1 Introduction

Physiological tremor (PT) is a ubiquitous, involutary, and irregular oscillatory movement present in the neuromuscular systems of all humans. It is most apparent as a high-frequency, low amplitude oscillation about a nominal reference position. The exact cause unknown; however, multiple competing theories concerning the origin and the purpose of PT have been proposed in the past 50 years. This paper will review several prominent theories and measurements of PT and examine the evidence and limitations of each.

Additionally, this paper will explore a common rule in photography to prevent camera shake - the inverse focal-length shutter speed limit - and compare the limitations on camera speed predicted by this rule with measured tremor data.

2 Tremor Theories

As might be expected from any phenomenon involving the neuromuscular system, conflicting theories attribute PT to both mechanical effects and neural sources. Studies support both a mechanical basis and a neural basis are presented in the subsequent two sections.

2.1 Mechanical Basis

2.1.1 Servomechanism Oscillation

One of the major theories of PT is that it is a persistent oscillation in the time-delayed, under-damped, and servo-mechanical muscles (Halliday and Redfearn, 1956; Lippold, 1970). The basis of this theory depends upon the feedback dynamics of the muscle spindles; there is an unavoidable time delay between the efferent alpha motor neuron, the force production and motion of the muscle, and the afferent signal received from the spindles. This time delay, combined with a loop gain above unity, establishes a persistent and quasi-stable oscillation.

Lippold conducted experiments to verify the reflex-based action of tremor using the apparatus shown in Figure 1. The fingers of subjects were connected to strain gages and a "prodder" that could record the tremor amplitude and apply disturbances impulses. The experiments tested the servomotor hypothesis by modifying the loop parameters - changing the transmission time, examining the phase delay between alpha motor neuron input and finger motion, and opening the feedback loop by interfering with the afferent neurons.
Lippold adjusted the water bath temperature between $7^\circ$ and $45^\circ$ C in an attempt to change the loop transmission delay. Warm muscles respond more quickly and cold muscles respond more slowly, and thus the servomechanism hypothesis predicts a positive correlation between temperature and tremor frequency. This correlation was confirmed by the results shown in Figure 2; the dominant tremor frequency shifted between 5 Hz in cold muscles to 15 Hz in warm muscles.

As shown in Figure 3, Lippold attached surface EMG sensors to the extensor muscles of the middle finger, and observed the muscle activation while disturbing the finger and recording the resulting oscillation. It is clearly evident from the second trace that the muscles are actively reinforcing the tremor; the amplitude of the tremor initially decreases, but is then restored and amplified. The frequency match and phase delay between the EMG and the oscillation are consistent even as the temperature of the arm changes.
A crucial point emphasized by Lippold was that the dominant 8-12 Hz tremor frequency in the fingers vanish completely if the feedback loop was opened. Citing investigations of deafferented cats and humans with tertiary syphilis (which affects the afferent neurons), as well as experiments with restricting blood flow to muscles to interfere with the muscle spindles, Lippold claimed that muscles without afferent feedback did not tremor.

Major criticisms of the servomechanism theory of tremor concern the inferences drawn from the experimental data; Rietz and Stiles (1974) found fault with the measurement techniques used in Lippold’s experiments. They contended that altering the temperature of the muscles simultaneously changed the muscle tension, polluting the results. Rietz and Stiles dismissed the phase-locked EMG results, claiming that the presence of the electrical activity did not necessarily imply that it had a major role in the tremor. Finally, Rietz and Stiles found fault with the claim that deafferented muscles did not tremor; they cited additional studies contradicting those results and postulated that the position transducers used by Lippold were not sensitive enough to measure the tremor.

2.1.2 Underdamped Mechanics

In contrast to the servomechanism theory, the underdamped mechanics theory of PT states that the oscillations reflect the resonant natural frequency of the underdamped viscoelastic muscle-load system (Randall, 1973; Rietz and Stiles, 1974). The broad-frequency forcing of the system due to the random intervals between muscle fiber firings is filtered by the viscoelastic muscles, such that only the resonant frequencies are expressed in motion. Thus the tremor is purely a result of the muscle dynamics and the noise source, and does not require the stretch reflex to be present.

Rietz and Stiles (1974) provided experimental evidence supporting the underdamped mechanics theory, using the experimental apparatus shown in Figure 4. The researchers conducted experiments to alter the mechanical properties of the muscle and demonstrate their influence on tremor.

