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Physiological Tremor in Handgun Aiming and Shooting Tasks

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PHYSIOLOGICAL TREMOR IN HANDGUN AIMING AND SHOOTING TASKS

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ABSTRACT

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When holding an outstretched limb or aiming at a target, humans produce small involuntary fluctuations that may hamper performance. Current strategies for minimizing the impact of tremulous oscillations predominantly include both extrinsic and intrinsic support. The aim of the current dissertation is to better understand the parameters of physiological tremor associated with handgun aiming with the end goal of improving shooting accuracy. Experiment 1 focused on handgun aiming and the influence of different arm posture adopted during aiming. Experiment 2 expanded upon the findings of experiment 1 by comparing tremor during finger pointing, handgun aiming, and handgun shooting. Experiment 3 attempted to confirm that both mechanical support and proprioceptive feedback play a role in both attenuation of tremor amplitude and handgun shooting accuracy.

In experiment 1, thirty volunteers stood 6.4 meters from a target and aimed a weighted mock handgun for 10 seconds per trial. Two hand grips (bilateral, unilateral) and two arm positions (bent elbow, straight elbow) were assessed for acceleration in the anterior-posterior (AP), medial-lateral (ML), and vertical (VT) directions. Amplitude, regularity, and a frequency spectrum analysis of the acceleration signals were analyzed. Tremor amplitudes (VT, ML) were reduced using a bilateral grip and by bending the elbows. The irregularity of the tremor signal was increased by using two hands to support the handgun. Interestingly, irrespective of the posture adopted, ML accelerations were of greater amplitude than VT oscillations. AP

oscillations were markedly smaller compared to VT and ML tremor, did not display consistent frequency peaks, and were not altered by the arm conditions.

During experiment 2, twenty volunteers, in a counterbalanced order, pointed their finger, aimed a training handgun, or shot a training handgun, for 10 seconds at a bullseye target 6.4 meters away. Amplitude, regularity, and frequency spectrum analysis of the acceleration signals were computed. Aiming with the mass of a gun in the hand has primarily a damping effect on the amplitude of tremor in the distal segments as well as resulting in more regular movements. Overall, aiming with a gun and pointing with a finger were similar tasks except for the added mass of the handgun aiming condition. Shooting accuracy and handgun shooting experience were also assessed for correlations with acceleration amplitude and regularity. Both handgun shooting accuracy and experience revealed a stronger correlation with increased irregularity of the acceleration signal than decreased acceleration amplitude. A correlation was also run between shooting accuracy and handgun shooting experience. An increase in accuracy had a significant, moderate relationship with an increase in handgun shooting experience.

Experiment 3 had twenty volunteers aim as well as shoot a training handgun at a bullseye target 6.4 meters away during two limb support conditions and two weight conditions for a total of four combinations. Amplitude, regularity, and frequency spectrum analysis of the acceleration signals were computed. Bilateral limb support again reduced tremor amplitude and increased the irregularity of the acceleration signal over unilateral conditions. Bilateral limb support also contributed to a significantly improved handgun shooting accuracy when compared to unilateral limb support conditions. By manipulating the weight of the handgun, the third study also indicated the addition of a second limb reduced acceleration amplitude through both mechanical support and proprioceptive feedback.

The experiments demonstrate that finger pointing and handgun aiming share similar tremulous characteristics in all three directions (VT, ML, AP). These experiments also indicate that acceleration amplitude can be reduced while acceleration regularity and shooting accuracy are increased through the use of a bilateral limb support posture.

ACKNOWLEDGEMENTS

This dissertation is dedicated to my family, which has grown during my doctoral studies. If it were not for their love and support my aspirations would still be dreams.

A special dedication to my Great-aunt Martha Ann Kelleran, your thirst for knowledge and dedication to family encourages us all.

To my dissertation committee, you have each taught me about our discipline and about being a professor. I want to thank each of you for the effort you have put into my education. I hope to make you proud someday.

I would also like to thank my fellow doctoral students for your support. You are the only ones who truly understand what this process entails.

Lastly, I want to thank my wife for her reassurance and love.

…to my daughter and any other children we may be graced with, take that shot, shoot for the stars!

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CHAPTER I

INTRODUCTION

Humans inherently have tremulous motion in the upper limb when held in an outstretched postural position. The magnitude of motion is dependent on the individual and task parameters, however, both may impact performance. Certain precision-based activities such as surgery, archery, and shooting a gun may be more susceptible to influence from involuntary or errant motions (Coulson, Slack, & Ma, 2010; Keast & Elliott, 1990; Tang, Zhang, Huang, Young, & Hwang, 2008).

These inherent, involuntary fluctuations are commonly referred to as physiological tremor and are one aspect of performing postural tasks that cannot be fully controlled (Arutyunyan, Gurfinkel, & Mirskii, 1968; Elble & Koller, 1990; Morrison & Newell, 1996; Tang et al., 2008). The current dissertation focused on understanding how people control or compensate for these involuntary fluctuations while aiming and shooting a handgun accurately at a target.

The current body of literature has established information on physiological tremor and motor control of the upper limb during postural tasks. The impact tremor has on the performance of fine motor skills such as shooting a gun is limited, however (Arutyunyan et al., 1968; Lakie, 2010; Pellegrini & Schena, 2005; Tang et al., 2008). The following chapter will provide a review of what physiological tremor is, how tremor is influenced, and what is known about the effects of tremor on handgun aiming and shooting. The subsequent chapters will make unique and original strides toward understanding the effects of tremor on handgun shooting tasks.

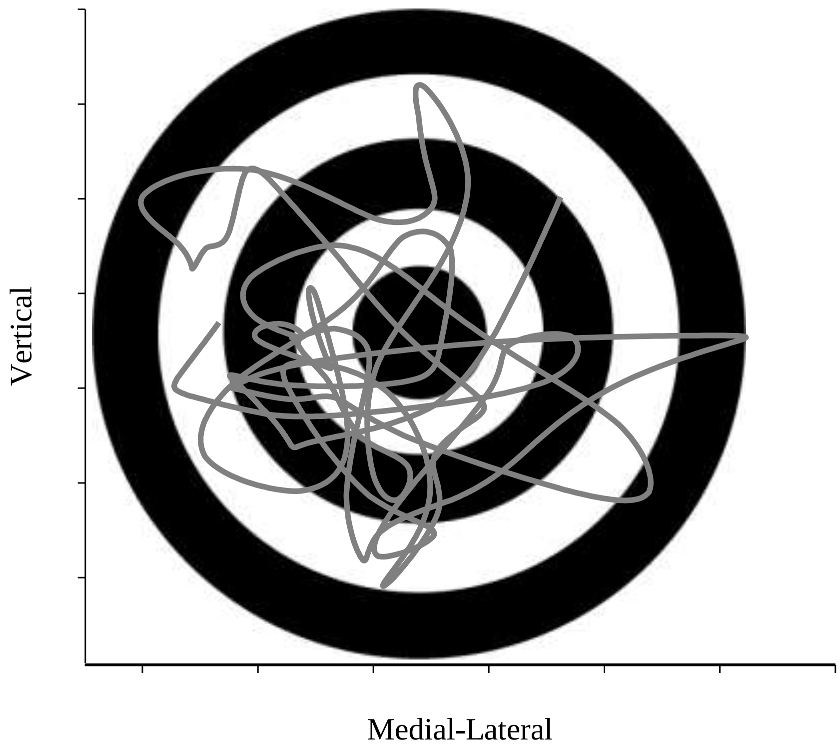

Figure 1.1: Example of aim-point fluctuations around a target.

Tremor is an intrinsic feature of the body. Researchers have spent over one hundred years investigating tremor but the exact origin is still debated. In healthy populations tremor is generally very small and only causes a problem during fine motor tasks or when enhanced by disease, medication, or physiological and psychological stressors. Because tremor becomes detrimental when the oscillations get too large for a given task, the primary measurement of tremor is commonly amplitude. Tremor has been investigated using different devices. Due to their relatively low cost and high sensitivity to small movements, accelerometers are often the most prevalent device used in published tremor literature. The use of accelerometers has allowed for deeper investigation into tremor beyond amplitude that has revealed structure within the tremor signal. In healthy adults, tremor is generally comprised of the mechanical and neural components but may also be impacted by cardiac, respiratory, and postural influences. The origins, measurement, and factors that affect tremor, along with how tremor impacts postural aiming and shooting tasks, will be discussed in the subsequent paragraphs.

Shooting a Handgun

Handgun shooting is utilized in law enforcement (Oudejans, 2008; Vickers & Lewinski, 2012), combat roles (Department of the Army, 2008; Marine Corps, 2003), and personal defense as well as sporting and recreational activities (Dadswell, Payton, Holmes, & Burden, 2013; Tang et al., 2008). Accuracy while shooting is unquestionably vital and in some scenarios a matter of life or death (Vila & Morrison, 1994). In its simplest form, accurately hitting the target involves lining up the sights of the gun with the center of the target in both the vertical and mediolateral axes (Ball, Best, & Wrigley, 2003). If humans were mechanical devices this would be an easy task, however, the inherent variability within the human body and environment compound the issue. If the task difficulty is too great to overcome it can result in an altered strike location from the desired shot placement.

Although environmental factors such as gravity and wind can play a large role in shooting accuracy they can be calculated and compensated for (Lakie, 2010). Intrinsic factors such as respiratory and cardiac events, body sway, and limb motion may impact handgun shooting accuracy (Ball et al., 2003; Dadswell et al., 2013; Lakie, 2010; Mason & Bond, 1990; Tang et al., 2008) and are not as easily mitigated due to the uniqueness of each individual. The level of experience an individual possesses may alter his or her ability to handle these intrinsic factors, but even in highly skilled individuals it will still exist. Of the many intrinsic factors that may affect shooting accuracy, some are involuntary, such as the heartbeat, and others can be partially controlled, such as a temporary pause in the respiratory cycle. The aiming limb is controlled voluntarily, however, an inherent component of postural tasks includes small involuntary tremulous movements that may hinder control.

Physiological Tremor and Performance of Postural Tasks

Coordination of precision aiming on target and maintaining the upper limb in an outstretched posture can be difficult due to the small tremulous movements of the limb (Morrison & Newell, 2000b; Tang et al., 2008). The movements can deviate the aim point taking the target off center and increasing the task demand requiring a correction in response. These semi-rhythmical oscillations are often described as physiological tremor and are present to some degree in all motor tasks (Elble, 1996; Elble & Koller, 1990; Llinás, 1984; Morrison, Sosnoff, Heffernan, Jae, & Fernhall, 2013). Early investigations into accuracy during precision movements (Woodworth, 1899) and body tremors (Eshner, 1897; Herringham, 1890) were noted prior to the 20th century. Later, observations in the 20th century led researchers to document the impact of tremor on precision tasks such as archery, rifle, and pistol shooting (Arutyunyan et al., 1968; Arutyunyan, Gurfinkel, & Mirskii, 1969; Keast & Elliott, 1990; Spaeth & Dunham, 1921). Advancements in both knowledge and technology have further led to a better understanding of physiological tremor.

Measuring and Assessing Tremor

Although physiological tremor can be visible to the naked eye, specialized equipment is available to make quantifying tremor easier. Early investigations into tremor and motor control utilized revolutionary equipment for their time involving brass plates and needles to record deviations (Binet, 1920; Spaeth & Dunham, 1921), however, our understanding of tremor has been greatly enhanced by technological development allowing for easier and more precise measurement. Some modern instrumentation used to quantify tremor includes motion capture (Mullineaux, Underwood, Shapiro, & Hall, 2012; Pellegrini, Faes, Nollo, & Schena, 2004; Pellegrini & Schena, 2005; Scholz, Schoner, & Latash, 2000), laser displacement (Beuter, de Geoffroy, & Cordo, 1994; Carignan, Daneault, & Duval, 2012b; Duval & Jones, 2005; Héroux, Pari, & Norman, 2009; Hwang, Chen, & Wu, 2009), and accelerometry (Elble & Randall, 1978; Morrison & Newell, 1996; Stiles & Randall, 1967). These devices measure tremor in terms of position, displacement, velocity, or acceleration. Displacement is the direction and distance of movement in a straight line. Velocity is the rate of change in position over time. Acceleration is a measure of the rate of change in velocity over time. The most commonly used device to quantify tremor is the accelerometer. There are many advantages to using accelerometers including their low cost and greater portability compared to the other devices. Given that the amplitude of tremor in healthy individuals is usually small, directly measuring acceleration is more sensitive to fluctuations in limb position and avoids the amplification of noise that occurs when double differentiating position or displacement data obtained from using lasers or motion capture. Double differentiation occurs in displacement data due to the need to calculate velocity and then calculate acceleration as opposed to the direct measure of acceleration from an accelerometer.

Measurement of Tremor

When using an accelerometer, acceleration is measured in units of meters per second squared ($m.s^{-2}$) or gravitational units (g); accelerometers are also sensitive to the pull of gravity. A variety of accelerometer technologies have been developed to assess tremor, among other motions in the human body, including capacitive, piezoelectric, and piezoresistive accelerometers. All three of these accelerometers have a mass inside them attached to either a resistor (piezoresistive), capacitor (capacitive), or crystals (piezoelectric) that output an electric current based upon the rate of acceleration when a force acts upon the internal mass. Hence, acceleration due to gravity is detected even when held in a static position. Accelerometers can also vary in terms of whether they are wired or wireless, or whether they measure a single- or multi-dimensions. Uni-axial accelerometers were often used in early tremor literature; they simply measure movement in one direction, usually vertical (Homberg, Hefter, Reiners, & Freund, 1987; Stiles & Randall, 1967). More recently, researchers have employed dual-axial accelerometers able to monitor two axes (Huang, Huang, Young, & Hwang, 2007; Hwang, Huang, Cherng, & Huang, 2006; Tang et al., 2008) or tri-axial accelerometers that can be used to measure three dimensions of acceleration, such as the vertical (VT), medial-lateral (ML), and anterior-posterior (AP) axes. However, most of the literature has focused on quantifying tremor in the VT axis and hence little is known about tremor in ML and AP dimensions.

Utilizing Accelerometers with Human Participants

When perfectly aligned with gravity in a static position, accelerometers record 1 g in the VT axis and 0 g in the AP and ML axes, if not aligned perfectly a component of the gravitational force may be recorded in an alternate axis. Placing accelerometers on humans can prove challenging due to soft tissue mobility, imperfect attachment points, and complexity of movement of the body and limbs (Elble & Koller, 1990). Due to these factors, when testing human subjects, if the accelerometers cannot be placed and maintained in perfect alignment to the designated axes, it may be necessary to realign the axes. Knowing the average value in three different axes allows the determination of the alignment/orientation angle of each axis with VT, which can then be used to compute the values of the true AP, ML and VT axes. One such approach, developed by Moe-Nilssen, allows for a correction factor to be applied to time series data in order to reorient the axes parallel or perpendicular to the pull of gravity (Moe-Nilssen, 1998a, 1998b).

Sampling rates for accelerometry vary by task. They generally follow the guideline of sampling at least twice the rate of the highest data frequency (Nyquist rate) being examined. During postural tasks utilizing measures of acceleration, this rule is usually applied (highest frequency tremor is approximately 25 Hz for the finger) and then commonly rounded to around 100 Hz (Keogh, Morrison, & Barrett, 2004; Morrison, Kavanagh, Obst, Irwin, & Haseler, 2005; Morrison & Keogh, 2001). Some studies sampled even higher at 400 Hz (Hwang et al., 2006; Tang et al., 2008). Systems often have sampling rates set to higher rates than necessary; if the sampling rate is too high, the signal can be down sampled to 100 Hz if necessary.

Due to their sensitive nature, when using accelerometers calibration is essential. Generally, a static calibration is completed by comparing the accelerometer output to a known constant. Often each axis of the accelerometer is recorded while exactly parallel and perpendicular to the constant acceleration of gravity. This calibration will result in two values, equivalent to 1 g (9.81 $m.s^{-2}$) and 0 g (0 $m.s^{-2}$), which allows for a two-point linear calibration. If the accelerometer signal is not demeaned, during a postural task the VT axis will generally fluctuate above and below 1 g, ML and AP axes will fluctuate around 0 g if properly aligned with their given direction. Demeaning the tremor signal is necessary for the calculation of some measures such as root mean square (RMS), but it is not necessary for others such as approximate entropy (ApEn) or spectral analysis. It also may be necessary to detrend the data if there is a drift in the mean value over time.

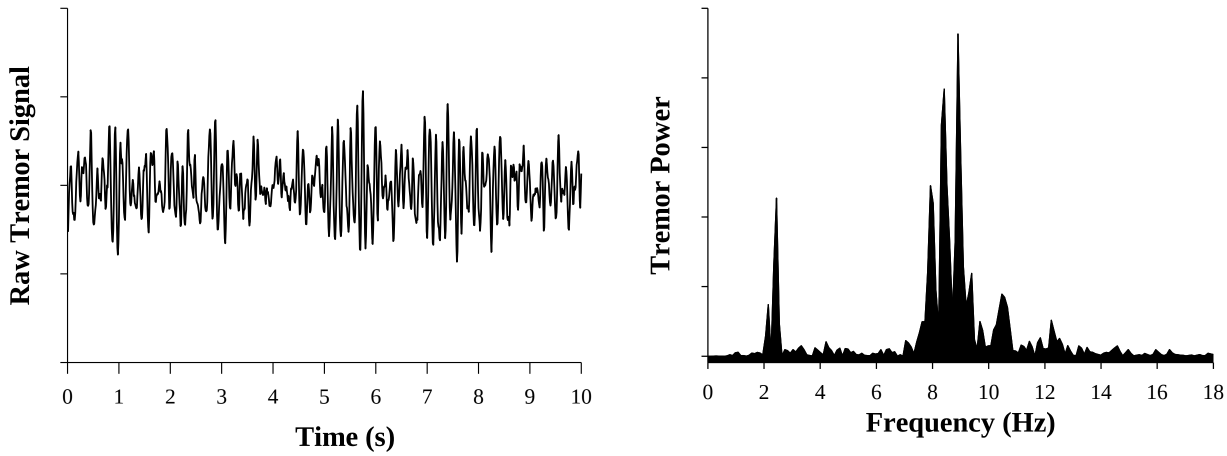

Figure 1.2: Example of a raw postural tremor trace and the corresponding spectral analysis graph of frequency peaks from a young healthy subject.

