity will make the primary ending responsive
to muscle shortening.

Matthews' paper (14) contains the following quotation which supports the idea of a velocity servo controlled by the spindle of the contracting muscle.

"The alpha route would perhaps be most efficiently employed in conjunction with sufficient fusimotor activity to prevent any decrease in spindle discharge occurring during the contraction; this would be achieved if the relative amounts of alpha and of gamma activity were adjusted to be appropriate for the velocity of shortening 'expected' under any particular set of conditions. Then if shortening proceeded faster than 'intended' by the higher centers, it would be slowed by servo action, and if shortening were hindered by some unexpected load it would be speeded up by servo action. Such a mode of action would not suffer from the slowness inherent in the excitation of muscle by the gamma route alone and would agree with the experimental finding that fusimotor neurons and ordinary motor neurons are often activated together, ..."3

The term "fusimotor" refers to the muscle fibres in the spindle innervated by the gamma nerve paths. It should be noted that all spindle actions are subconscious and are not used by the brain for conscious "position sense".

The proposed handwriting model requires a control of muscle (or contractile element) velocity of shortening and final position. It also assumes the capability of some control generator to issue "preprogrammed" commands which are in effect for preprogrammed lengths of time. The physiological evidence suggests that a feedback system may be present which can control the velocity of shortening of a muscle. The velocity sensors (muscle spindles) can also be made to respond to position so that the same feedback system could control the final position of a muscle. One important fact should be noted. The computer model simulating handwriting used only 4 bits to specify slope.

This corresponds to 16 discrete velocities so that a velocity feedback system would not require a high degree of resolution. Both Lashley (12) and Denier van der Gon (6) proposed some form of preprogrammed nervous mechanism which could issue preset commands for preset lengths of time. Thus there is a fair degree of physiological evidence to support the proposed handwriting model.

6. CONCLUSIONS

A mechanical model of an antagonistic muscle system was developed using known muscle characteristics. This model was compared with human responses using the following tests; frequency response for simple unidirectional strokes, impulse response, step response and response to sliding friction disturbances. The model with its final mechanical parameters compared well with a human subject. The control system developed for the model required the control of velocity of muscle shortening, final muscle position and time for each segment. The control was of a discrete nature, changing only at the required times. Both displacement and acceleration waveforms produced by the mechanical model and the control system agreed with a sample of human writing. Physiological evidence was found which supports the proposed control scheme. Although the proposed model and control scheme have not been shown exactly analogous to the human system, the model does agree well with observed human responses and all the necessary components for the control scheme have some degree of physiological backing.
APPENDIX I

Electrolytic tank measurement system

The first step in studying handwriting control is to obtain a permanent record of the pen position as a function of time. The equipment used for this is almost identical to that used by MacDonald (13). A four foot square electrolytic tank was used as the basic measurement apparatus. Water was used to fill the tank to a depth of 3/4 inch. Four brass electrodes were attached along the perimeter of the tank and a small dc current (100-600 microamperes) was injected into the water through the pen. Two opposing electrodes were connected to the inputs of a differential amplifier which converted the difference of the two input currents into a voltage proportional to position. If the pen was in the centre of the tank, equal currents arrived at the opposing sides and the output of the differential amplifier was zero. If the pen moved closer to one side, that side received more current and the output voltage increased proportionately. Two such arrangements were used to provide vertical and horizontal positions.

The whole measurement system is shown in Figure A1-1. The output of the differential amplifier was fed through a 100 Hz low pass filter and through a differentiating circuit to produce a velocity signal. The velocity signal passed through another 100 Hz low pass filter and through a 180 Hz notch filter to eliminate the third harmonic of the power line frequencies. The notch filter output was again differentiated to produce a signal proportional to acceleration. The low pass filters were necessary to eliminate noise and unwanted signals introduced by the differentiations.
FIGURE A1-1 MEASUREMENT SYSTEM

To eliminate power line interference a small 60 Hz voltage was injected directly into the differential amplifier inputs. The phase and amplitude were adjusted to cancel the voltages picked up by the large tank electrodes. The whole measurement system produced six outputs corresponding to the horizontal and vertical position, velocity and acceleration of the pen in the tank. These outputs were recorded on an eight channel chart recorder.

In addition to the electrolytic tank, a large electromagnet was constructed and installed directly under the writing area. A plastic tank was made for use with the magnet since the original tank was teflon coated iron sheet. The magnet used a laminated core with a pole face of approximately 2 3/4 inches by 4 inches. A coil of 600 turns was wound on this core and a
dc current of up to 20 amperes was used in the coil. The current was supplied through a relay from three 12 volt storage batteries in series. The magnet system was used in the sliding friction experiments.