Rietz and Stiles predicted that, as muscles responded like an underdamped system, the inverse square of the resonant frequency should be positively correlated with the system mass. This comes from the fact that the natural frequency of an underdamped system is \( \omega_0 = \sqrt{k/m} \); by inverting and squaring both sides, it can be seen that \( 1/\omega_0^2 = m/k \). The researchers tested this hypothesis by adding additional inertial mass to the experimental apparatus shown in Figure 4 and observing the resulting tremor frequency. As seen in Figure 5, the measured tremor frequency of the rat muscles did indeed scale linearly with additional mass.
Figure 4: Experimental apparatus used by Rietz and Stiles (1974). The muscle shown is composed of the gastrocnemius and plantaris of a rat. Additional mass could be added symmetrically to the lever to add inertial but not gravitational mass, and the muscle could be neurally isolated by severing the sciatic nerve.

Figure 5: Experimental results comparing inverse square tremor frequency to additional inertial mass from Rietz and Stiles (1974). Each of the five plots is from a different rat subject, and each data point is the average of multiple trials.
In addition to citing previous work demonstrating tremor in neurally isolated muscles, Rietz and Stiles deafferented their rat subjects and artificially induced contractions with electrical stimulation. Contrary to the change in tremor characteristics observed by Lippold (1970), Rietz and Stiles found no difference in the tremor. The power spectral density of normal and deafferented muscles at two different contraction lengths are presented in Figure 6.

With their results, Rietz and Stiles concluded that the stretch reflex was entirely superfluous to the tremor phenomenon. The primary objections to this underdamped mechanics model are articulated by Lippold (1971); he contended that the broad-frequency forcing of the randomly firing muscle fibers could not produce muscle tremor unless there were an external synchronization. He also claimed muscle fatigue would tend to reduce the tremor frequency, where it in fact tended to slightly increase the tremor frequency.

2.1.3 Composite Model

In examining the underdamped mechanics and servomechanical stretch reflex theories of PT, it is immediately apparent that there is a wealth of contradictory evidence. Later researchers found fault with the experimental techniques of both Lippold and Rietz and Stiles, calling for a unified model that incorporated both muscle dynamics and feedback mechanics into the tremor model (Elble and Randall, 1978; Vaillancourt and Newell, 2000). Elble and Randall in particular cited the incredibly complex physiology of the hands and the crude nature of the existing techniques; changing the temperature of the muscles or neurally isolating muscles introduced unanticipated side effects, polluting the experimental results. Furthermore, they asserted that the mechanical coupling between fingers and hands or forelegs and upper legs made comparing tremor results from any experiments not conducted in exactly the same manner meaningless.
2.2 Neural Basis

Given the reality of the physiology - the existing muscles and their inherent transmission delays and relatively static nerve innervation - any changes to the tremor characteristics not involving a physical change must be neurological. The following two sections detail studies exploring the influence of the central nervous system on tremor.

2.2.1 Voluntary Control

Strong evidence for a neural basis of PT was presented by Carignan et al. (2009). In this experiment, Carignan et al. measured and displayed the tremor amplitude of a single finger while test subjects comfortably rested their arms and wrists on foam supports. They observed the tremor in four conditions: (A) eyes closed, with no attempt to modulate tremor, (B) eyes open, with subjects attempting to reduce tremor amplitude, (C) subjects attempting to reduce tremor amplitude while observing a real-time display of their own tremor, and (D) subjects attempting to reduce tremor by co-contracting finger muscles.

![Figure 7: Experimental results of finger tremor amplitude from Carignan et al. (2009). From left to right, the experimental conditions are: eyes closed, eyes open, subjects observing real-time tremor data, and subjects co-contracting finger muscles.](image)

The results of these trials are shown in Figure 7. The most striking results are the complete elimination of the 8-12 Hz tremor in condition (C) and the massive increase in tremor amplitude in condition (D).

The loss of the 8-12 Hz tremor is strong evidence in favor of a neurological basis; the subjects were specifically instructed to not contract their fingers while attempting to quiet their tremor. If this tremor were indeed due to the feedback loop transmission delay, or the a resonance of the
finger, it seems unlikely that the amplitude could have been voluntarily controlled. Indeed, the observation that co-activating the fingers made the tremor much worse implies this as well.