Time Series Analysis of Tremor

Accelerometer signals can be processed in both the time and frequency domain. Time series analysis involves an examination of the data set over consecutive equivalent points in time (Figure 1.2). Time series analyses for tremor generally involve an assessment of magnitude and structure of the oscillations. The magnitude of these fluctuations can be quantified by the RMS and quantifies how much tremor is in the signal. RMS is calculated on demeaned data by taking the square root of the mean of a series of numbers after they have each been squared (x = data points in series, n = number of data points in series) to determine the average fluctuation from the mean.

$$xRMS = \sqrt{\frac{(x_1^2 + x_2^2 + x_3^2 \ldots x_n^2)}{n}} \qquad (1)$$

The structure of the signal can be quantified by a number of measures including ApEn, sample entropy (SampEn), and Multiscale Entropy Analysis (MSE). ApEn, which determines how regular or irregular the signal is through calculating the probability that a sequence of data points will repeat itself within the time series (Pincus & Goldberger, 1994; Pincus, 1991, 2001). Specifically, utilizing a scale of 0 to 2, with higher values indicating a more complex or irregular signal this analysis, measures the time-dependent repeatability of a signal (*X*) by calculating the natural logarithm of the ratio of the count of recurring vectors of length *m* against that of *m*+1. Often for postural tasks, parameters of *m*=2 and error tolerance of *r*= 0.2 multiplied by the standard deviation of the signal are used (Hong, James, & Newell, 2008; Morrison & Sosnoff, 2009). If the tremor signal repeats itself regularly it can be considered predictable and therefore would score low on the 0 to 2 ApEn scale. If the data are irregular, the signal would score higher on the 0 to 2 ApEn scale indicating a less predictable or more complex signal.

$$ApEn(\vec{X}, m, r) = \ln\left[\frac{C_m(r)}{C_{m+1}(r)}\right] \qquad (2)$$

Frequency Analysis of Tremor

Raw, time-dependent signals can be dissected into a combination of sine and cosine waves (Cooley, Lewis, & Welch, 1969; Warner, 1998). To observe the separate waves extracted from the raw signal and evaluate the composition of the tremor signal a spectral frequency analysis is performed, often utilizing Welch's power spectral density estimate. This process turns the raw data, which is a time dependent variable, into a frequency dependent variable and separates the individual sine and cosine waves by plotting them according to the signal power of a given frequency (Figure 1.2). This results in peaks measured by power on the vertical axis at certain frequencies across the horizontal axis that can then be quantified for analysis.

Because tremor consists of a number of distinct frequency components (McAuley, Rothwell, & Marsden, 1997), frequency analysis for postural tasks of the upper limbs are often performed within 0-30 Hz for pointing tasks (Morrison & Newell, 1996) and even handgun aiming tasks (Tang et al., 2008). Spectral analysis of the tremor signal is often assessed within certain band widths based on the mechanical resonant frequency of the relevant segment (upper arm: 1-3 Hz, forearm: 2-4 Hz, hand: 8-12 Hz, finger: 20-25 Hz), as well as the 8-12 Hz neural component (Elble & Koller, 1990; Elble & Randall, 1978; Homberg et al., 1987; Hwang, Chen, et al., 2009; Joyce & Rack, 1974). The power from the dominant frequency peak (peak power) and frequency at which the peak power occurred (Hz) in each bandwidth are then recorded and assessed.

Basic Properties of Tremor

Physiological tremor during a postural task is often viewed in terms of magnitude of oscillation (Carignan et al., 2012b; Frost, 1978; Hwang, Chen, et al., 2009; Morrison & Newell, 2000b). Magnitude of the oscillation often correlates with the impact tremor has on a given task (Coulson et al., 2010; Harwell & Ferguson, 1983; Lakie, 2010; Lakie, Villagra, Bowman, & Wilby, 1995; Mason & Bond, 1990). Understanding physiological tremor is not as simple as assessing its magnitude though. Physiological tremor as a whole reflects the combined output from central and peripheral neural influences, cardiac and respiratory actions, as well as mechanical properties of the body segments (Elble, 2000; Elble & Randall, 1976, 1978; Marsden, 1984; McAuley et al., 1997). By looking at different frequencies within the tremor signal we can better understand the impact these influences have on the magnitude of tremor and a given task.

Many of the foundational physiological studies that focused on examining the separate components of tremor were assessed within a single segment (Elble & Randall, 1976, 1978; Stiles, 1976, 1980; Stiles & Randall, 1967). These studies often supported or secured the forearm to reduce the influence and contribution of tremor of the arm to better examine tremor at the finger or hand (Elble & Randall, 1978; Homberg et al., 1987; Stiles & Randall, 1967). These studies found that there were two dissimilar frequencies that fluctuated within the tremor signal, a steady frequency peak between 8-12 Hz and a variable peak that was found at different frequencies based upon the segment of the limb observed and if mass was added to the limb (Elble, 1986, 2013; Elble & Koller, 1990; Elble & Randall, 1976; Hwang et al., 2006; Morrison & Newell, 1996, 1999).

8-12 Hz Neural Component

The spectral frequency peak found in the 8-12 Hz range has been labeled as the central component of physiological tremor (Elble & Koller, 1990). The 8-12 Hz central component is considered relatively stable because it is not affected by limb mechanics (Elble & Randall, 1978), but, rather, it has been suggested that it originates somewhere in the central nervous system at an unknown central neuronal oscillator (Elble, 1996). A number of proposed origins for the 8-12 Hz central oscillator have been suggested including the spinal cord or alpha motor neurons as well as certain parts of the brain, such as the inferior olive, thalamus, and cerebellum, because they naturally oscillate around 8-12 Hz (Deuschl, Raethjen, Lindemann, & Krack, 2001; Elble, 1996; Elble & Koller, 1990).

Mechanical-Reflex Component

The passive mechanical properties of the limb and the stretch reflex comprise the mechanical-reflex component of physiological tremor, which contributes the largest portion of the tremor signal (Elble, 2013). The mechanical-reflex component integrates the mechanical properties of the limb and the limbs' response to irregularities and perturbations of the contractile properties of the muscle and external influences, respectively (Elble, 1986, 2013). The stretch reflex contributes to tremulous oscillations through response to perturbations of the upper limb. The response is a brief activation of muscles opposite to the direction of the perturbation as a correction. The mechanical-reflex component of tremor differs as a function of mass with heavier segments having a lower frequency of oscillation (Elble & Randall, 1978; Stiles, 1976, 1980; Stiles & Randall, 1967).

Mechanical models can be used to represent motion of the human body. One model that has been utilized previously is the mass-spring model. This model takes in to account stiffness and mass of the limb to replicate the oscillations seen in the body (Homberg et al., 1987; Stiles, 1976; Stiles & Randall, 1967). one segment with a known mass (M) and pivot point together with an established stiffness of (K) are used to predict the resonant frequency of the limb (Morrison & Newell, 2000a).

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \qquad (3)$$

In this model, an increase in mass would result in a decrease in frequency and increase in power of the mechanical-reflex component (Homberg et al., 1987; Raethjen, Pawlas, Lindemann, Wenzelburger, & Deuschl, 2000; Takanokura & Sakamoto, 2001). For example, the resonant frequency properties of the finger, hand, and forearm segments have been reported at 20-25 Hz, 8-12 Hz and 2-4 Hz, respectively (Elble & Koller, 1990; Elble & Randall, 1978; Homberg et al., 1987; Hwang, Chen, et al., 2009; Joyce & Rack, 1974). Limb stiffness (K) has an inverse effect on the mechanical-reflex component of tremor as compared to an increase in mass. An increase in limb stiffness through means such as voluntary co-contraction results in an increase in the frequency of oscillation for the mechanical-reflex component of the respective limb segment (Elble, 2013; Morrison & Newell, 2000a).

Development of Muscle Force in Tremor

Fluctuations in the limb are not surprising given, among other factors, the inability of muscles to produce a constant force. Motor units fire at different rates, the combination of the motor units produce the overall force output. Varying rates of firing in the muscles fibers smooths the output of a muscle contraction (Harwell & Ferguson, 1983). Conversely, increased recruitment of motor units due to fatigue, effort of contraction, or synchronization of the muscle fibers, causes an increase in tremor output (Harwell & Ferguson, 1983). If a limb is being held against gravity, particularly with an added mass, then we would not expect a stationary position due to the fluctuations in force summation.

Tremor in Multiple Linked Segments

Performance of many motor tasks involve multiple limb segments within the body. During these tasks the individual is not responsible for controlling both voluntary motor tasks and respond to involuntary fluctuations within a single segment. The complexity of the problem is amplified by the demand to control the entire limb in addition to motion at the trunk including postural sway, heart, and respiratory actions (Hwang et al., 2006; Keogh et al., 2004; Morrison & Keogh, 2001). An important finding of the early multiple segment studies reported that during postural tasks with the upper limb, an increase in amplitude from proximal (upper arm) to distal (hand) segments (Hwang, Chen, et al., 2009; Hwang et al., 2006; Morrison & Newell, 1996, 1999; Takanokura, Makabe, Kaneko, Mito, & Sakamoto, 2007). In addition, it would seem that when performing postural aiming tasks in a standing position, the tremor evident in any outstretched limb is not coupled to whole body postural motion (Hwang et al., 2006; Kerr, Morrison, & Silburn, 2008) or even to the tremor in the contralateral limb (Morrison & Newell, 1996, 1999). This suggests that concurrent tasks performed by the opposite limb may not directly influence a given limb. Also, it suggests that while the control structure of the central nervous system may control limbs simultaneously, it does not control the limbs during motor tasks in the same identical manner.

Importance of Medial-Lateral and Anterior-Posterior Motion in Postural Aiming

An underlying assumption of tremor is that control over VT motion is the greatest challenge given the person has to compensate for effects related to the force of gravity to maintain the limb extended. This assumption combined with the availability of uniaxial accelerometers led most tremor research to be focused on the VT axis. However, motion may also be found in the ML and AP directions during aiming tasks (Frost, 1978; Hong et al., 2008; Lakie et al., 1995; Mullineaux et al., 2012; Pellegrini & Schena, 2005; Tang et al., 2008). Some studies reported oscillations in the ML direction are comparable in amplitude and structure to that seen in the VT direction with a dual peak (0-7 and 7-14 Hz) frequency spectrum output (Pellegrini & Schena, 2005; Tang et al., 2008). Tang and colleagues (2008) further assessed tremor in the ML and VT directions by separately examining shooting performance in elite and pre-elite athletes. For a single arm-shooting task, they reported that elite athletes exhibited smaller oscillations in the ML direction compared to the VT. Contrastingly, the pre-elite athletes exhibited greater ML motion compared to VT. Few studies have examined tremor in the AP direction, those that have found AP tremor in the distal segment (handgun barrel) to be approximately half the amplitude of the ML and VT tremor (Tang et al., 2008). Unfortunately, no frequency analysis on the AP dimension has been reported in the literature. Amplitude, regularity, and frequency properties of VT, ML, and AP tremor need to be further assessed in order to understand the potential underlying mechanism or mechanisms driving these motions **(see Experiment I)**.

Altering Tremor Dynamics During Postural Tasks

As mentioned previously, tremor within a single limb reflects the contribution from a number of sources, the predominant ones being those related to the mechanical-resonant properties of the segments and those of neural origin (Elble, 1996; Elble & Randall, 1976, 1978; McAuley et al., 1997). The mechanical resonant properties of the limb may be altered by manipulating aspects such as mass and stiffness. Manipulations such as these are often used to dissect tremor for deeper understanding or to further examine the impact tremor has on certain tasks.

Effect of Mass on Tremor

Previous research has shown that the addition of an external weight alters the effective inertia of that segment leading to a change in the tremor dynamics. More specifically, the addition of a mass to the limb increases overall tremor amplitude (Duval & Jones, 2005; Takanokura et al., 2007). The changes seen due to an increase in mass predominately influence the mechanical resonant properties of the limb with a decrease in the spectral peak frequency of the associated segment (Elble & Koller, 1990; Elble & Randall, 1978; Homberg et al., 1987; Stiles & Randall, 1967). As previously stated, the 8-12 Hz neural component is relatively stable and not easily altered by changes in mass (Elble & Koller, 1990; Elble & Randall, 1978). An important aspect to remember when working with tremor is the mechanical resonant peak of the hand as well as the neural component of tremor can both oscillate within the 8-12 Hz band. This may lead to confusion but the two separate peaks can also be teased apart by the addition of mass causing a shift of the mechanical resonant frequency downward often resulting in a double peak (Elble & Randall, 1978; Homberg et al., 1987; Stiles & Randall, 1967). Location of the mass placement is important to note as well due to it being a multilinked system; mass added to one segment can alter the tremor profile of other segments due to altering the mass of the limb as a whole (Raethjen et al., 2000; Stiles & Randall, 1967; Takanokura et al., 2007).

Effect of Stiffness on Tremor

Like mass, altering the support and stiffness can impact tremor dynamics of the aiming limb. Commonly there have been three types of “alterations” that have been utilized to further understand tremor, these consist of intrinsic stiffening through co-contraction of antagonist muscles (Morrison & Newell, 2000a), restricting the motion about a joint through external splinting (Morrison & Newell, 1999), and external support (Carignan, Daneault, & Duval, 2012a; Morrison & Newell, 2000b; Takanokura & Sakamoto, 2001). In general, during postural tasks, when parts of the limb are stiffened the mechanical resonant component of tremor will increase while external support will decrease tremor amplitude. More specifically, voluntarily co-contracting antagonist muscles groups to intrinsically stiffen the limb cause the limb to increase both the frequency and power of the 2-4 Hz, and 8-12 Hz mechanical-resonant tremor peaks (Morrison & Newell, 2000a). Similarly, externally splinting the joints of the limb increases the peak power in the 2-4 Hz and 8-12 Hz bands as well as the frequency of the peak in the 2-4 Hz band, but the frequency of the peak in the 8-12 Hz band decreases with splinting (Morrison & Newell, 1999). Conversely to the findings about stiffening, supporting the limb decreases both the 1-4 Hz and the 8-12 Hz peak power and frequency (Morrison & Newell, 2000b). These studies however used a limb segment (hand) that has a mechanical-resonant tremor frequency approximately the same as the 8-12 Hz neural peak, so it is difficult to differentiate the effect of stiffening on the neural component, also in the 8-12 Hz band.

Influence of Goal Directed Tasks on Tremor

Information about the dynamics of tremor can also be gathered through changing the goal of the task such as manipulating visual focus (Morrison & Keogh, 2001; Pellegrini et al., 2004; Pellegrini & Schena, 2005). When holding an outstretched limb, the tremor profile may change with a given task. For example, the tremor profile may vary if a pointed finger is simply held in an outstretched position or if it is aimed at a target. When pointing with a finger, the ability to see the limb doesn't appear to have an effect on tremor when the goal is an intrinsic focus on reducing tremor of a given segment (Morrison & Newell, 1996); however, when transitioned to extrinsic focus such as maintaining aim at a target, tremor at the finger increased but the rest of the limb did not change significantly (Keogh et al., 2004; Morrison & Keogh, 2001). It is important to note the focus for these studies was finger aiming, so there may be some sort of control about the finger that increases finger tremor but not the other segments. Whether tremor of a handheld gun changes based on whether the gun is simply being aimed or shot at a target is not known **(see Experiment II)**.

Movement Control in Handgun Aiming and Shooting

Tremor is omnipresent in all movements as an inherent property of the neuromuscular system (Elble, 1996; Elble & Koller, 1990; Llinás, 1984), these small oscillations generally do not directly influence many motor tasks due to their size. Many fine motor skills that require minimization of movement about a single endpoint (surgery, archery, shooting) may be negatively impacted by tremor (Hsu & Cooley, 2003; Stuart & Atha, 1990; Tang et al., 2008). These findings have particular relevance for tasks such as pistol shooting, where there is a need to maintain precision and accuracy with the arm extended while also compensating for the added mass of the object (i.e., the gun) being held (Lakie et al., 1995; Pellegrini & Schena, 2005; Tang et al., 2008). The mass of the limb segment would be increased by the addition of a gun. This change in mass would be expected to increase the tremor amplitude and decrease the frequency of tremor in this segment (Pellegrini & Schena, 2005; Tang et al., 2008). The frequency of the 8-12 Hz neural peak should not be affected however an increase in peak power may accompany an increase in mass (Elble & Randall, 1976; Hwang, Chen, et al., 2009; Hwang et al., 2006). These predicted outcomes have not yet been quantified. These predictions based on the addition of the weight of the gun can be evaluated though a comparison of tremor during finger pointing and gun aiming **(see Experiment II).**

Control About the Wrist

In addition to the general findings about tremor amplitude and frequency, altering the limb also revealed an interesting dynamic between the arm and hand. The wrist joint has displayed greater importance during control of a postural task (Coulson et al., 2010). Tremor research has shown there to be greater coupling between segments proximal to the wrist joint as well as segments distal to the wrist joint. The wrist joint does not display as strong of coupling with other joints of the upper limb (Arutyunyan et al., 1968; Hwang et al., 2006; Morrison & Newell, 1996; Pellegrini et al., 2004). Through examining the increase in tremor regularity (lower ApEn) at the hand when compared to other segments as well as the lower coupling between the hand-forearm when compared to other linked segment pairs, it appears that a significant amount of control occurs about the wrist (Morrison & Newell, 1999, 2000a, 2000b). Whether the aiming is completed with the hand or finger, it is important to note the wrist joint displays this feature regardless, unless the wrist joint is immobilized (Morrison & Newell, 1999, 2000b). Because of the control at the wrist in the upper limb, it is important to have an accelerometer both distal and proximal to the wrist joint to examine the effects on either side of this joint during postural tasks.

Degrees of Freedom and the Handgun Control Paradigm

Shooting a handgun from a standing position involves many segments of the body. From a motor control perspective, there are many degrees of freedom (DOF) at the level of the joint space, referring to the number of possible independent dimensions of motion at each joint, that must be controlled (Bernstein, 1967). For example, the distal joint of the first phalanx of the hand can move in just one plane, resulting in one DOF. The shoulder on the other hand, due to the freedom of movement it has, would have three DOF. As we add up the number of DOF across the whole body at the level of the joint space, the complexity in controlling that many independent motions becomes apparent. Indeed, for Nikolai Bernstein, the central problem in motor control was in understanding how humans control the many DOF of the body to perform an action (Bernstein, 1967; Turvey, 1990). In shooting, individuals may reduce the number of DOF involved in the task by sitting or lying down, by bracing against another body part or external surface, or by restricting motion in some DOF while allowing it in others.

Bernstein proposed that, initially multiple DOF act as a hindrance for the novice, who solves the problem by freezing DOF through stiffening some joints (Bernstein, 1967), although we know that stiffening can increase tremor amplitude (Morrison & Newell, 2000a). With experience the individual learns to release DOF, allowing them to move more independently to enhance performance (Bernstein, 1967). Evidence for this process of freezing and then freeing DOF with practice has been observed in a ski simulator task (Vereijken, van Emmerik, Whiting, & Newell, 1992) and for kicking a soccer ball (Anderson & Sidaway, 1994). This can be observed in handgun aiming and shooting with novices becoming rigid and freezing segments except for the minimum essential movements to perform the task until a level of comfort with the task is achieved (Tuller, Turvey, & Fitch, 1982). Experienced marksmen however have been found to free and coordinate DOF in the wrist and shoulder in a compensatory manner to achieve greater efficiency of movement and precision for a given task (Arutyunyan et al., 1968, 1969). While research on tremor has extended consideration of one segment to multi-segments linked together, the influence of the number of degrees of freedom on tremor and handgun shooting has not been considered. Different aiming postures could encourage or discourage the freezing/freeing of DOF. It is unknown whether altering handgun shooting postures to freeze or free more DOF could reduce tremor and increase accuracy or have the opposite effect.

Handgun Aiming Postures

The task of shooting a pistol from a standing position requires minimizing the fluctuations that cause motion at the gun through controlling motion at the joints. In order to overcome some of the control issues evident during aiming tasks, various practices such as shooting with a slightly bent elbow or linking the hands together have been advocated (Department of the Army, 2008; Marine Corps, 2003). These postures have been suggested to reduce lateral torque of the gun during trigger pull and vertical and anterior-posterior torque during recoil. They may also assist in support and control of the handgun during aiming and shooting tasks.