APPENDIX II

Computer controlled simulator

To simulate the system proposed in the introduction, the following equipment was used. A Digital PDP 9 computer was used to simulate the command generator. This enabled tables of values for force, slope and displacement to be set up easily. An interface connected the computer to external hardware which was used to represent the force generator, analogue system and the comparator. A block diagram of the system is shown in Figure A 2-1.

\[ \text{FIGURE A2-1 COMPUTER CONTROLLED SIMULATOR} \]
The external part of the simulator was both analogue and digital. For each segment the PDP 9 put out an 18 bit word through the interface. Seven bits of the word corresponded to the final value of force. Four bits represented the slope and 7 bits were put into a D/A converter to yield an analogue signal proportional to the desired turnover displacement. The force generator is shown in Figure A 2-2. A digital comparator compared the 7 bits from the PDP 9 to the contents of a 7 bit up-down counter. The digital comparator enabled either an up line or a down line to the up-down counter if the two digital words were not equal. The 4 bits for slope set the frequency of a variable rate clock which toggled the counter. The up-down counter counted towards the new value from the PDP 9 at a rate set by the 4 bits corresponding to slope and when the two digital values were equal the counter stopped until the value from the PDP 9 changed. The number in the counter was converted to an analogue level by a 7 bit D/A converter. This level was fed into the analogue section which contained two integrators in series. The output from the second integrator corresponded to displacement and was compared to the preset value from the PDP 9. In this model the hand was represented as a point mass with negligible damping.

When the analogue comparator found its two input values equal, an interrupt was sent to the PDP 9 causing a new set of values to be sent to the simulator. After the table in the PDP 9 was finished the integrators were reset and the whole process was repeated. Two identical systems were used for the vertical and horizontal directions.
The improved model developed in the paper used the system outlined above except that the analogue system was simulated on an EAI 231-R PACE analogue computer. The "force" signal now corresponded to the desired mass position (L). The 7 bits corresponding to the preset displacement were now used to set up a counter in the PDP 9. An external clock interrupted the PDP 9 at 500 microsecond intervals and incremented the counter. When the counter overflowed the next set of values for the final position L and the slope were issued to the external electronics. With this system the PDP 9 and the external electronics produced a trapezoidal signal (L) which was fed to the analogue computer. The PDP 9 also reset the analogue computer when the tables for position, slope and time were finished. The system is shown in Figure A 2-3.
The software written for the PDP 9 included routines to service interrupts from the external simulator and to allow easy modification of the tables while the simulator was running. Tables could be modified or entered from the teletype and the teletype could give a hard copy table listing. The whole set of tables could also be dumped or loaded from paper tape. However, the majority of table manipulation was done with an oscilloscope display and light pen tied to the PDP 9. Software was written to display graphs of the values in the tables. Any value could be selected and modified from the display. Segments could also be added or removed from the tables using the light pen. These modifications could be done while the simulator was running.
so that any change was seen immediately.

The outputs of the two analogue systems were displayed on an X-Y oscilloscope. A projection screen and an oscilloscope camera were arranged so that a photograph of handwriting done in the electrolytic tank could be superimposed on the output of the simulator. In this way one could compare the simulator and handwriting and easily modify the simulator parameters to produce an accurate match.

APPENDIX III

Constant current stimulator

A constant current stimulator was constructed with the following characteristics. An adjustable pulse width from 100 microseconds to 10 milliseconds was available with repetition rates from 0.1 Hz to 10 Hz. The pulse could also be manually triggered. Skin resistances of the order of several thousand ohms could be expected and constant pulse currents up to 10 milli-amperes could be delivered into such loads. A synchronizing pulse was available to trigger an oscilloscope.

The most important features of the stimulator involved safety. The skin electrodes provide a low resistance path to the body. The stimulation experiments were done with the electrolytic tank and its electronics plus the 8 channel chart recorder and an oscilloscope. With this much equipment, the possibility of ground loops or faults existed. There were also other grounded items within reach of the tank such as ground busses on lab benches and water pipes. In accordance with good medical electronics standards the whole stimulator was electrically isolated from other equipment. A high frequency inverter was used with the isolation being provided by the inverter transformer. The oscilloscope synchronizing pulse was coupled out through a pulse transformer.
The inverter supplied 110 volts dc for the constant current source and 20 volts for the timing electronics. The input voltage to the inverter was 12 volts. In order to protect against excess current flowing to the electrodes due to a fault in the stimulator, the following precautions were taken. The output current of the high voltage supply was limited to 25 milliamperes by a resistor. An SCR circuit provided an overcurrent shutdown of the high voltage supply at adjustable current levels from 1 milliamperes to 10 milliamperes. As a final

**Figure A3-1 Constant Current Stimulator**
fail-safe precaution 10 milliampere fuses were used in series with each electrode. A block diagram of the stimulator is shown in the figure A 3-1.
REFERENCES