2.2.2 Postural Exploration

Figure 8: Apparatus used to quiet center of mass motion and observe center of pressure variation. Carpenter et al. (2010).

In order to explore the effect of quieting the motion of the center of mass, researchers constructed an apparatus that could artificially fix a subject’s center of mass (COM) while observing their postural center of pressure (COP) in an upright stance (Carpenter et al., 2010). As seen in Figure 8, this device could be operated without alerting the subject. The resulting COP motion can be seen in Figure 9. In contrast to the expectations of the researchers, COP motion drastically increased during the minute-long interval in which the body was held still. These results were interpreted as evidence that the central nervous system intentionally imposes a low level of postural sway; when the body is externally stilled the force applied at the feet correspondingly increases to overcome the disturbance.

Carpenter et al. postulated that this is done to keep proprioceptive sensors active; sensors such as the muscle spindles have static and dynamic responses, and the greatest wealth of incoming information is obtained by constantly stretching and relaxing the spindles.

3 Tremor in Photography

Photography is an excellent medium to practically examine PT in a real-world application. The amplitude of the tremor is amplified twice: once during the image exposure, as the linear shake of the hands is transformed into a rotary shake of the camera, and once during the enlargement process from exposure to print or display. This amplification, when combined with the optics of human vision, greatly increases the visibility of tremor. In order to characterize photographic blur and link it to the tremor amplitude, some discussion of the optics of both cameras and the human eye is necessary.

3.1 Optics of the Eye

The useful optics of the eye are defined by three important characteristics: visual acuity, the near distance of distinct vision ($D_v$), and the comfortable field of view. Normal visual acuity, or 20/20
vision, is defined as the ability to distinguish a line whose thickness subtends an angle of 1 arc minute (book reference). This corresponds to being able to identify a 3.5mm tall letter "E" at 6 meters, and is limited by the finite size of the light receptors on the retina. The near distance of distinct vision is the minimum distance at which the eye can comfortably focus, which is approximately 250 mm. The comfortable field of view is the cone of vision in which we place objects we are directly examining; while the eye has an absolutely field of view of nearly 180°, the comfortable field of view is limited to 50°-60°.

From these three measures we can determine the maximum acceptable size of a picture element that is to be perceived as a point. Assuming the viewer will examine the photograph at $D_v$, their normal visual acuity will be able to identify a spatial cycle of 2 arc minutes, or approximately 0.15 mm. In most of the literature it is assumed that perfect conditions are not met, and this condition is relaxed to a standard accepted visible resolution limit of 0.2 mm. This value is often called the minimum permissible circle of confusion, $C_{max}$, as it defines the largest circle that is indistinguishable from a true point. Again assuming that the photograph will be examined at $D_v$, the comfortable field of view defines a final image dimension of approximately 250 mm, or 10 inches.

From this examination of the optics of the eye, it is reasonable to expect that a sharp photograph will have motion streaks no longer than 0.2 mm when enlarged to a 8” x 10” print size.

### 3.2 Camera Optics

Single-lens reflex (SLR) and digital single-lens reflex (DSLR) cameras operate by having the lens focus the scene onto the 36 mm wide x 24 mm tall film strip or sensor. The important measures in this case are the focal length of the lens and the exposure time of the image. Photographic lenses define the focal length, $L$, as the distance between the "intersection point" of the light rays and the sensor; a 50 mm lens focuses as if it were a single lens located 50 mm from the sensor. The exposure time or shutter speed, $\delta t$, is the length of time the shutter is open.

As can be seen from Figure 10, a single light ray entering a camera that is rotating at angular
velocity $\omega$ will move linearly across the film surface. This blur length, $b$, can be measured as:

$$b = \omega \cdot L \cdot \delta t$$  \hspace{1cm} (1)

Enlarging a photograph from a 36 mm x 24 mm exposure to a 8” x 10” print requires a 7x enlargement. As the minimum permissible circle of confusion is 0.2 mm for the purposes of this experiment (as shown in Section 3.1), the maximum permissible size of $b$ is:

$$b_{\text{max}} \approx C_{\text{max}} \approx 0.028 \text{ mm}$$  \hspace{1cm} (3)