Bent vs. Straight Arm Postures

Utilizing a straight arm during handgun aiming and shooting may reduce the DOF to be controlled my minimizing motion at the elbow and possibly the wrist. While reducing the number of DOF theoretically decreases the control problem it could reduce the ability to compensate for fluctuations through multiple DOF. Instead, bending the elbow encourages use of the elbow and wrist joints (increased DOF) to contribute to controlling the endpoint position rather than focusing control about the shoulder (Arutyunyan et al., 1968, 1969). Alternatively, the recommendation to shoot with a bent rather than a straight elbow may capitalize on a reduced moment of inertia about the shoulder joint by bringing the arm and gun closer to the body, and thereby requiring lower muscle activation of the shoulder flexors to hold the arm up against gravity. Currently, it is unknown whether using a bent elbow improves or worsens the control of aiming and its impact on tremor amplitude. Greater control has been linked with a more regular signal (Morrison & Keogh, 2001; Pincus & Singer, 1996). Presumably, if more control was achieved through bending the elbow lower ApEn value would accompany the increased control **(see Experiment I)**.

Bilateral vs. Unilateral Grip

Holding a handgun with a two-handed grip increases the number of DOF involved in the task through the additional shoulder, elbow and wrist. These additional DOF may provide more control options, which could reduce tremor during aiming and shooting of a handgun (Morrison & Newell, 1999). Employing a double-hand grip during aiming is also believed to provide greater support for holding the mass attributable to the gun, by involving the musculature of the second arm. Finally, a second hand has also been shown to provide additional proprioceptive sensory and joint position information (Aruin, 2005) as well as cause a reduction of muscular grip force in the primary hand (Scholz & Latash, 1998) providing the potential for greater control and decreased amounts of muscle activation (Aruin, 2015). Conversely, an opposing argument could be made that adopting such a posture may result in increased tremor as now the system has to compensate for tremor in both limbs being propagated towards the distal endpoint. Subsequently, if the demand of controlling the oscillations within the two limbs outweighs the support benefit, an overall increase in tremor at the gun may occur **(see Experiment I)**. If two limbs were to prove more effective at reducing tremor, determining whether an increase in support for the mass or increased control and feedback from the second limb caused the improvements would be imperative **(see Experiment III)**. By adding two different masses (heavy, light) to the gun while holding it in an outstretched position with both double and single limbs as support, it can be determined if support or feedback and control is the main contributor. This would be observed by measuring the tremor amplitude during the single limb support condition and determining if adding the second limb or reducing the mass provides a greater reduction in tremor amplitude. As previously mentioned, examining signal regularity and frequency of the aiming postures can lend insight into control (Morrison & Newell, 1999; Pincus & Singer, 1996) and mass support (Homberg et al., 1987; Stiles & Randall, 1967) of the aiming limb. Hence, frequency and regularity measures will be recorded to lend insight into the control mechanisms of these alterations.

Summary

This chapter has outlined the development of projectile use by humans, basics of tremor, how they interact, and how these interactions can be measured through the use of accelerometry. The current research studies seek to answer questions not yet addressed by the existing body of literature. First, linking the hands together to employ a double-hand grip during pistol aiming and shooting is often recommended. In addition to using two limbs during handgun aiming and shooting tasks, slightly bending the elbows has also been endorsed. Examining various combinations of these aiming postures through the use of accelerometry may reveal an optimal combination of support and control for handgun use **(see Experiment I)**. Second, tremor has been assessed separately in the outstretched limb with finger pointing and aiming a gun, however, a comparison of the similarities and differences between the two tasks in a single study has not been completed. A study that could compare the two could link the traditional tremor literature with the pistol shooting literature **(see Experiment II)**. Third, using two hands as opposed to a single-hand grip in handgun shooting could reduce tremor by providing a simple mechanical advantage or through the involvement of more degrees of freedom, but this is not yet known **(see Experiment III)**. Overall, the combination of these three experiments seeks to expand upon the current knowledge of both motor control and performance of handgun aiming and shooting.

Experiment I

Title

Three-dimensional Assessment of Postural Tremor during Goal-Directed Aiming.

Statement of Purpose

The purpose of this investigation was to assess the tremor dynamics of aiming a handgun and determine whether altering the aiming posture can minimize the tremulous perturbations associated with a goal-directed aiming task.

Research Hypotheses

1. Distal segment tremor will be larger and more regular than the proximal segment.

2. Tremor in the vertical direction will have a greater amplitude when compared to tremor in the medio-lateral and anterior-posterior direction.

3. Oscillations during bilateral aiming postures will have a smaller amplitude and more regular signal when compared to unilateral aiming postures.

4. Oscillations during bent elbow aiming postures will be lower and more regular when compared to straight elbow aiming postures.

Experiment II

Title

Acceleration Dynamics of Finger Pointing, Handgun Aiming, and Handgun Shooting

Statement of Purpose

The purpose of this study is to determine how tremor dynamics impact handgun shooting by assessing tremor in the segments of the upper limb during finger pointing, handgun aiming, and handgun shooting.

Research Hypotheses

1. The acceleration profile of the forearm and upper arm during handgun aiming will be comparable to the tremor profile of finger pointing condition in all three directions.

2. Gun barrel accelerations in all three directions will be similar to the hand tremor profile rather than the finger due to the handgrip used as well as the mass of the gun being more similar to the hand than the finger. The gun and hand will display a smaller more regular acceleration signal and will lack the higher frequency peak (18-25 Hz) usually found in finger tremor.

3. The increased load will lead to an overall decrease in amplitude of acceleration and increase in regularity.

4. The handgun shooting condition will have a greater amplitude and regularity of oscillation in all three directions when compared to finger pointing or handgun aiming.

Experiment III

Title

Influence of Handgun Grip and Weight on Shooting Accuracy and Involuntary Oscillations of the Upper Limb

Statement of Purpose

The purpose of this study is to determine if utilizing two hands provides strictly a mechanical advantage of holding the weight of the gun or whether the second limb provides additional aiming control and shooting accuracy.

Research Hypotheses

1. Bilateral limb support will decrease tremor amplitude and decrease regularity of the tremor signal in all three directions as compared to unilateral limb support.
2. Double weight condition will lead to an overall decrease in amplitude of acceleration and increase in regularity in all three directions as compared to the single weight condition.
3. Bilateral limb support will improve shooting accuracy as compared to unilateral limb support.
4. Double weight condition will improve shooting accuracy as compared to the single weight condition.

Limitations

1. The current studies did not assess postural sway.
2. Experiment I only assessed tremor at the gun barrel and forearm.
3. Experiment II and III did not assess tremor of the non-dominant limb.

Delimitations

Experiment I: A potential delimitation of the current design was the lack of any distinct measure of accuracy during the aiming task.

Experiment II and III: A potential delimitation of the current design is the lack of actual shooting accuracy during the task. Although accuracy is measured by laser, the true response to a live fire situation may be different than observed during this study.

Operational Definitions

1. Frequency- a measure of the quantity of occurrences per unit of time. In accelerometry this is most often used to assess the oscillations in the tremor signal per second.
2. Motor control- Motor control is the integration of the brain and musculoskeletal system used to coordinate the body for postural and motor tasks.
3. Spectral analysis- converts time series data to frequency dependent data, used in tremor analysis to break down the raw signal into separate oscillating frequencies for further examination.
4. Time series- Values measured over time.
5. Tremor- Involuntary oscillations causing the limb to fluctuate in an approximately rhythmical manner, often difficult to see to the naked eye in healthy persons.

CHAPTER II

EXPERIMENT I

Title

Three-dimensional Assessment of Postural Tremor during Goal-Directed Aiming.

Introduction

When performing a goal directed aiming task requiring a degree of precision and accuracy, small tremulous fluctuations in a limb segment can negatively impact performance (Harwell & Ferguson, 1983; Hsu & Cooley, 2003; Keogh et al., 2004; Pellegrini et al., 2004; Tang et al., 2008). Within a limb, these small, involuntary oscillations are referred to as physiological tremor and reflect the combined output from central oscillatory sources, peripheral neural influences (i.e., stretch reflex involvement), cardioballistic events, and resonant (mechanical) properties of the segment in question (Elble, 2000; Elble & Randall, 1976, 1978; Marsden, 1984; McAuley et al., 1997). While tremor is considered an invariant property of the neuromuscular system, and so is always present to some degree in all movements (Elble, 1996; Elble & Koller, 1990; Llinás, 1984), these oscillations are usually of small amplitude and so do not directly influence many motor tasks. However, the performance of many fine motor skills that require minimization of movement about a single endpoint, such as that found during many surgical techniques (Coulson et al., 2010; Fargen, Turner, & Spiotta, 2016; Harwell & Ferguson, 1983; Hsu & Cooley, 2003; Safwat, Su, Gassert, Teo, & Burdet, 2009) or for goal-directed aiming tasks such as pistol shooting (Lakie et al., 1995; Pellegrini & Schena, 2005; Tang et al., 2008) and archery (Keast & Elliott, 1990; Stuart & Atha, 1990), can be impacted by tremulous activity.

In contrast to many of the foundational physiological studies of tremor that have focused on studying tremor within a single segment (Elble & Randall, 1976, 1978; Stiles, 1976, 1980; Stiles & Randall, 1967), the performance of precision tasks of this nature usually involves multiple limb segments within the body. Consequently, the control problem faced by the individual does not simply involve minimizing tremor within a single segment, but now involves accounting and compensating for the different oscillatory properties within the body (i.e., postural sway, tremor, cardiac events) and their interaction – both of which could affect performance (Hwang et al., 2006; Keogh et al., 2004). Previous studies have reported that when performing a postural pointing task with the upper limb, the pattern of tremor increases in amplitude from proximal to distal, although the increase from segment-to-segment is not the product of simple linear addition (Hwang, Chen, et al., 2009; Hwang et al., 2006; Morrison & Newell, 1996). Within a single limb, the pattern of tremor appears to be organized about the wrist joint in a compensatory manner, with tighter coupling between the more proximal (i.e., upper arm-forearm) and distal (i.e., hand-finger) being evident (Arutyunyan et al., 1968; Hwang et al., 2006; Morrison & Newell, 1996; Pellegrini et al., 2004). This compensatory coupling arrangement effectively reduces the total number of individual segments (i.e., joint space degrees of freedom, DOF) to be controlled by restricting the motion about certain upper limb joints (e.g., elbow, metacarpophalangeal) while allowing motion about other joints (e.g., wrist) in order to meet the goal of minimizing tremor at the endpoint (Vereijken et al., 1992). However, freezing the upper limb joint DOF's through active stiffening of the arm by co-contracting antagonist muscles (Bernstein, 1967; Vereijken et al., 1992) has been shown to be less effective, leading to an overall increase in tremor at the periphery (Morrison & Newell, 2000a). Other practices that have been adopted in an effort to minimize tremor during aiming tasks include linking the hands together or shooting with a slightly bent elbow (Department of the Army, 2008; Marine Corps, 2003). From a control perspective, linking the hands together during aiming is believed to provide greater support while holding the gun by increasing the number of DOF involved in the task. However, this strategy may come with a cost, since the adoption of such a position could lead to an increase in tremor due to the summative effect of tremor from both limbs converging on the endpoint. The recommendation to shoot with a bent elbow (rather than a straight one) may afford the system two advantages; with the arm bent, the moment of inertia of the upper arm relative to the shoulder would be effectively reduced and so less muscle activation of the shoulder flexors would be required. Similarly, performing the aiming task with a bent elbow (rather than an extended one) means that control can be exerted separately over motion at the shoulder, elbow, and wrist joints (increased DOF), rather than focused on the shoulder alone (decreased DOF), to control the endpoint position (Arutyunyan et al., 1968, 1969).

While tremor is an intrinsic output of the motor system that is generally of low amplitude, these oscillations can be enhanced by specific task conditions such as exercise-induced fatigue (Bousfield, 1932; Huang et al., 2007; Palmer, 1991; Saxton et al., 1995), changing the number of segments (more joint DOF) used in the task (Morrison & Newell, 2000b; Morrison & Sosnoff, 2009), or by altering the mechanical properties of the limb by adding weights to the limb (Hwang, Chen, et al., 2009; Stiles, 1980; Takanokura et al., 2007). The findings of the latter studies have particular relevance for the performance of skilled aiming tasks such as pistol shooting (Lakie et al., 1995; Pellegrini & Schena, 2005; Tang et al., 2008), where there is a need to maintain precision and accuracy while also compensating for the added mass of the object being held (i.e., the gun). As mentioned previously, the tremor within a single limb reflects the contribution from a number of sources, including those of central and peripheral (i.e., reflex) neural origin, and mechanical-resonant properties of the segment (Elble, 1996; Lakie, Walsh, & Wright, 1986; McAuley et al., 1997; Stiles, 1980; Stiles & Randall, 1967). The fact that peripheral stretch reflex involvement is inter-related with limb mechanics means that these two sources are interwoven and are often collectively referred to as mechanical-reflex oscillator (Elble & Koller, 1990; Stiles, 1976). The primary central neural peak is commonly seen within the 8-12 Hz range and reflects input from such structures as the basal ganglia and thalamus (Elble, 1996, 2000; Marsden, 1984). The mechanical-reflex component differs as a function of change in inertia with heavier segments having a lower frequency of oscillation (Stiles, 1980; Stiles & Randall, 1967). For example, the resonant frequency properties of the finger, hand and forearm segments have been reported at 20-25 Hz, 8-12 Hz and 2-4 Hz respectively (Elble & Koller, 1990; Elble & Randall, 1978; Homberg et al., 1987; Hwang, Chen, et al., 2009; Joyce & Rack, 1974). Consequently, holding a gun in the hand would increase the effective mass of this segment leading to a predictable decrease in the resonant frequency of tremor in this segment (Pellegrini & Schena, 2005; Tang et al., 2008) while reducing the amplitude but not the frequency of the neural 8-12 Hz peak (Elble & Randall, 1976; Hwang, Chen, et al., 2009; Hwang et al., 2006).

When performing tasks of this nature, an underlying assumption is that control over vertical (VT) motion is the greatest challenge given the person has to compensate for effects related to the force of gravity to maintain the limb extended. However, motion may also be found in the medial-lateral (ML) and anterior-posterior (AP) directions during aiming tasks (Hong et al., 2008; Lakie et al., 1995; Mullineaux et al., 2012; Pellegrini et al., 2004; Pellegrini & Schena, 2005; Tang et al., 2008). Interestingly, several studies have reported that oscillations in the ML direction are comparable in amplitude to that seen in the VT direction (Pellegrini et al., 2004;

Tang et al., 2008). Both studies emphasized that the large amplitude tremor-like motion in the ML direction was an important component of goal directed pointing tasks, although the exact origin(s) of this component of tremor still needs to be determined. Similarly, there have been very few studies that have captured tremor in the AP direction for comparison.

The current study was designed to assess the dynamics of tremor in the AP, ML and VT directions when performing a goal-directed aiming task. Due to the need to counteract the force of gravity, it was hypothesized that tremor in the VT direction will have a greater amplitude when compared to tremor in the AP or ML direction. The structure of tremor in each direction was also investigated to provide information about the sources of these. A secondary aim was to examine the impact of adding more DOF to be controlled during the pointing task. To this effect, we compared the tremor output for the forearm and gun barrel under conditions where the task was performed with one or two arms and under different arm postures (extended/flexed elbow). For this aim, we hypothesized that tremor would be less when performing the task with both arms (i.e., greater control with additional DOF) and when having a bent elbow (i.e., encouraging motion at the elbow and wrist in addition to the shoulder to control the gun position).

Methods

Participants

Thirty healthy participants (12 women and 18 men, mean age 26.9 $\pm$ 7.8 years), volunteered for the study. All participants self-reported as being right hand dominant and reported no current heart, respiratory, neurological, or musculoskeletal health issues. Written informed consent was obtained from each subject prior to testing. All experimental procedures were approved by the university's Institutional Review Board.

Apparatus

Acceleration (tremor) about the forearm and gun barrel were measured using three lightweight Noraxon triaxial accelerometers (2.8 grams, range ±2 g; Noraxon U.S.A. Inc., Scottsdale, AZ). For the forearm, accelerometers were securely attached to the dorsal aspect of each wrist, approximately 1 cm proximal to the radio-carpal joint. This placement, when the gun was in the hand oriented vertically, allowed the wrist to orient itself facing medially aligning the wrist accelerometers with the appropriate axes. The third accelerometer was affixed to the distal, lower portion of the gun barrel on the rail, ensuring the vertical axis was perpendicular to the ground while aiming. Figure 2.1 illustrates the general position of the accelerometers during the double-arm aiming posture. A Blueguns (Ring's Manufacturing, Melbourne, FL) Smith and Wesson M&P40 replica, weighted training gun (0.8 kg), was used for all trials. Accelerometers were tethered to the Noraxon TeleMyo 2400T G2 transmitter affixed to the waist of the participant. A 17 cm, 5 ring, black and white bull's-eye target was used for all aiming tasks. The target was positioned at a height of 1.5 meters and at a distance of 6.4 meters.

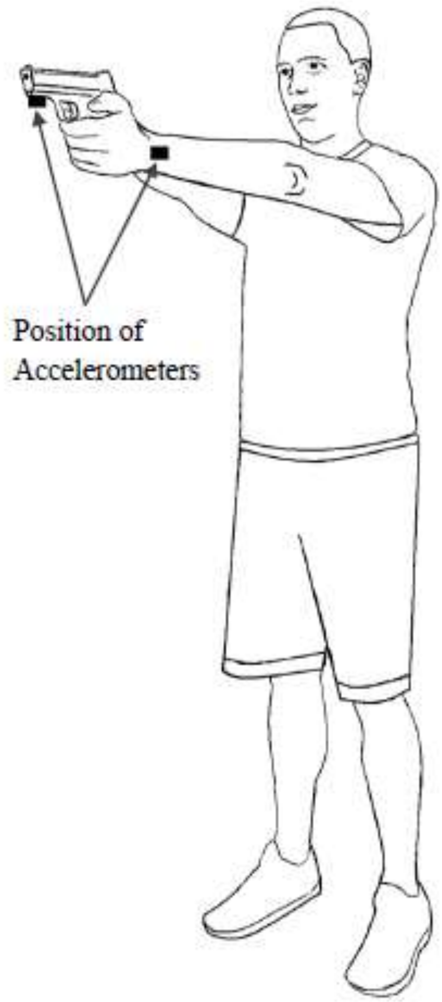

Fig. 2.1: Illustration of the standing position during the bilateral, straight arm shooting task. The placement of the trial axial accelerometers on the forearm and gun barrel are highlighted.

Experimental protocol

Each person completed a series of aiming postures where tremor from the forearm and gun barrel was recorded. The specific conditions were; 1) double hand grip/bent elbows, 2) double hand grip/straight elbows, 3) right hand grip/bent elbow, 4) right hand grip/straight elbow, 5) left hand grip/bent elbow, 6) left hand grip/straight elbow. During bilateral conditions the secondary hand was utilized to support and assist with aiming of the handgun whereas the unilateral condition only had one hand on the gun. Straight conditions utilized a fully extended and locked elbow while bent conditions required the elbow to be flexed to allow more motion at the elbow joint. The degree of tilt at the wrist and gun was assessed from accelerometer data during each trial. Analysis of the accelerometers' tilt revealed a significant difference ($p<0.001$) in the angle of the forearm accelerometer during straight and bent conditions (5.96 ± 4.38 and 23.34 ± 10.75 degrees, respectively) but no significant change ($p=.09$) in the angle of the gun accelerometer between straight and bent conditions (12.11 ± 1.75 and 12.30 ± 1.36 degrees, respectively). The order with which the six aiming postures were performed was counter-balanced between participants. All subjects completed five, 10-second trials for each of the aiming postures before switching to the next condition. Participants were given a 10-second period of rest between trials and approximately one minute of rest between conditions to offset any fatigue effects.

The participants performed the task while standing. On the command to "aim" the participant raised the gun to the pre-determined posture and maintained a steady aim and focus at the target. Once in position the researcher started data collection. After 10 seconds, data collection automatically stopped and the instruction was given to "lower the gun." This same procedure was repeated for each trial and all conditions.

Data analysis

Data from the triaxial accelerometers were collected at 1500 Hz via Vicon Nexus 1.8.1 (Vicon Motion Systems Ltd., Oxford, England) and processed using custom written Matlab software (R2012A, MathWorks, Natick, MA). After collection, all acceleration data were down sampled to 100 Hz for subsequent analysis. A second-order, zero-lag, low-pass Butterworth filter with a 50 Hz cutoff frequency was used to filter the data. The axes were transformed to a horizontal-vertical coordinate system according to the algorithm determined by Moe-Nilssen (Moe-Nilssen, 1998a, 1998b). This alignment correction was also custom written in Matlab.

For each segment, the tremor (acceleration) data were assessed in the anterior-posterior (AP), medial-lateral (ML) and vertical (VT) axes. Initial analysis revealed no differences between the left and right forearms during any conditions so, as a result, data from these segments were collapsed across limbs, the values averaged and reported as one combined wrist segment. Analysis of the acceleration data was designed to assess changes in signal amplitude, regularity and frequency.

Amplitude: The amplitude of the tremulous oscillations in the AP, ML and VT dimensions were examined from root mean square (RMS) accelerations (g).

Regularity: An indication of the pattern of regularity of the acceleration signals was determined using Approximate Entropy (ApEn). This analysis, measures the time-dependent repeatability of a signal (X) by calculating the natural logarithm of the ratio of the count of recurring vectors of length m against that of m+1. For the current analysis m=2. The error tolerance was set as r= 0.2 and multiplied by the standard deviation of the signal. The output of this analysis is a single number from 0 to 2 with lower values indicating increased regularity or predictability for a given signal. The equation for ApEn is as follows:

$$ApEn(\vec{X}, m, r) = \ln\left[\frac{C_m(r)}{C_{m+1}(r)}\right] \qquad (1)$$

Frequency: Analysis of tremor in the AP, ML and VT axes were evaluated using Welch's power spectral density estimate within the range of 0-30 Hz. The spectral analysis was performed using a 512-data point length FFT (256 data point window size, 128 data point overlap). As tremor consists of a number of distinct frequency components (McAuley et al., 1997), frequency analysis was performed within 0-6 Hz and 6-14 Hz ranges. For the acceleration data, the power from the dominant frequency peak (peak power, g^2), and frequency at which the peak power occurred (Hz) were calculated for each bandwidth and trial.

Statistical analysis

Statistical analyses were conducted using SAS software (Version 9.3, SAS Institute Inc., Cary, NC, USA). The analysis was designed to address two principal questions; 1) how tremor varied by segment (forearm vs. gun) and direction (AP, ML and VT) and, 2) what specific effects the different aiming positions have on the tremor dynamics. For the first analysis, a 2 x 2 (segment by direction) repeated measures generalized linear model (GLM) was employed. For the second analysis, each dependent variable was analyzed as a function of limb support (double, single) and arm posture (bent, straight). Main effects for both designs were analyzed using the *Tukey–Kramer* method confidence interval adjustment. Data are presented as mean ± standard deviation (SD) unless stated otherwise. The significance for all tests was set at an alpha level of 0.05.

Results

The pattern of the tremor between the gun barrel and forearm, as shown in figure 2.2, was similar across all of the postural aiming conditions. This figure highlights the tremor in the three directions (AP, ML, and VT) for each segment and the respective frequency profiles during a single aiming condition. This figure also illustrates the relative size of the oscillations seen at each point, with both tremor in the ML and VT being markedly higher than for the AP direction.

Three-Dimensional Tremor Features during Aiming

RMS Amplitude: Figure 2.3 illustrates the mean RMS values for the AP, ML and VT tremor for the forearm and gun barrel. A significant segment by direction effect was found for mean RMS amplitude ($F_{2,58}$ =507.39, p <0.001) with both VT and ML tremor being greater at the gun barrel compared to the forearm (p's <0.001). No difference was seen for acceleration in the AP direction between the forearm and gun barrel. Across segments ML tremor was significantly greater than the VT (p <0.001) and AP was significantly lower than both, approximately half the amplitude of ML (p <0.001) and VT (p <0.001).

Regularity: A significant segment by direction effect was found for ApEn ($F_{2,58}$ =459.00, p <0.001). For tremor in the AP, ML and VT directions, ApEn values decreased from the forearm to the gun barrel with the changes for VT and AP tremor being significant (p <0.001) while the decline for ML values was not (p =0.389). Figure 2.3 illustrates the general pattern of change for the ApEn values as a function of direction (AP, ML and VT) and segment.

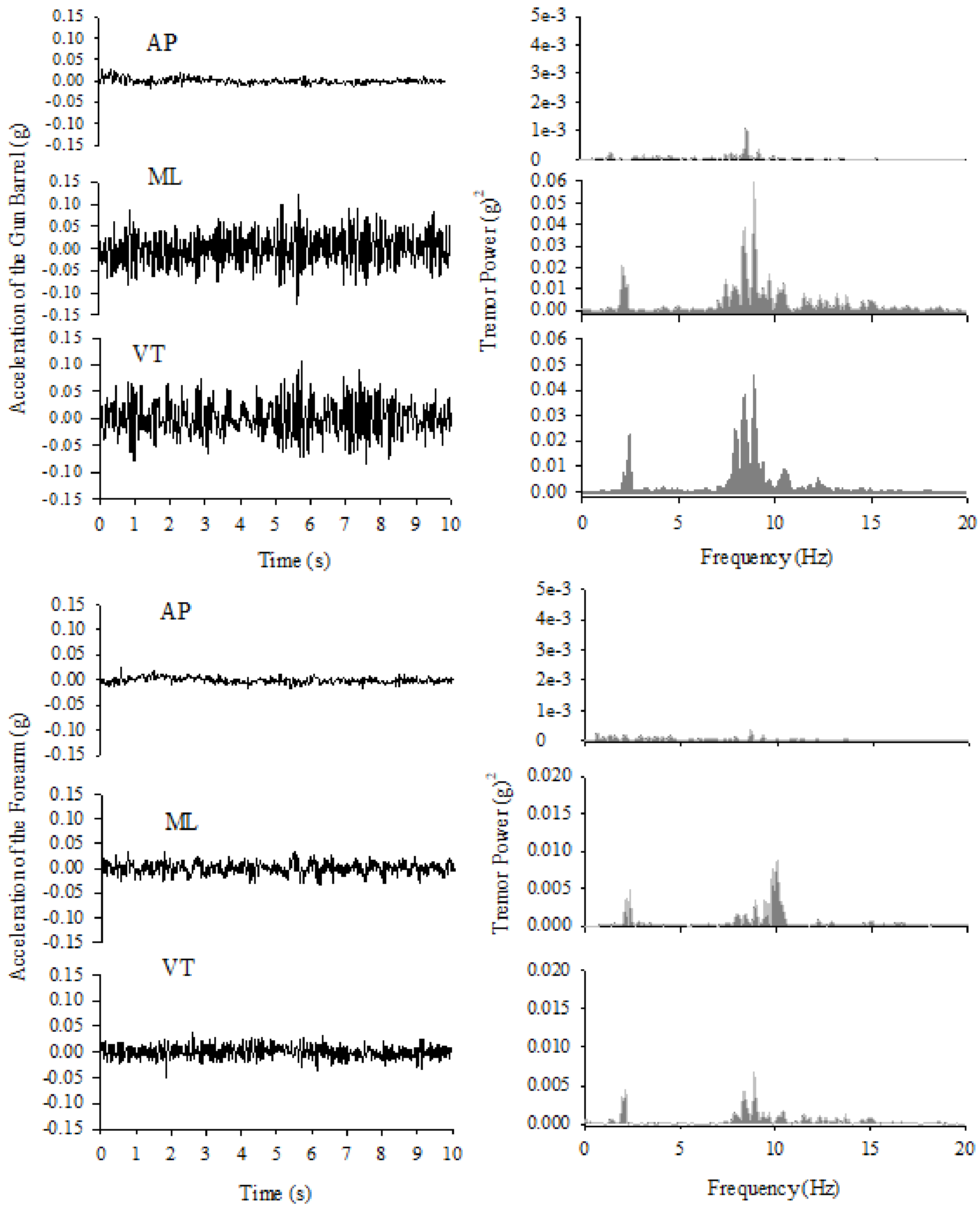

Fig. 2.2: Representative raw acceleration traces (left column) for tremor oscillations at the gun barrel and the forearm in the anterior-posterior (AP), medial-lateral (ML), and vertical (VT) directions for a single subject. Power spectral density plots (right column) for each acceleration trace are also shown.

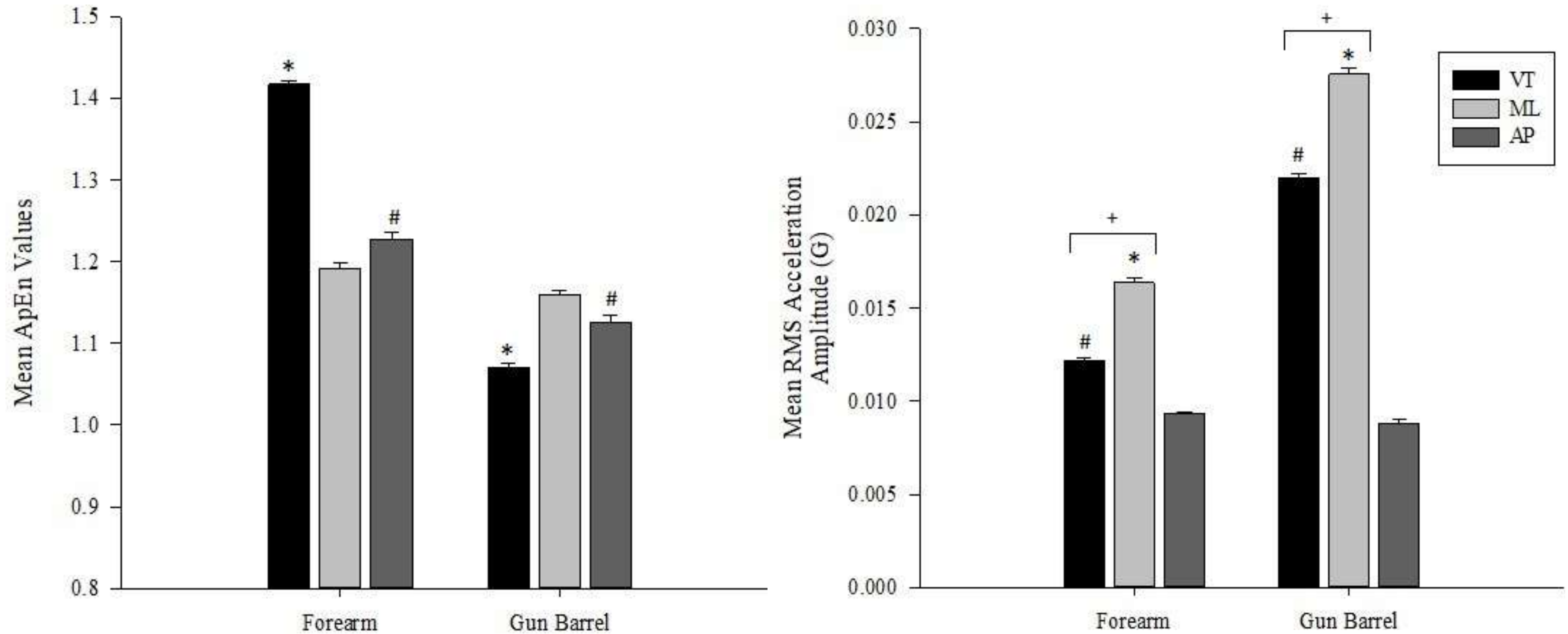

Fig. 2.3: Changes in mean RMS acceleration amplitude and mean ApEn values for the forearm and gun in the vertical (VT), medial-lateral (ML), and anterior-posterior (AP) directions. Values were collapsed across all four aiming positions to ascertain the overall pattern of change across all conditions. Error bars represent one standard error from the mean. $^+$ML RMS is significantly greater than VT at the gun barrel and the forearm, both are significantly greater than AP. *ML RMS at the gun barrel is significantly greater than at the forearm. $^\#$VT RMS at the gun barrel is significantly greater than at the forearm. *ML and $^\#$AP ApEn values were significantly greater at the forearm than at the gun barrel.

Frequency: The frequency profile for the forearm and gun barrel oscillations in the VT and ML directions was characterized by two prominent peaks, a lower frequency component between 1-4 Hz (Forearm- VT: 2.3$\pm$0.7 Hz, ML: 1.1$\pm$1.1 Hz; Gun barrel- VT: 2.6$\pm$1.1 Hz, ML: 4.1$\pm$2.0 Hz) and a second peak between 8-12 Hz (Forearm- VT: 9.8$\pm$2.0 Hz, ML: 10.1$\pm$2.0 Hz; Gun barrel- VT: 8.8 $\pm$ 2.0 Hz, ML: 9.4 $\pm$ 2.1 Hz). Tremor in the AP direction was more broadband in appearance, with the typical signal exhibiting a low level of power with no single prominent peak(s). The changes in mean peak power and frequency of the peaks within the 1-4 Hz and 8-12 Hz ranges are shown in figure 2.4 as a function of segment and direction.

While the general frequency profile was similar across segments and between the two directions, there were differences in terms of peak power (amplitude) and frequency at which this peak was seen within each bandwidth (Figure 2.4). Within the lower frequency range (1-4 Hz), a significant segment by direction interaction effect was found for both peak power ($F_{2,58}$ =85.87, $p<0.001$) and frequency ($F_{2,58}$ =632.86, $p<0.001$). Peak power was greatest for the VT oscillations at the gun barrel, decreasing for ML and AP oscillations at the same point. Peak power in the ML direction was significantly smaller at the forearm compared to the gun barrel (p's<0.001). Peak power of the tremor in the AP direction was not significantly different between the forearm and gun barrel (p=0.437). For the frequency of these peaks, the ML peak for the gun barrel was the highest (~ 4 Hz), while the forearm was lowest (~ 1 Hz). In contrast, the VT peak for the gun barrel and the forearm were similar (both around 2 Hz).

For oscillations within the 8-12 Hz range, a significant segment by direction interaction effect was found for peak power ($F_{2,58}$ =187.67, $p<0.001$). The amplitude of oscillations at the gun barrel was considerably larger than at the forearm. For both segments, peak power was highest in the ML direction, followed by VT and then AP. A significant main effect for segment was found for the frequency of the 8-12 Hz peak ($F_{2,58}$ =14.71, $p<0.001$), with the peak being found at a higher frequency within the forearm as compared to the gun barrel. No significant main effect for direction or interaction was observed for frequency of the peak power.

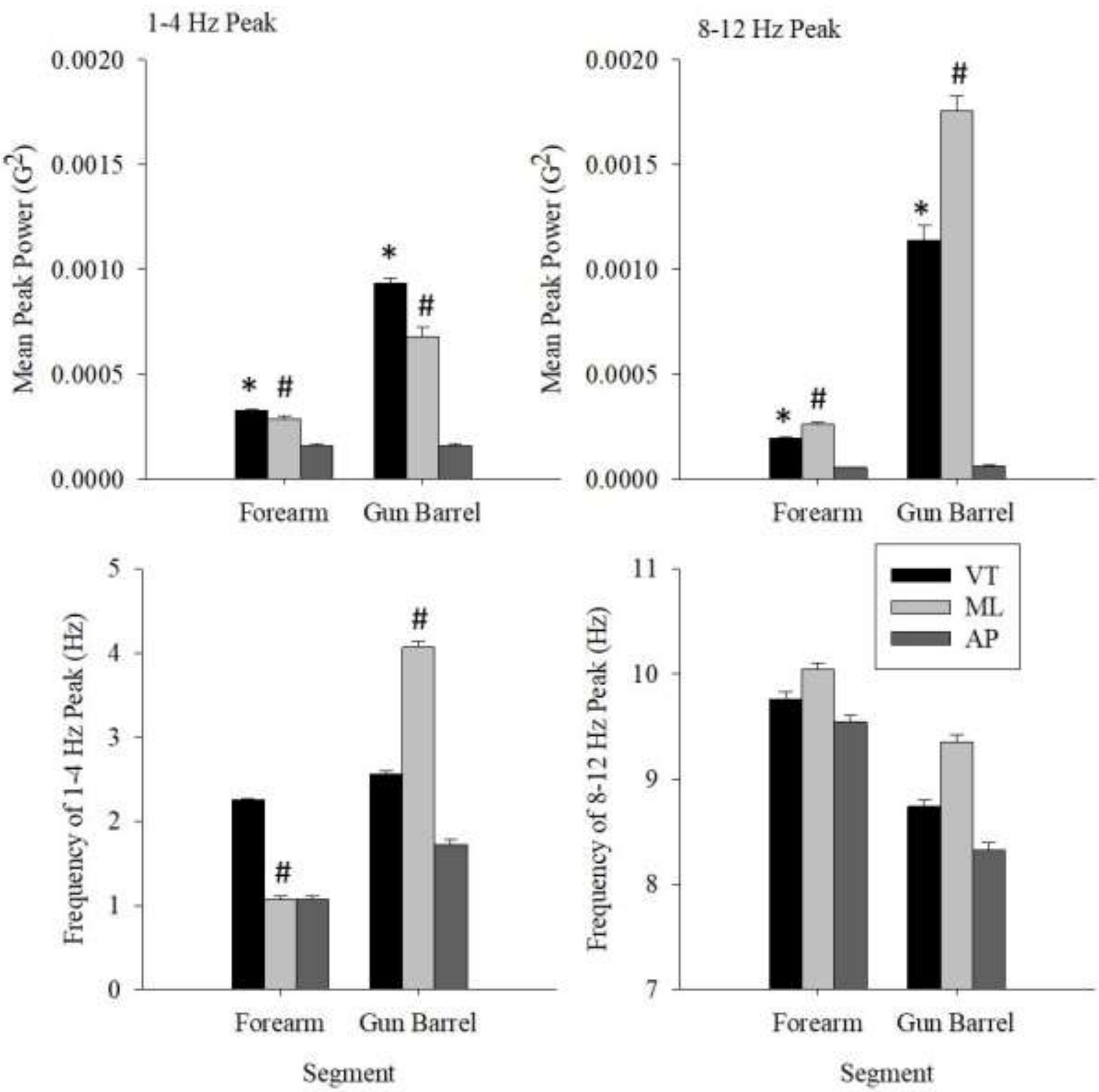

Fig. 2.4: Changes in frequency feature of the tremor signals (peak power, frequency of peak power) within the 1-4 Hz (left column) and 8-12 Hz (right column) bands. *VT and #ML peak power were significantly greater at the gun than the forearm for both the 1-4 and 8-12 Hz peaks. #Frequency of the 1-4 Hz peak in the ML direction were significantly greater at the gun barrel when compared to the forearm. Error bars represent one standard error from the mean.