The general rule-of-thumb used in handheld photography is that the minimum shutter speed to prevent image shake is the inverse of the focal length; for example, a 200 mm lens has a minimum shutter speed of 1/200 of a second. Mathematically, this is:

$$|\delta t_{\text{min}}[s]| = \left| \frac{1}{L[\text{mm}]} \right|$$  \hspace{1cm} (4)

Combining Equations (1) and (4) with the calculated amplitude of $b_{\text{max}}$, the maximum allowable angular velocity of the camera becomes:

$$\omega_{\text{max}} = \frac{b_{\text{max}}[\text{mm}]}{L[\text{mm}] \cdot \delta t[s]} = 28 \cdot 10^{-3} \text{ rad/s}.$$  \hspace{1cm} (5)

### 3.3 Tremor Model

In determining a suitable model for PT, it seemed suitable to examine measured data from several different sections of the body. When holding a camera the fingers, hands, and head (through contact with the viewfinder) influence the involuntary motion.

For simplicity, the tremor is modeled as a simple sinusoidal motion with amplitude $A$ and frequency $f$:

$$x(t) = A \sin(2\pi ft).$$  \hspace{1cm} (6)
For one of the data sources, the tremor data was given as an acceleration; in this case, the tremor model is:

\[ \alpha(t) = \alpha \sin(2\pi ft). \]  

(7)

By differentiating Equation (6) and integrating Equation (7), the maximum velocity of the tremor is found to be:

\[ v_{\text{max}} = 2\pi f A = \frac{\alpha}{2\pi f}. \]  

(8)

When holding an SLR camera with one hand supporting the body and one supporting the lens, the two hands are placed approximately 10 cm apart (denoted as 2L below). In the worst-case scenario that the hands are shaking perfectly out of phase, each side of the camera will move at \( v_{\text{max}} \) at a distance \( L \), allowing the maximum angular velocity to be found as:

\[ \omega_{\text{max}} = \frac{v_{\text{max}}}{L} = \frac{2\pi f A}{L} = \frac{\alpha}{2\pi f L}. \]  

(9)

Tremor data for fingers, hands, and heads extracted from several scientific papers is collected in Table 1, along with the angular velocity calculated from this data using Equation (9).

3.4 Results

Table 1: Tremor data from scientific papers and the corresponding camera angular velocity.

<table>
<thead>
<tr>
<th>Source</th>
<th>Feature</th>
<th>( f ) (Hz)</th>
<th>( A ) (( \mu )m)</th>
<th>( \alpha ) (m/s(^2))</th>
<th>( \omega_{\text{max}} ) (mrad/s(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carignan et al. (2009)</td>
<td>Finger</td>
<td>9</td>
<td>100</td>
<td>X</td>
<td>113</td>
</tr>
<tr>
<td>Stiles (1976)</td>
<td>Hand</td>
<td>9</td>
<td>20</td>
<td>X</td>
<td>22.6</td>
</tr>
<tr>
<td>Findley et al. (1985)</td>
<td>Head</td>
<td>6.5</td>
<td>X</td>
<td>0.0392</td>
<td>13.9</td>
</tr>
</tbody>
</table>

In comparing the results of Equation (5) and Table 1, it is apparent that the theoretical limit implied by the inverse focal length shutter speed rule matches very well with actual data. The finger tremor data has the largest amplitude and the highest frequency of the three sources (as might be expected from such light and strong appendages), and correspondingly predicts the highest sway rate for a camera. Tremor data from the hands and the head, which are more larger appendages and more reasonable tremor sources, match the rule exceedingly well.

4 Conclusions

Physiological tremor is a highly complex phenomenon. The high-frequency, low-amplitude oscillators arise from a mixture of mechanics, stretch reflex feedback, and central neural control. The most current research holds that each of these factors influences tremor within relatively distinct frequency bands, but existing measurement techniques are limited in the information they report; externally measured acceleration or position data only report the mechanical filtering of the muscle activity, while surface EMG readings only show the aggregate activity of multiple muscle fibers. The imperfect nature of the measurement techniques, combined with the high level of mechanical and neurological coupling in the body, make it exceedingly difficult to isolate and investigate a single variable.
Despite this, a relatively simple sinusoidal model, combined with experimental data, is able to closely match predictions made by photographers on the limits of human quiet posture. The high level of complexity does not prevent useful information from being extracted and used from existing tremor data.

Bibliography