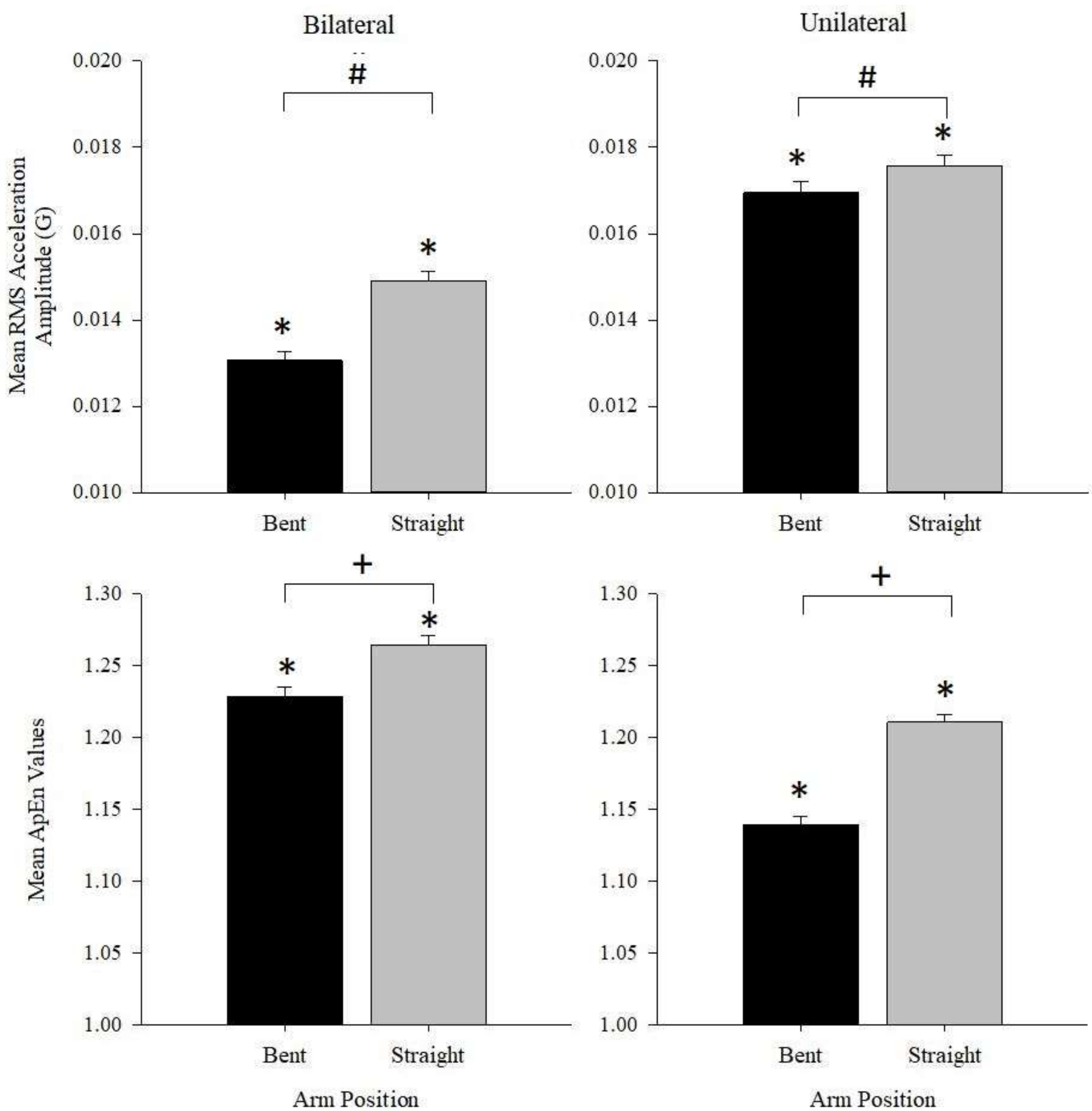

Fig. 2.5: Differences in mean acceleration amplitude (RMS) and ApEn values as a function of arm position (i.e., bent, straight elbow) and limb used (single arm or two arms). Values were collapsed across direction and segment to ascertain the overall pattern of change due to the four aiming positions. #Bilateral RMS was significantly lower than unilateral. +Bilateral ApEn was significantly greater than unilateral. *Bent was significantly lower than straight for both RMS and ApEn. Error bars represent one standard error from the mean.

Effect of Aiming Postures

RMS Amplitude: The amplitude of oscillations was significantly lower during the bilateral conditions as compared to the unilateral support conditions ($F_{1,29}$ =409.53, p<0.001). For the arm position conditions, tremor was significantly greater during the straight arm posture compared to when the aiming task was performed with a bent elbow ($F_{1,29}$ =57.93, p<0.001). There was no significant interaction effect between handgrip or arm posture. The changes in mean RMS and ApEn as a function of limb used (i.e., bilateral and unilateral) and arm position (i.e., bent vs. straight) are shown in figure 2.5.

Regularity: During the bilateral handgrip task, tremor was less regular (higher ApEn value) compared to the unilateral support conditions ($F_{1,29}$ =255.11, p<0.001). For the arm posture conditions, ApEn values were significantly lower (i.e., the signal was more regular) during the bent elbow condition compared to when a straight elbow was used ($F_{1,29}$ =145.74, p<0.001). There was no significant interaction effect between limb used and arm posture.

Frequency Analysis: Under bilateral handgrip conditions, the peak power (amplitude) of both the 1-4 Hz component ($F_{1,29}$ =136.7, p<.001) and the 8-12 Hz component ($F_{1,29}$ =204.99, p<0.001) were significantly less than that seen for unilateral conditions. Regarding the frequency of these peaks, under bilateral conditions peak power was seen at a lower frequency for the 1-4 Hz peak ($F_{1,29}$= 12.32, p=0.002) and slightly higher frequency for the 8-12 Hz peak ($F_{1,29}$ =2.42, p<0.001) compared to unilateral conditions.

When the aiming task was performed with the arm straight, the amplitudes of both peaks (i.e., 1-4 Hz and 8-12 Hz) were significantly greater than under conditions when a bent elbow posture was used (1-4 Hz: $F_{1,29}$ =10.48, p=.003; 8-12 Hz: $F_{1,29}$ =61.63, p<0.001). Analysis of the peak frequency revealed that, under the straight arm conditions 8-12 Hz peaks were observed at higher frequency ($F_{1,29}$ =4.43, p=0.044), while 1-4 Hz did not change significantly ($F_{1,29}$ =.60, p=0.444) when compared to bent elbow conditions.

Discussion

When people hold their arm outstretched during the performance of a goal directed aiming task, small tremulous oscillations within the limb segment can become problematic for maintaining precision and accuracy. The current study was designed to examine the pattern of tremulous oscillations in the anterior-posterior (AP), medial-lateral (ML), and vertical (VT) directions during the performance of a goal-directed aiming task whereby different arm postures were adopted. Overall, the tremor recorded for the forearm(s) and gun barrel were remarkably similar across conditions, irrespective of the posture adopted. Both ML and VT tremor at the more distal aspect (the gun barrel) was signficantly greater in amplitude than the tremor observed within the forearm. Interestingly, oscillations in the ML direction were greater than the VT tremor across all conditions, a finding which may reflect compensatory adjustments made during the aiming tasks. Tremor in the AP direction was markedly less than the ML and VT components and did not alter signficantly from the forearm to the gun barrel.

Tremor Profiles during Aiming

When using the entire arm to perform a postural aiming task, the resultant tremor (in the VT direction) tends to increase in amplitude from proximal to distal segments (Hwang, Chen, et al., 2009; Hwang et al., 2006; Morrison & Newell, 1996, 1999), although this progressive increase is not in a linear fashion. However, tremulous motion for a task of this nature is not restricted to one direction or plane of movement (Pellegrini et al., 2004; Tang et al., 2008) and so one goal of this study was to capture the tremor dynamics in all three directions during the pointing task. The results from the current study demonstrate that side-to-side (ML) tremor follows a similar trend to the VT oscillations, increasing from proximal to distal while AP oscillations did not tend to change appreciably from forearm to gun barrel.

Regarding the ML tremor, a notable feature was that across all aiming postures ML oscillations were greater in amplitude than the oscillations seen in the VT and AP directions. This result is similar to that previously reported by both Pellegrini and Schena (2005) and Tang et al. (2008). The frequency characteristics of the ML tremor were similar to the VT tremor, with two distinct frequency peaks (between 1-4 Hz and 8-12 Hz), being observed (Hwang, Chen, et al., 2009; Hwang et al., 2006; Keogh et al., 2004; Morrison & Newell, 1996, 1999; Tang et al., 2008). It should be noted that the lower frequency component cited by Tang et al (2008) was between 4-7 Hz (not 1-4 Hz), although methodological and subject variations may account for this difference.

While ML tremor has been reported previously (Hong et al., 2008; Hsu & Cooley, 2003; Pellegrini et al., 2004; Pellegrini & Schena, 2005; Tang et al., 2008), there is still some discussion as to the origin of these oscillations. One assumption is that these oscillations could reflect voluntary corrective adjustments during the aiming tasks to maintain accuracy (Pellegrini et al., 2004). This result is certainly borne out by the presence of tremor within the lower frequency range (i.e., 1-4 Hz), given that oscillations within this bandwidth have been attributed to visuomotor processing during movement tasks (Foulkes & Miall, 2000; Miall, Weir, & Stein, 1985; Reed, Liu, & Miall, 2003). However, a larger contribution to the overall ML tremor signal was derived from the 8-12 Hz component, a frequency above the maximum speed at which voluntarily movement has been reported to be performed (Aoki & Kinoshita, 2001; Arunachalam, Weerasinghe, & Mills, 2005; Jobbagy, Harcos, Karoly, & Fazekas, 2005). Given that the ML oscillations are not directly affected by gravity, the major inputs driving postural tremor in the VT direction are unlikely to exert a similar influence on tremor in the ML plane. For example, while resonant properties of the hand do fall within the 8-12 Hz range, the emergence of this peak is typically linked to the effects of gravity (Lakie et al., 1986; Stiles, 1976, 1980; Stiles & Randall, 1967). For ML motion, the effects of gravity are perpendicular to the plane of movement meaning the direct contribution of resonant effects for the ML 8-12 Hz component is probably diminished. A more likely argument is that a significant component of the 8-12 Hz ML tremor reflects input from central neural influences. In a series of studies, Wessberg and colleagues reported that slow, voluntary movements are often characterized by fluctuations in the motor signal within the 8-10 Hz range (Vallbo & Wessberg, 1993; Wessberg & Vallbo, 1996; Wessberg & Vallbo, 1995). They concluded that these 8-10 Hz discontinuities are driven by central modulation of motor unit activity leading to small, tremor-like fluctuations in the resultant movement signal. Thus, the resultant ML tremor signal could reflect both low frequency corrective adjustments (below 4 Hz) and involuntary 8-10 Hz fluctuations derived from central sources. One additional possibility is that in an effort to control oscillations in the VT direction, there is a “spillover” effect to ML motion, especially given that some of the upper limb muscles involved in this task do not exert force in a single direction (Pellegrini et al., 2004). However, given that the ML tremor was greater in amplitude than the tremor in the VT direction and that the 1-4 Hz peaks occurred at significantly different frequencies, this later argument cannot fully explain this result.

The potential origins of oscillations in the AP direction are less obvious. These oscillations were considerably lower in amplitude compared to the ML and VT tremor and showed no appreciable change from proximal to distal segments. While a link between postural motion and tremor in this plane is one obvious consideration, the frequency profile of the AP tremor (which was more broadband) does not appear similar to that previous reported for postural motion in task of this nature (Hwang et al., 2006; Morrison, Kerr, Newell, & Silburn, 2008). Cardiovascular and/or respiratory events may also play a role in these low amplitude oscillations but we are unable to fully discern any origins within the current experimental design.

Analysis of the pattern of regularity for the tremor revealed that the tremor in the AP, ML, and VT directions was more regular (lower ApEn) at the gun barrel compared to the forearm. Lower ApEn values for a given segment are of some significance, since a more regular signal has been linked to greater control being exerted over that aspect (Keogh et al., 2004; Pincus & Singer, 1996). The decrease in ApEn values from the forearm to the gun was largest in the VT direction, and overall VT tremor at the gun barrel was more regular than for any other direction and segment. Interestingly, the decrease in ApEn values from proximal to distal (across all three directions) was evident even though there was an increase in ML and VT tremor amplitude from the forearm to the gun barrel. Taken together, these results reveal that the ability to control tremor at the periphery is not simply the by-product of mechanically linking joint segments together but rather more likely reflects the consequence of an active control process. Previous research has proposed that, for upper limb tasks of this nature, the minimization of limb tremor is achieved through a pattern of intra-limb coupling organized about the action of the wrist (Morrison & Newell, 1996; Pellegrini et al., 2004; Tang et al., 2008). Further, Pellegrini et al. (2004) speculated that the emergence of notable tremor in both the VT and ML directions reflects the need to adopt a strategy whereby controlling motion in more than one direction is necessary for optimal performance.

Effects of Postural Positions on Tremor

Small tremulous oscillations in a limb segment can become problematic during goal directed aiming tasks which require a degree of precision and accuracy (Arblaster, Lakie, Powers, Villagra, & Wright, 1991; Arutyunyan et al., 1968; Harwell & Ferguson, 1983; Keogh et al., 2004; Tang et al., 2008). An aim of the current project was to examine what effect changing the upper limb position would have on the underlying tremor dynamics. Performing the aiming task with two hands resulted in decreased tremor amplitude compared to when a single arm was used. Hence, rather than tremor from both limbs having an additive effect on oscillations of the gun the use of two arms had an attenuating effect. There are a number of reasons for this reduction in tremor when adopting this position. When linking the two arms together to help meet the task goal, the number of DOF involved in the task are increased through the possible joint motions of the additional limb. Previous research has shown that performance of many tasks tends to improve under conditions where more DOF are available to meet the movement goals (Chow, Davids, Button, & Koh, 2008; Hong & Newell, 2006; Morrison & Newell, 1999; Wang, Ko, Challis, & Newell, 2014). In addition to the two arms being able to work together to reduce the transmission of any tremulous oscillations for the more proximal segments, the extra support provided by using two arms linked to a common endpoint could also be a factor. For the single arm actions, the individual has to hold his or her upper arm, with an estimated mass of 3.6 kg (de Leva, 1996), in addition to the extra mass of the weighted gun (0.8 kg). The use of a second arm may assist in reducing the load at the distal segment since each arm could now provide support to offset the weight of the gun.

In addition to these changes, the tremor seen when individuals performed the task with a slightly bent elbow was less than when a straight arm was used. Possible reasons to explain the decreased amplitude of tremor include the increased motion (possibly DOF) about the elbow joint facilitating the control of tremor during the task, decreased moment arm generated by bending the elbow (and so reducing the strain on the shoulder muscles), and (potentially) decreased muscle activation across the wrist and elbow joints. Previous research has shown that when limb stiffness is increased in similar tasks through increasing muscle activity, a resultant increase in tremor at the periphery occurs (Morrison & Newell, 2000a). Consequently, any adjustment that decreases the load at the endpoint (either by using two hands or shortening one limb), may have resulted in decreased muscle activity in the relevant upper limb muscle groups, which would be reflected by decreased tremor.

Limitations

A potential limitation of the current design was the lack of any distinct measure of accuracy during the aiming task. It has been shown previously that the act of firing the weapon momentarily alters the tremor within the limb segment (Lakie, Frymann, Villagra, & Jakeman, 1994; Tang et al., 2008). Consequently, our goal was to gain a better understanding of the tremor dynamics for the forearm and gun barrel during the aiming component of the task. Further, we wished to ascertain how the different task constraints/positions would affect the control of limb tremor during the aiming tasks. While the current results provide little direct information regarding accuracy of shooting performance across tasks, the findings are still relevant to the task of aiming and to understanding how tremor impacts on precise movements of this nature.

Conclusion

Physiological tremor can be a problem for optimal performance of many goal-directed aiming tasks that require a degree of accuracy. The current study was designed to examine the similarities and differences in tremor (in the AP, ML, and VT directions) during the performance of a goal-directed aiming task under conditions where different arm postures were adopted. Overall, the tremor pattern for the segments assessed (i.e., each forearm and gun barrel) were remarkably similar across conditions. Irrespective of the posture adopted, ML and VT tremor at the more distal aspect (the gun barrel) was of greater amplitude than the forearm. Interestingly, oscillations in the ML direction were greater than the VT tremor across all conditions, a finding that may reflect compensatory adjustments during the aiming task. The form of the oscillations in the ML direction (i.e., peaks within the 1-4 Hz and 8-12 Hz ranges) is consistent with previous research examining physiological tremor in the VT direction. In contrast, tremor in the AP direction was markedly lower than both ML and VT directions, and did not display any consistent spectral peaks. Tremor at the gun barrel can be reduced by using two arms to hold the gun and by bending the elbow(s). This may reflect recruitment of more DOF’s or possibly reduced muscle activity required to hold the gun in position due to a decreased moment arm.

CHAPTER III

EXPERIMENT II

Title

Acceleration Dynamics of Finger Pointing, Handgun Aiming, and Handgun Shooting

Introduction

Inherent, involuntary oscillations are pervasive in the limbs of the body during postural tasks (Elble & Koller, 1990; Marsden, 1984; Morrison & Newell, 1999; Takanokura & Sakamoto, 2001). These oscillations arise from normal interactions with the neuromuscular system and, in healthy individuals, are referred to as physiological tremor (Elble & Koller, 1990; Morrison & Newell, 2000b). Normally, these oscillations are minimal and nearly imperceptible, however, they can be exacerbated by physiological and psychological stressors (Elble, 2013; Morrison et al., 2005). These small oscillations generally have a nominal impact on most motor tasks, however, fine motor skills requiring a level of precision, for instance in medical procedures (Coulson et al., 2010; Fargen et al., 2016; Harwell & Ferguson, 1983; Hsu & Cooley, 2003; Safwat et al., 2009) and marksmanship activities (Keast & Elliott, 1990; Lakie et al., 1995; Pellegrini & Schena, 2005; Stuart & Atha, 1990; Tang et al., 2008), may be severely impacted by slight fluctuations within the limb. In fact, multiple studies have found a correlation between an increase in gun motion or acceleration and a decrease in shot accuracy during pistol shooting (Ball et al., 2003; Lakie et al., 1995; Mason & Bond, 1990; Tang et al., 2008). While physiological tremor has been studied extensively in postural pointing tasks it has been studied less in applied tasks such as shooting. A direct comparison of acceleration during both tasks may provide a bridge between the basic science of neuromuscular control (e.g., pointing) and the performance of applied tasks (e.g., handgun shooting).

Tremor of the upper limb has most commonly been examined in the vertical (VT) direction due to the availability of light weight uniaxial accelerometers and the importance of counteracting the force of gravity as a finger, hand, or arm is held in an outstretched position (Aalto, Pyykkö, Ilmarinen, Kähkönen, & Starck, 1990; Elble & Randall, 1978; Morrison & Newell, 1996; Stiles & Randall, 1967). However, motion in the medial-lateral (ML) and anterior-posterior (AP) axes would also appear to be of concern for some precision-based tasks (e.g., surgery or shooting). The development of light weight triaxial accelerometers and motion capture systems have allowed for simultaneous measurement of tremor in multiple dimensions. Recent studies examining multiple axes have revealed the significance of stabilizing tremor in directions other than VT (Hong et al., 2008; Hwang et al., 2006; Pellegrini et al., 2004). Perhaps due to the importance of aligning the axes during aiming and shooting tasks, investigations into the structure of ML and AP oscillations (in addition to VT) during aiming and shooting have shared more information on the dynamics of three-dimensional oscillations (Aalto et al., 1990; Kelleran, Morrison, & Russell, 2016; Pellegrini et al., 2004; Pellegrini & Schena, 2005; Tang et al., 2008). Pellegrini et al. (2004) found a significant, structured oscillation in the ML direction comparable to that of the VT during a goal directed task involving a laser pointer. Studies involving handgun aiming and shooting also reported that oscillations in the ML direction are comparable in amplitude and structure to that seen in the VT direction with a dual peak (0-7 and 7-14 Hz) frequency spectrum output (Kelleran et al., 2016; Pellegrini & Schena, 2005; Tang et al., 2008). Even fewer studies have examined tremor in the AP direction. Those that have, found AP oscillations in the distal segment (handgun barrel) were approximately half the amplitude of the ML and VT oscillations (Kelleran et al., 2016; Tang et al., 2008), with no discernable or consistent peaks in the frequency spectrum (Kelleran et al., 2016).

The studies investigating tremor during handgun aiming and shooting inherently have an increased mass at the hand segment from the weight of the gun (Kelleran et al., 2016; Pellegrini & Schena, 2005; Tang et al., 2008). Previous research has found that the addition of mass to the hand [1200g, 1700g] (Takanokura et al., 2007) can increase overall oscillation amplitude, or show no significant change due to load [300g] (Elble, 2003), [500g] (Takanokura et al., 2007) at the hand when held for a duration of approximately 60 seconds. Postural tasks held for approximately 30 seconds have demonstrated no significant difference between the hand being loaded [500g, 1000g] and unloaded [0g] conditions (Raethjen et al., 2004). Postural tasks lasting approximately 10 seconds or less have shown a dampening of tremor amplitude with the addition of mass to the hand [480-960g] (Morgan, Hewer, & Cooper, 1975). At the finger the addition of mass [70g] (Duval & Jones, 2005) [50g, 100g] (Hwang, Chen, et al., 2009; Hwang, Lin, & Wu, 2009) can increase overall oscillation amplitude when held for a duration of approximately 60 seconds and 20 seconds, respectively. Interestingly, when that load is applied to the finger, a decrease in tremor of the hand has been observed despite the previously reported increase in tremor of the finger as well an increase in tremor of the forearm (Hwang, Chen, et al., 2009; Hwang, Lin, et al., 2009). These findings suggest a load in the hand may initially dampen tremor at the hand, but the impact on other segments or dimensions need to be analyzed. Increased tremor amplitude as the load is held for longer periods of time (20 s or more) may arise from fatigue, therefore short trials (e.g., 10 s) should be used to investigate the effect without fatiguing influence.

The addition of mass will also alter the mechanical resonant properties of the limb. Some research has found it decreased the frequency and increased the peak amplitude of the associated segment (Elble & Koller, 1990; Elble & Randall, 1978; Homberg et al., 1987; Stiles & Randall, 1967). The 8-12 Hz neural component of the frequency spectrum is relatively stable and not easily altered by changes in mass, however, it must be noted that the mechanical resonant peak of the hand segment can also oscillate within the 8-12 Hz band so changes due to mass may still be observed in the 8-12 Hz band (Elble & Randall, 1978; Homberg et al., 1987; Stiles & Randall, 1967). The influence of holding a handgun, as compared to finger pointing, has on the tremor profile of the outstretched limb has yet to be established.

Previous research often focused on the influence of mass on the segment where the mass was affixed in the VT direction. Examining involuntary oscillations during handgun aiming and shooting, it is important to examine all segments to determine how the weight of the gun influences the ability to steadily aim the handgun. When examining specific limb segments relevant to both pointing and handgun shooting (hand, forearm, upper arm) it is also important to consider the role all three axes (VT, ML, AP) play on each segment and how they influence shooting accuracy. Although yet to be established, increased mass may not have a direct gravitational influence on the ML and AP direction but changes may be seen to spillover from VT limb artifact. This indirect gravitational influence may be caused by compensatory muscles responding to the gravitational pull in the VT direction or momentum changes in the ML and AP direction due to additional mass. The current study examines VT, ML, and AP dimensions to understand the influence motion in different axes has on the others along the segments of the arm.

Shooting a handgun has the distinction of being different from most postural aiming tasks in that it includes both muscular contraction of the limb to pull the trigger as well as control and recovery of the recoil. Both of these actions will cause extraneous motion that must be compensated for during the shot and to prepare for a subsequent shot. Trigger pull may rotate the gun medially and alter multiple segments due to the combined actions of the finger flexor muscles including wrist and elbow flexion as well as their origins at the forearm and elbow (Floyd, 2009). Finger placement on the trigger (too medial or lateral), improper trigger pull, and weight of the trigger pull may also influence motion and accuracy. Control of recoil following a shot to realign the gun to the target for subsequent shots presents an issue as well due to the magnitude of the perturbation to the system (Walmsley & Williams, 1994). This study focuses on the voluntary action of pulling the trigger and eliminates recoil by using a simulated gun that does not fire live rounds.

Tremulous oscillations of a limb would appear to negatively impact performance during handgun aiming and shooting tasks (Kelleran et al., 2016; Lakie et al., 1995; Mason & Bond, 1990; Tang et al., 2008). The purpose of this study was to assess the similarities and differences in oscillations of the upper limb segments during the tasks of finger pointing, handgun aiming, and handgun shooting. This will be accomplished through evaluating the amplitude and structure of oscillations for each segment in the AP, ML, and VT direction. Structure in the accelerations will be assessed by spectral analysis and Approximate Entropy (ApEn), which quantifies regularity or predictability of the signal. Initial assessment of the finger pointing condition will establish a baseline similar to previous research on tremor of the outstretched limb (Morrison & Newell, 2000b; Takanokura & Sakamoto, 2001) in order to compare it to the limb during the handgun aiming (Kelleran et al., 2016) and shooting (Arutyunyan et al., 1969; Pellegrini & Schena, 2005; Tang et al., 2008). Tremors have been assumed to influence shooting accuracy (Ball et al., 2003; Lakie et al., 1995; Mason & Bond, 1990; Tang et al., 2008). This will be examined by measuring shooting accuracy and correlating it with measures of the amount and regularity of tremor in each dimension at the different segments. Individual experience also influences shooting performance (Arutyunyan et al., 1968, 1969; Tang et al., 2008), with elite shooters demonstrating both a lower amplitude of motions due to tremor and increased accuracy over pre-elite shooters (Tang et al., 2008). In the current study, the relationship between experience and tremor or shooting accuracy will also be established through correlation analysis of individuals with a broad range of shooting experiences.

Several specific hypotheses will be examined. It is hypothesized that the acceleration profile of the upper limb during handgun aiming will be comparable to the tremor profile of finger pointing condition in all three directions. Gun barrel accelerations will be similar to the hand tremor profile rather than the finger due to the handgrip used as well as the mass of the gun being more similar to the hand than the finger. The gun and hand will display a smaller more regular acceleration signal and will lack the higher frequency peak (18-25 Hz) usually found in finger tremor. The increased load will lead to an overall decrease in amplitude of acceleration and increase in regularity. This prediction is predicated upon the dampening effect mass would have on the hand and subsequent reduction in small oscillations and corrections at the distal segments of the limb. The handgun shooting condition will have a greater amplitude and regularity of oscillation when compared to finger pointing or handgun aiming. Comparisons between the pointing, aiming, and shooting conditions will allow for a greater understanding of the control process involved in postural motor tasks.

Methods

Participants

Twenty healthy (12 male, 8 female) participants with a mean age of 28.1$\pm$3.9 years volunteered, all self-reported as right hand dominant. Volunteers had all previously shot a handgun (Table 3.1) and self-reported how many calendar years they had shot a handgun (8.7±7.5 years of experience). Anthropometric dimensions were recorded for height (172.5±9.2 cm), weight (78.7±14.6 kg), and hand and arm length. The arm length was measured in a straight line from the acromion to the radial styloid of the forearm. Hand length was measured from the wrist joint center to the third metacarpophalangeal joint as well as the tip of the second distal phalange. All experimental procedures were approved by the university's Institutional Review Board and written informed consent was obtained from each subject prior to testing.

Group	**1**	**2**	**3**	**4**	**5**
Experience (Years)	0	1-3	4-6	7-10	>10
Number of Subjects	0	7	4	2	7

Table 3.1: Classification of handgun shooting experience levels of the participant population

Apparatus

Upper arm (UA), forearm (FA), hand (HA), and pointer finger or gun barrel (GF-gun/finger based on condition) accelerations were measured using lightweight Noraxon triaxial accelerometers (weight 2.8 g, range ± 19.62 m/s^2) (Noraxon U.S.A. Inc., Scottsdale, AZ). One accelerometer was affixed to each of the following anatomical locations: the lateral aspect of the upper arm approximately half way between the acromion and olecranon process, the dorsal aspect of the forearm approximately 6 cm proximal to the radiocarpal joint, the dorsum of the hand placed centrally on the length of the third metacarpal, the end of the index finger over the finger nail (see Fig. 3.1). Anatomical accelerometers were secured with double sided and Powerflex tape (Andover Healthcare, Inc, Salisbury, MA). A SIRT training pistol (634 g, Next

Level Training, Ferndale, WA) was used for all trials involving handgun aiming or shooting. Upon pulling the trigger (2.04-kg trigger pull weight), the training handgun momentarily emits a red laser beam. An accelerometer was also affixed to the distal, lower portion of the gun barrel on the rail, ensuring the vertical axis is perpendicular to the ground while aiming. Accelerometers were tethered to the Noraxon TeleMyo 2400T G2 transmitter affixed to a table near the participant. Data were collected at 1000 Hz. Prior to each testing session a calibration trial was collected for each axis of the triaxial accelerometers.

A 20-cm, 5-ring, black and white bull's-eye target was used for all aiming tasks. Shots were recorded using the Laser Activated Shot Reporter (LASR Team LLC., Lincoln, NE). Accuracy was assessed for radial error based on the shot location in the target's five rings, each 2.2 centimeters wide. A score of 1 indicated a bull's-eye with each subsequent ring increasing in value to a score of 5 for the outer ring, a score of 6 was recorded for a missed target. Shot scores were averaged for each trial. The target was positioned at a height of 1.55 meters and a distance of 6.4 meters from the participant (Tueller, 1983).

Experimental protocol

Participants completed three conditions: 1) index finger pointing at target, 2) gun aiming at target 3) gun shooting at target. All conditions utilized the dominant hand and were completed in a straight arm position with the shoulder flexed to 90 degrees (arm approximately parallel to the ground), the elbow fully extended, and the wrist and hand rotated medially. During the finger aiming condition the index finger was extended and aligned with the target while the thumb was adducted and fingers 3, 4, 5 were flexed in to the palm (Morrison & Newell, 1996). During conditions involving the handgun, the gun was held by the dominant hand in an upright position with the sights and barrel aligned with the target. During each trial of the handgun shooting condition, subjects were given 10 seconds to take 5 shots as accurately as possible, and to maintain aim in between each shot. The order of the three conditions was counter balanced for each participant. All subjects completed each of the conditions five times, for a duration of 10 seconds apiece. Participants were given 10 seconds of rest between trials.

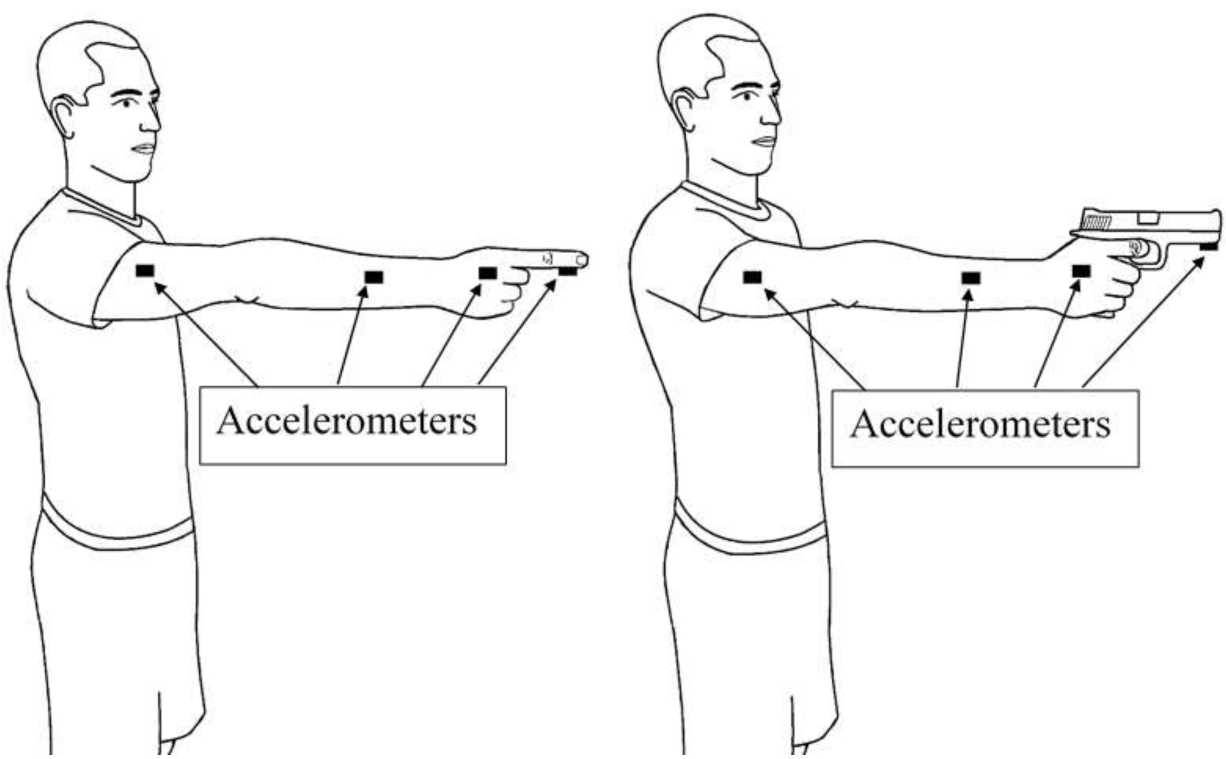

Fig. 3.1: Illustration of accelerometer placement for finger pointing and handgun aiming/shooting tasks.

The participants were instructed to maintain a bilateral stance with their toes behind the 21-foot line marked by a piece of tape. On the command to "aim" the participant raised his or her arm with either the index finger extended or the gun in hand to the pre-determined posture and maintain a steady aim at the target. Once in position the researcher started data collection. After 10 seconds, data collection automatically stopped. At the end of the trial the researcher gave the instruction to "relax" where they would lower their arm for 10 seconds of rest between trials. This procedure was repeated for each trial under all three conditions. If the participant held an incorrect posture or another error occurred the trial was repeated.

Data analysis

Postural tremor was recorded by Noraxon tri-axial accelerometers and Noraxon MyoResearch (XP) software (Noraxon U.S.A. Inc., Scottsdale, AZ) then analyzed using custom written Matlab software (R2012A, MathWorks, Natick, MA). Data were down sampled to 100 Hz. A second-order, zero-lag, low-pass Butterworth filter with a 50 Hz cutoff frequency was used to filter the data.

Time series analysis included both measures of amplitude and regularity of the recorded data. Acceleration data were examined in the AP, ML, and VT axes. Root mean square (RMS) quantified the average amplitude of fluctuation in the acceleration signals to assess the steadiness of each aiming posture (Keogh, Morrison, & Barrett, 2010; Morrison et al., 2013). Approximate entropy (ApEn) was used to assess the regularity, or predictability, of the acceleration signal. Specifically, ApEn calculates the probability that a sequence of data points repeats itself within a given signal. ApEn utilizes a scale of 0 to 2 with 0 being perfectly predictable and 2 indicating a highly complex signal with little repetition of vectors in the data (Hwang et al., 2006; Morrison & Newell, 1996; Pincus, 1991; Pincus, Gladstone, & Ehrenkranz, 1991).

Frequency analysis of acceleration was evaluated using Welch's power spectral density estimate within the range of 0-21 Hz. The spectral analyses were performed using a 512-data point length fast Fourier transform, with a 256-data point window size and 128 data point overlap. Three band widths (0-7 Hz, 7-14 Hz, 14-21Hz) were analyzed, with peak magnitude and its corresponding frequency determined for each band width.

Statistical analysis

The statistical analyses were conducted with SAS software (Version 9.3, SAS Institute Inc., Cary, NC, USA). To determine differences between conditions each dependent variable was analyzed using the GLM mixed function. Significant main effects were analyzed using the *Tukey–Kramer* method confidence interval adjustment. To determine correlations, the Pearson product moment correlation was computed in SAS and subsequently assessed by significance and strength (weak 0.10-0.29, moderate 0.30-0.49, strong 0.50-1.0) (Cohen, 1988, 1992). Data were presented as mean ± SD unless stated otherwise. The significance for all tests was set at an alpha level of 0.05.

Results

Representative traces of the raw acceleration signal from the distal most accelerometer are shown in Fig. 3.2. While comparable, the amplitude of ML acceleration was greatest, followed by VT. The amplitude of AP acceleration is approximately half or less, of the other two signals. Amplitude of acceleration during finger pointing and handgun aiming are similar while obvious and expected differences during the shooting condition are evident in the bottom row of Fig. 3.2. The five spikes in amplitude correspond to the five shots taken during the shooting condition.

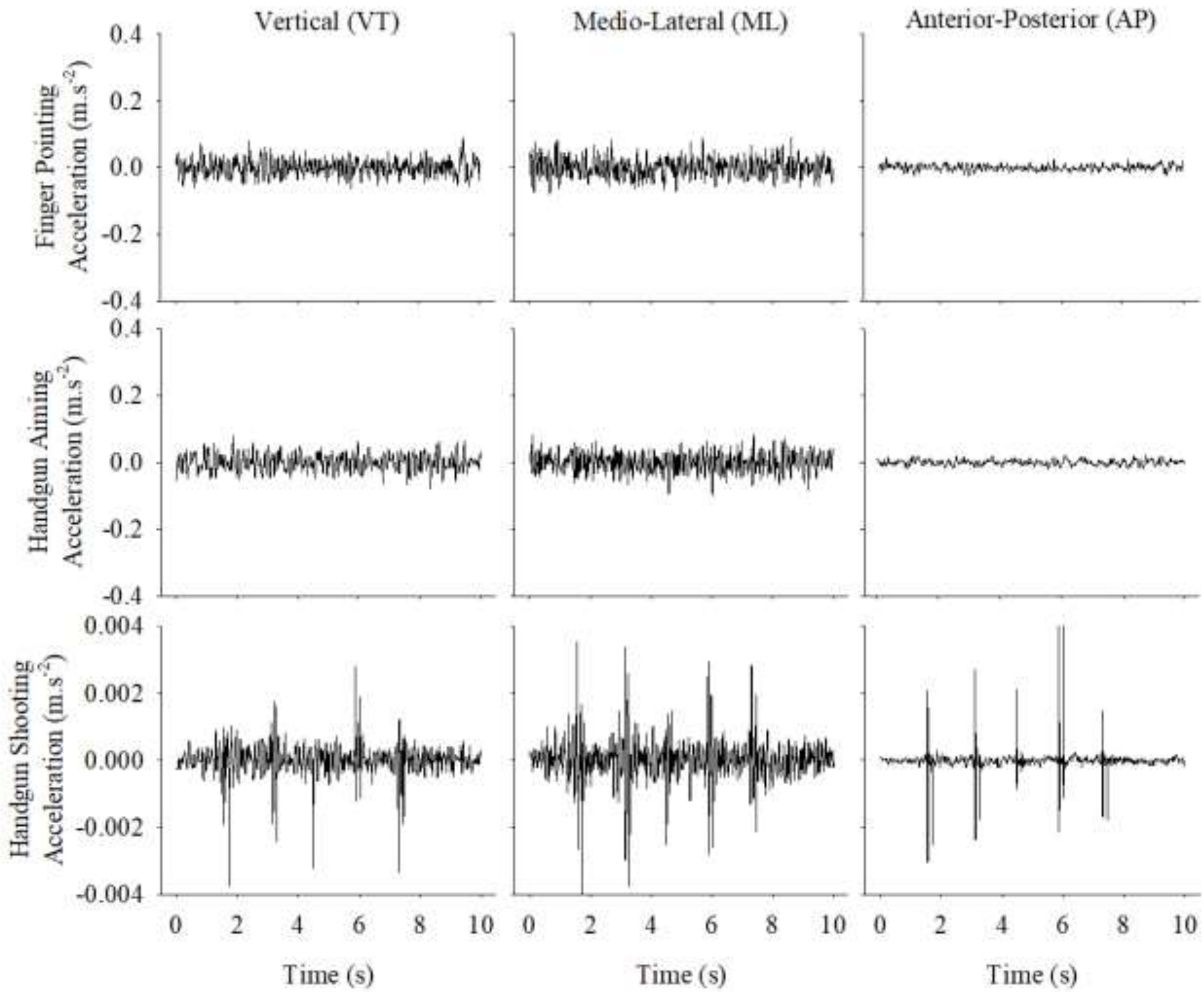

Fig. 3.2: Example of raw acceleration in three-dimensions from the distal (finger, handgun) accelerometer during each of the three experimental conditions (finger pointing, handgun aiming, handgun shooting).

Amplitude of Acceleration

Amplitude of the acceleration signal for each condition (point, aim, shoot) was assessed in all three directions (VT, ML, AP) at each of the four segments (UA, FA, HA, GF). RMS of each segment, direction, and condition are displayed in the left column of Fig. 3.3. Assessed by segment, amplitude of acceleration in the VT direction was significantly different ($F_{3,57}$ = 637.68, p<0.001). The UA, FA, HA, and GF segments were all significantly different from each other (p's<0.001), RMS acceleration increased in amplitude from proximal to distal segments (Fig. 3.3). There was also a significant interaction effect between segment and condition ($F_{6,114}$ = 95.91, p<0.001). The effect the different conditions had on the three more proximal segments (UA, FA, HA) was consistent in the VT direction with finger pointing and handgun aiming conditions displaying a similar, lower amplitude (p's>0.05). The handgun shooting condition was significantly and substantially greater than both finger pointing and handgun aiming in the three more proximal segments (p's<0.001). At the distal segment (GF), significant differences were seen between all three conditions (p's<0.001) in the VT direction. Aiming the gun resulted in the lowest mean amplitude of acceleration at the distal segment (GF), then pointing the finger, followed by the handgun shooting condition (Fig. 3.3).

Amplitude of acceleration in the ML direction was also significantly different when assessed by segment ($F_{3,57}$ = 1175.48, p<0.001). All segments were significantly different from each other in the ML direction (p's<0.001), except for the FA and HA segments (p=0.361), as seen in Fig. 3.3. There was also a significant interaction effect between segment and condition in the ML direction ($F_{6,114}$ = 111.10, p<0.001). The effect different conditions had on the segments varied more in the ML direction than previously described for the VT direction. During the pointing and aiming conditions acceleration in the two proximal segments (UA, FA) were not significantly altered (p's>0.05) but mean amplitude was significantly and substantially greater in both segments during the shooting condition (p's<0.001). The HA and GF segments were significantly affected by condition (p's<0.001) and followed a similar pattern with the handgun aiming condition resulting in the lowest amplitude of acceleration followed by finger pointing and then handgun shooting (Fig. 3.3).

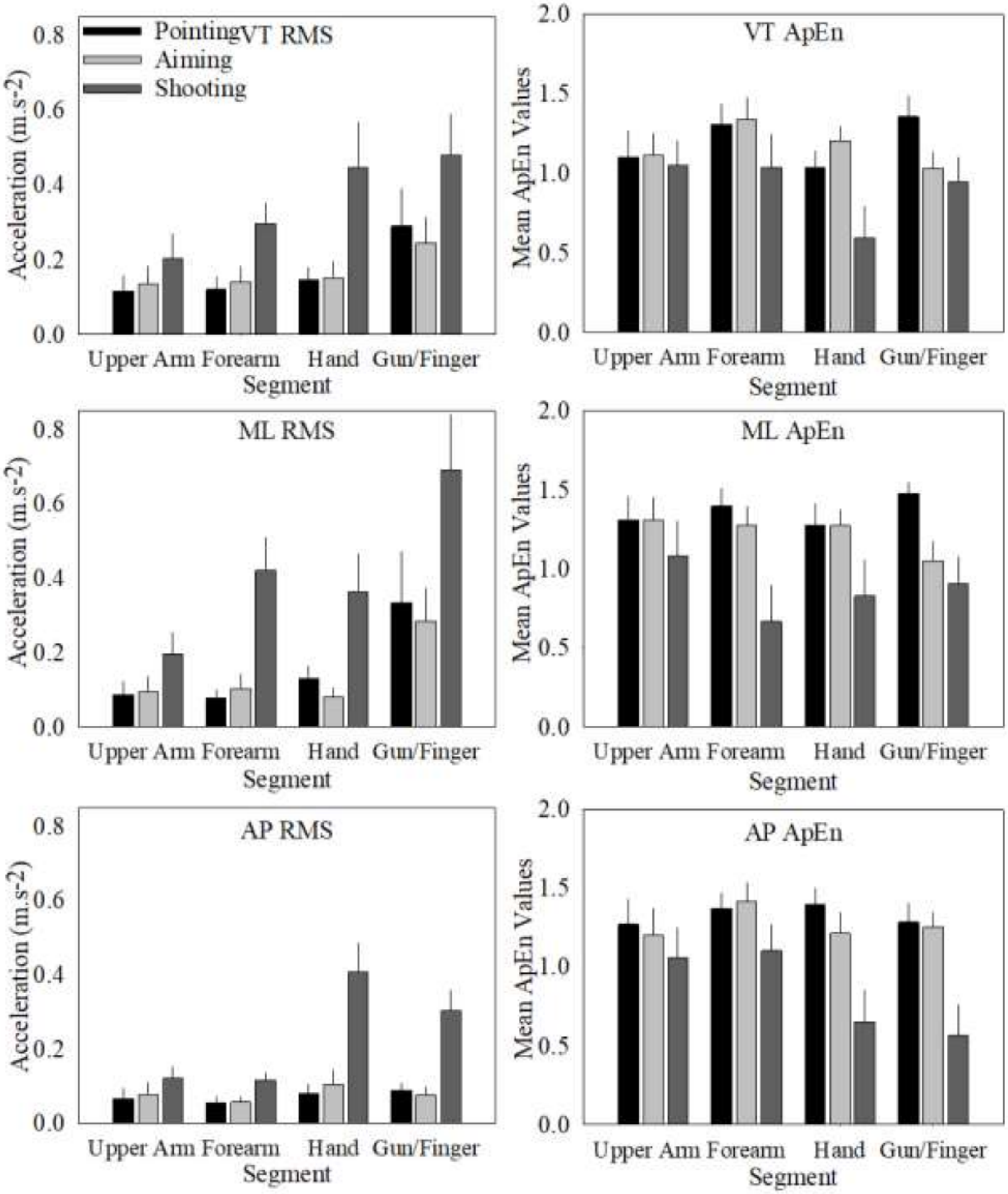

Fig. 3.3: Mean acceleration amplitude (RMS) and regularity (ApEn) of the segments assessed (upper arm, forearm, hand, and gun barrel or finger) by condition (pointing, aiming, shooting) in all three directions (VT, ML, AP). See text for significant differences. Error bars represent one standard deviation from the mean.

Acceleration of the upper limb segments in the AP direction were also significantly different ($F_{3,57} = 948.48$, $p<0.001$). All the segments were significantly different (p's<0.001) although they did not follow the proximal to distal pattern of VT. The lowest mean amplitude of acceleration was found at the FA followed by the UA, the GF, and then the HA with the highest mean amplitude (Fig. 3.3). A significant interaction effect was also present between segment and condition in the AP direction ($F_{6,114} = 546.64$, $p<0.001$). Assessing amplitude of acceleration in the AP direction demonstrated a significant difference between the three conditions at each segment. There was not a significant difference between pointing and aiming at the UA, FA, or GF segments (p's>0.05), however, handgun aiming was significantly greater than finger pointing at the HA segment ($p<0.001$). The shooting condition was significantly greater than the pointing and aiming conditions at all four segments (p's<0.001).

Regularity of Acceleration

Assessment of each condition for regularity of the acceleration signal at each of the four segments was assessed in all three directions. ApEn of each direction, segment, and condition are displayed in the right column of Fig. 3.3. Examination of the regularity of the acceleration signal in the VT direction found a significant difference between the segments ($F_{3,57} = 306.71$, $p<0.001$). The most regular signal was found at the HA segment followed by the UA, the GF and the most irregular signal was at the FA as shown in Fig. 3.3. All segments were significantly different from each other (p's<0.001) except for the UA and GF ($p=0.07$). There was also a significant interaction effect between segment and condition ($F_{6,114} = 114$, $p<0.001$). In the VT direction, the UA saw a significant difference between the aiming and shooting condition ($p<0.05$) with shooting being more regular than aiming but pointing was not significantly different than aiming or shooting (p's>0.05). The FA was not significantly different between pointing and aiming (p's>0.05), but the shooting condition was significantly more regular than the other two conditions (p's<0.001). All the three conditions significantly impacted the HA segment differently with shooting the most regular, then pointing, and handgun aiming as most irregular (p's<0.001). The GF segment was also significantly impacted by all three conditions but not in the same pattern (p's<.001). The shooting condition was again the most regular, then the aiming condition, followed by the finger pointing as the most irregular condition (Fig. 3.3).

In the ML direction, significant differences in accelerometer signal regularity were found between the segments ($F_{3,57} = 58.19$, $p<0.001$). The FA was most regular, then HA, GF, and then the UA. Significant differences were present between all segments (p's<0.05) except the FA and HA (p=0.58) as well as the HA and GF (p=0.25). Significant interaction effects were observed for segment and condition in the ML direction ($F_{6,114} = 142.12$, $p<0.001$). At the UA and HA pointing and aiming were not significantly different (p's>0.05) however shooting was significantly more regular than the other two conditions (p's<0.001). The FA and GF followed a similar pattern with all three conditions significantly different at their respective segments (p's<0.001). Finger pointing was most irregular at both the FA and GF segments, then handgun aiming followed by the shooting condition as the most regular (Fig. 3.3).

Regularity of acceleration signal in the AP direction displayed a significant difference for segment ($F_{3,57} = 218.65$, $p<0.001$). All four segments in the AP direction were significantly different from each other (p's<0.001) with HA as most regular followed by GF, UA, and FA as most irregular. A significant segment by condition interaction effect was also detected ($F_{6,114} = 137.55$, $p<0.001$). In the AP direction the UA and HA segments were significantly different (p's<0.05) across the three conditions with finger pointing as most irregular followed by handgun aiming and then handgun shooting as most regular. In the FA and GF segments the pointing and aiming conditions were not significantly different ($p\text{'s}>0.05$), the shooting condition was significantly more regular ($p\text{'s}<0.001$) than the other two conditions (Fig. 3.3).

Frequency Analysis

Frequency and amplitude of the peaks were analyzed in the 0-7 Hz, 7-14 Hz, and 14-21 Hz bands. The spectral analysis exhibited standard frequency peaks for the involved segments of the upper limb including the gun segment during all three conditions. Peak power values during pointing and aiming were similar, during the handgun shooting condition the excess motion from the trigger pull and recovery of accuracy caused an increase in power predominantly in the 7-14 Hz range (Fig. 3.4).

There was a significant difference in peak amplitude between segments for each of the frequency peaks in all three directions ($p\text{'s}<0.001$). Generally, the frequency peak was smallest at the upper arm and increased in amplitude with the more distal segments. All four segments were affected in a similar manner by the conditions. All segments did not show a significant difference between the finger pointing condition and the handgun aiming condition ($p\text{'s}>0.05$). The only exception was the peak for the finger segment during pointing being significantly greater than the handgun segment during aiming in the VT 14-21 Hz band ($p<0.05$) and the hand segment having a lower amplitude during finger pointing when compared to handgun aiming in the AP 7-14 Hz band ($p<0.05$). The power of most peaks were greater ($p\text{'s}<0.05$) during the shooting condition, especially at the more distal segments, when compared to the other two conditions.

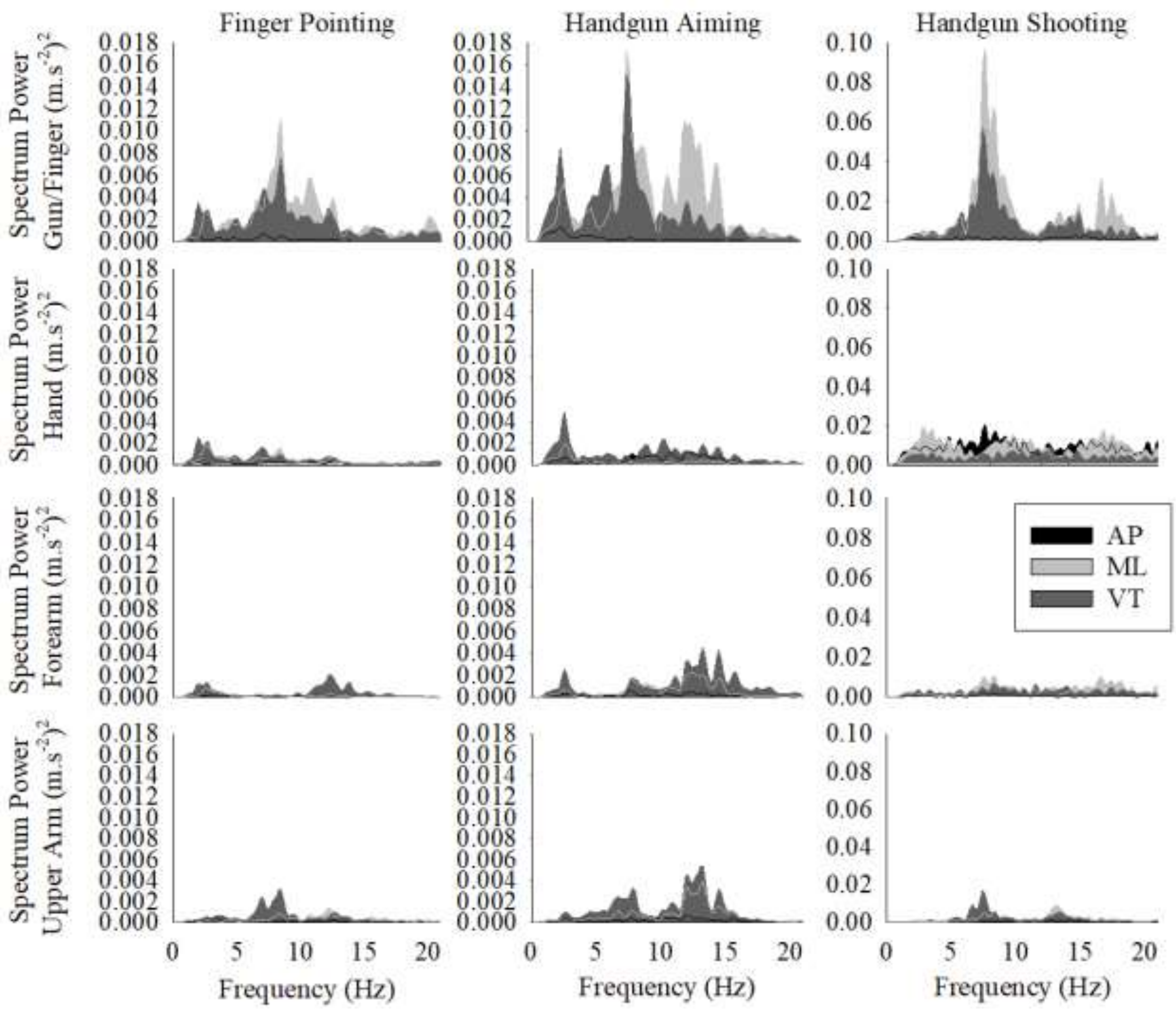

Fig. 3.4: Examples of the spectral frequency analysis for each segment (UA, FA, HA, GF), direction (VT, ML, AP), and condition (Pointing, Aiming, Shooting). Handgun shooting condition "Y" axes differ from pointing and aiming due to amplitude.

A prominent peak was evident in the 0-7 Hz (4.53 $\pm$ 1.25 Hz) and 7-14 Hz (9.72 $\pm$ 0.89 Hz) bands with a smaller peak in the 14-21 Hz (15.5 $\pm$ 0.88 Hz) band. Significant differences were also found between segments for the frequency of the peak (p's<0.001). When comparing finger pointing to handgun aiming in the 0-7 Hz band, the gun in hand had either no effect or led to a peak at a significantly greater frequency for all segments. In the 7-14 Hz and 14-21 Hz bands, the effect of the gun in the hand during the aiming condition resulted in either a lower peak frequency or no significant differences compared to pointing. The shooting condition predominantly had peaks at frequencies greater than the pointing or aiming conditions for all segments, directions, and frequency bands (p’s<0.05).

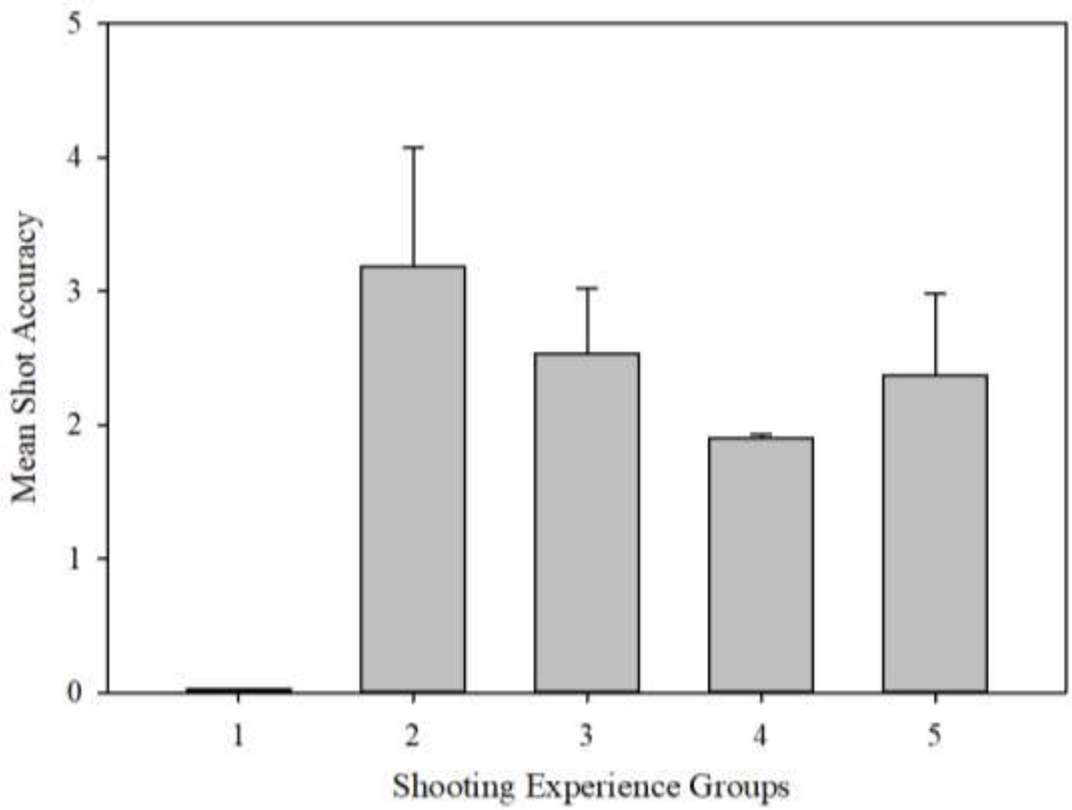

Fig. 3.5: Mean shot accuracy data for each experience level group. Grouping for experience level is further explained in the methodology. Group 1 had 0 subjects. Each ring of the target was 2.2-cm wide, scored 2-5 starting with the ring closest to center (score of 1), a score of 6 was a miss. Error bars represent one standard deviation from the mean.

Correlation Analysis

Multiple correlation analyses were conducted (Table 3.2 and Table 3.3) to determine if parameters of the acceleration signal were correlated to shot score or experience (Fig. 3.5). First, mean shot score for each trial were correlated to both the amplitude (RMS) and the regularity (ApEn) for each of the three conditions (finger pointing, handgun aiming, handgun shooting) in all three directions (VT, ML, AP) at each of the four segments (UA, FA, HA, GF). Significant correlations were found in acceleration amplitude and regularity for both analyses.

A decrease in shot score and a decrease in tremor amplitude would result in a positive correlation, increased RMS would result in a negative correlation. Only eleven significant correlations of a possible 36 were found for shot score and signal amplitude, predominately in the upper arm (Table 3.2). Acceleration amplitude (RMS) was negatively correlated to shot score during pointing and aiming, indicating larger RMS at the forearm and hand was associated with more accurate shots (smaller shot score). While shooting, smaller acceleration amplitude at the forearm and gun were positively correlated with better (lower) shot score. However, the small number of significant correlations indicates there is a low to moderate relationship between tremor amplitude and shot score. In contrast, there were 28 significant correlations between regularity of the acceleration signal and shot score (Table 3.2). The significant correlations revealed a consistent negative relationship, with higher ApEn indicating amore irregular signal correlated with more accurate (lower) shot score. The strongest correlations were found during the shooting condition and included all three axes for the upper arm and VT and ML at the gun (Table 3.2).

Experience had little effect on RMS, with only seven significant correlations (6-low, 1-moderate) (Table 3.3). Of those, four were positive, indicating greater experience resulted in larger accelerations, while three significant correlations were negative, showing the opposite effect. These results indicate there is little relationship between experience of the participants and acceleration amplitude (RMS). Interestingly stronger correlations between regularity of the acceleration signal and experience were found (Table 3.3). All thirty-two significant correlations between acceleration signal regularity and experience were positive indicating motions of the limb were more irregular in experienced handgun shooters (Table 3.3).

The impact of participant handgun shooting experience had a significant, moderate relationship with shot score (r=-0.467, p=0.032). An increase in accuracy (decreased shot score) was observed with an increase in handgun shooting experience (Fig. 3.5).

			Upper Arm			Forearm			Hand			Gun/Finger		
			Point	Aim	Shoot	Point	Aim	Shoot	Point	Aim	Shoot	Point	Aim	Shoot
RMS	VT	r =	-0.32**	-0.26*	-0.02	-0.23*	-0.08	0.39*	-0.24*	-0.05	0.19	-0.05	-0.11	0.20*
		p =	<0.01	0.01	0.87	0.02	0.44	<0.01	0.02	0.65	0.06	0.60	0.30	0.05
	ML	r =	-0.38*	-0.23*	<0.01	-0.17	-0.05	0.18	-0.21*	-0.11	0.07	-0.10	-0.19	0.04
		p =	<0.01	0.02	0.98	0.09	0.63	0.08	0.03	0.30	0.49	0.33	0.07	0.66
	AP	r =	-0.18	-0.06	0.15	-0.11	-0.02	0.20*	-0.15	-0.09	-0.06	0.01	-0.12	0.24*
		p =	0.07	0.53	0.13	0.27	0.84	0.04	0.15	0.37	0.54	0.90	0.23	0.01
APEN	VT	r =	-0.48**	-0.25*	-0.59***	-0.15	0.03	-0.49**	-0.22*	-0.24*	-0.25*	-0.27*	-0.37**	-0.62***
		p =	<0.01	0.01	<0.01	0.14	0.75	<0.01	0.03	0.01	0.01	0.01	<0.01	<0.01
	ML	r =	-0.28*	-0.26*	-0.57***	-0.39**	-0.21*	-0.26*	-0.30*	-0.39**	-0.49**	-0.16	-0.30**	-0.51***
		p =	<0.01	0.01	<0.01	<0.01	0.04	0.01	<0.01	<0.01	<0.01	0.10	<0.01	<0.01
	AP	r =	-0.36**	-0.32**	-0.56***	-0.06	-0.10	-0.34**	-0.30*	-0.07	-0.19	-0.24*	-0.01	-0.28*
		p =	<0.01	<0.01	<0.01	0.57	0.32	<0.01	<0.01	0.47	0.06	0.01	0.90	<0.01

Table 3.2: Correlation (*r* value) and significance (p value) between mean shot score and the amplitude (RMS) and regularity (ApEn) of the acceleration signal for each condition. Comparisons were made at each segment (UA, FA, HA, GF) in each direction (VT, ML, AP). Significant ($p < .05$) correlations indicated by strength: Weak .10-.30 (*), Moderate .30-.50 (**), Strong .50-1.0 (***).

			Upper Arm			Forearm			Hand			Gun/Finger		
			Point	Aim	Shoot	Point	Aim	Shoot	Point	Aim	Shoot	Point	Aim	Shoot
RMS	VT	r =	0.01	0.03	0.11	-0.10	0.05	-0.09	-0.04	0.07	-0.34**	0.21*	0.29*	0.09
		p =	0.95	0.80	0.28	0.34	0.60	0.35	0.72	0.48	<.01	0.04	<.01	0.35
	ML	r =	0.07	0.03	0.04	-0.07	0.08	-0.27*	0.01	0.17*	-0.29*	0.12	0.18	0.21*
		p =	0.51	0.77	0.66	0.50	0.41	0.01	0.89	0.10	<.01	0.25	0.07	0.04
	AP	r =	-0.14	-0.17	-0.13	-0.15	0.19	0.07	-0.06	0.03	-0.01	0.14	0.12	0.07
		p =	0.16	0.08	0.22	0.15	0.07	0.52	0.57	0.76	0.95	0.18	0.22	0.48
APEN	VT	r =	0.37**	0.45**	0.32**	0.28*	0.14	0.38**	0.34**	0.37**	0.34**	0.17	0.37**	0.45**
		p =	<.01	<.01	<.01	0.01	0.17	<.01	<.01	<.01	<.01	0.09	<.01	<.01
	ML	r =	0.14	0.24*	0.32**	0.47**	0.45**	0.39**	0.35**	0.41**	0.59**	0.22*	0.31**	0.32**
		p =	0.17	0.02	<.01	<.01	<.01	<.01	<.01	<.01	<.01	0.03	<.01	<.01
	AP	r =	0.46**	0.39**	0.47**	0.27*	0.14	0.27*	0.37**	0.32**	0.27*	0.45**	0.44**	0.31**
		p =	<.01	<.01	<.01	0.01	0.17	0.01	<.01	<.01	0.01	<.01	<.01	<.01

Table 3.3: Correlation (*r* value) and significance (p value) between handgun shooting experience and the amplitude RMS) and regularity (ApEn) of the acceleration signal for each condition. Comparisons were made at each segment (UA, FA, HA, GF) in each direction (VT, ML, AP). Significant ($p < 0.05$) correlations indicated by strength: Weak 0.10-0.30 (*), Moderate 0.30-0.50 (**), Strong 0.50-1.0 (***).

Discussion

Regardless of the task, an arm held in an outstretched position will exhibit small oscillations. If the task requires precision these small oscillations may impact the performance. The current experiment sought to establish a link between studies investigating postural acceleration of the outstretched upper limb (Aalto et al., 1990; Hwang, Chen, et al., 2009; Morrison & Newell, 2000b; Takanokura et al., 2007) and studies investigating movements associated with aiming and shooting a handgun (Kelleran et al., 2016; Pellegrini & Schena, 2005; Tang et al., 2008). Accelerations of the upper limb were recorded at each of the three segments (upper arm, forearm, hand) as well as at the gun/finger and assessed in three directions (VT, ML, AP). Overall the accelerations of the limb were very similar between the finger pointing and handgun aiming conditions. The handgun shooting condition with trigger pull, even without a gunpowder recoil, had a much greater amplitude of acceleration than either of the other conditions, which is likely attributable to contraction of forearm and finger muscles during trigger pull. The relationship between measures of tremor (i.e., acceleration amplitude or regularity) and shooting accuracy or experience were assessed. An interesting finding was the strength of correlations between the regularity of the acceleration signal (ApEn) and both shot score and experience level. This finding indicated that a more irregular (complex) signal was associated with increased accuracy and greater experience shooting a handgun.

Pointing a Finger vs. Aiming a Handgun

Pointing a finger and aiming a handgun in a unilateral posture share a lot of similarities; each require a limb to be held up in space, the target must be acquired and maintained, and corrections must be made to maintain steady aim at a given target. Obvious differences are present as well including the additional mass of the gun in hand. These differences appear to become more prevalent at the distal segments. In general tremor amplitude increased from proximal to distal segments in a nonlinear manner for both the finger pointing (Hwang et al., 2006; Morrison & Newell, 1996) and the handgun aiming condition despite the additional mass (Hwang, Chen, et al., 2009; Hwang, Lin, et al., 2009). Holding a gun had no significant effect on acceleration amplitude of the hand in the VT axis, but it decreased amplitude in the ML axis and increased it in the AP axis. The acceleration amplitude of the gun itself during the aiming task was smaller than the finger during the pointing task. However, the amplitude of acceleration for the arm segments (UA, FA) were not significantly altered between the pointing or aiming conditions suggesting dissipation of the acceleration changes at the proximal segments. The power spectrum results indicated similar frequency peaks and peak power for handgun aiming and finger pointing with only a few significant differences. Motor control of the pointing and aiming tasks may play a role in limiting the clear peaks due to corrective measures of maintaining proper aim. These results would indicate that finger pointing and handgun aiming share similar traits for their respective segments and tasks.

These changes in amplitude coupled with a more irregular signal during the finger pointing condition suggest the additional mass of the handgun may dampen (Elble & Randall, 1978; Homberg et al., 1987; Morgan et al., 1975; Stiles & Randall, 1967) the accelerations during the short 10 seconds of aiming required for each trial of the current study. Trials of longer duration may see an increase in acceleration amplitude due to fatigue (Takanokura et al., 2007). The increased mass also appears to create a more regular signal, either due to fewer corrections needed as a result of a lower acceleration amplitude or possibly a greater moment of inertia where the limb is slightly slower to react to perturbations due to a greater resistance toward change of angular acceleration.

Handgun Shooting Compared to Aiming

The handgun shooting condition consistently across segment and direction had a greater mean amplitude of acceleration while simultaneously producing a more regular acceleration signal as compared to the pointing and aiming conditions. The contraction of muscles used to pull the trigger, the minimal trigger recoil after each shot, and the limb control necessary to re-aim after the shot, may account for the majority of the three-dimensional increase in amplitude of acceleration (RMS) throughout the limb segments of the arm during the shooting condition. The increased regularity may be the result of having large deliberate motions in all three axes (VT, ML, AP) from the trigger pull. Intentional motion and control of said motion has been demonstrated to decrease the ApEn value, increasing the regularity of the motion (Keogh et al., 2004; Pincus & Singer, 1996). To our knowledge this has not been reported before. Many tremor studies involving shooting cut off the signal upon firing the weapon thereby eliminating the acceleration of the actual shot (Tang et al., 2008).

The Relationship between Shooting Accuracy, Experience and Tremor

Previous research has investigated motion during the aiming condition prior to taking a shot and found they are related to shooting accuracy (Pellegrini & Schena, 2005; Tang et al., 2008) but few have assessed the motion during repeated shots in a single trial (Walmsley & Williams, 1994). The handgun shooting condition of the current study was recorded with accelerometers as well as a measure of accuracy via a laser shot recorder. This information allowed us to quantify the shot placement as well as investigate the accelerations at each segment. Correlating acceleration signals in the current study to shot accuracy and experience resulted in an intriguing finding. Aligned with previous research, experience shooting handguns had a moderate correlation to shooting accuracy indicating more experience resulted in greater accuracy (Arutyunyan et al., 1969; Tang et al., 2008). Similarly, Pellegrini et al. (2005) found tremor amplitude during aiming was lower in individuals with greater pistol shooting experience. While there were some significant correlations between amplitude of acceleration (RMS) and shot score, greater number and strength of correlations were found between shot accuracy and the regularity of the acceleration signal. This indicates that acceleration amplitude may not be the most important factor in shooting accuracy. Negative correlations between shot score where a lower number equals greater accuracy and ApEn where a greater value equals more irregular or complex signal indicates a better shot score may come as a result of a more complex acceleration signal. Interestingly, the strongest correlations with shot score were negative correlations found in the regularity (ApEn) of the acceleration signal and occurred at the UA and GF segments during the shooting condition. Similarly, the relationship between experience and acceleration amplitude was small, but more experience was positively correlated to irregularity of the acceleration signal across segments and tasks. Experience level and ApEn shared a strong positive correlation indicating individuals with more experience demonstrated greater irregularity in their limb accelerations than less experienced individuals who had a more regular signal. The strength of these correlations indicates a noteworthy relationship between both accuracy-irregularity and experience-irregularity. The more complex acceleration signal may be indicative of a release of degrees of freedom with increased skill which occurred concomitant with additional experience and improvements in performance (Anderson & Sidaway, 1994;

Vereijken et al., 1992). Changes in degrees of freedom may be the mechanism explaining the correlation of irregularity (increased ApEn) with the observed increase in accuracy and experience level (Arutyunyan et al., 1968, 1969; Bernstein, 1967). These findings in conjunction with the significant moderate strength correlation between experience and accuracy would thereby suggest that experienced individuals were more accurate via greater control of the handgun (Arutyunyan et al., 1969; Tang et al., 2008).

Although there were fewer correlations for amplitude (RMS) and accuracy, an interesting finding was present. The significant correlations at the UA were negative while the significant correlations at the GF were positive. Negative correlation with RMS at UA but positive at GF could indicate more motion at UA compensating for accelerations resulting in improved accuracy. Decreased acceleration amplitude at the GF coinciding with increased accuracy is a logical result because motion at the distal segment would be expected to directly impact the precision of accuracy in a negative manner.

Conclusion

The protocols set forth for the current study sought to compare finger pointing, handgun aiming, and handgun shooting to bridge physiological tremor and handgun shooting literature. The current study delivers quantification of acceleration amplitude and regularity for finger pointing, handgun aiming, and handgun shooting of the outstretched limb. The study also provides a comprehensive analysis of the correlations between the acceleration signals, shooting experience, and handgun shooting accuracy. Results of the current study demonstrated many similarities in both acceleration amplitude and regularity between finger pointing and handgun aiming deviating slightly at the distal segments due to the mass of the gun in the hand. Due to pulling the trigger, the shooting conditions were generally greater in amplitude and more regular than the pointing and aiming conditions. Finally, shooting accuracy or experience was more strongly related to the irregularity of the acceleration signal than the amplitude of tremor per se.

CHAPTER IV

EXPERIMENT III

Title

Influence of Handgun Grip and Weight on Shooting Accuracy and Involuntary Oscillations of the Upper Limb

Introduction

Maintenance of a stable posture during a goal-directed task requires the motor system to minimize the intrinsic oscillations that are present (Hwang, Chen, et al., 2009; Morrison & Keogh, 2001). These small involuntary oscillations in the limbs of healthy individuals are commonly referred to as physiological tremor (Elble & Koller, 1990). Early examination found that tremor can be affected by altering the stiffness and mass of the limb (Elble & Randall, 1978; Homberg et al., 1987; Stiles & Randall, 1967). Further investigation into the effects of additional mass led to the discovery of two separate components fluctuating within the tremor signal, a steady frequency peak between 8-12 Hz (neural component) and a variable peak (mechanical-reflex component) that was found at different frequencies based upon the segment of the limb observed as well as other factors (Elble & Randall, 1978; Homberg et al., 1987; Stiles & Randall, 1967). Subsequent investigation has shown that the addition of mass can alter tremor amplitude (Duval & Jones, 2005; Takanokura et al., 2007), motor control, and task performance (Hwang, Chen, et al., 2009) dependent upon quantity of mass and duration of the postural task (Morgan et al., 1975; Raethjen et al., 2004; Takanokura et al., 2007). Because mass can affect tremor dynamics and tremor can impact motor tasks it is important to understand the impact of mass on motor performance.

Holding a mass in an outstretched arm influences accelerations throughout the limb. Hwang et al. (2009) compared oscillations of the upper limb (finger, hand, forearm, upper arm, neck) under three separate loads applied at the index finger. Load led to increased tremor of the finger, forearm, and upper arm, however, the load caused a progressive decrease in tremor for the hand (Hwang, Chen, et al., 2009). Increased mass can be of particular concern for performance while performing a precision based task such as surgery (Coulson et al., 2010) or aiming and shooting a gun (Tang et al., 2008). One strategy that individuals adopt in an effort to minimize the effects of the oscillations is to support the limb. The addition of support to a limb alters the tremor profile and reduces tremor amplitude in various tasks (Coulson et al., 2010; Kelleran et al., 2016; Morrison & Newell, 2000b). The impact of support involving rigid external structures such as braces and stands has been examined (Coulson et al., 2010; Morrison & Newell, 2000b). These studies found a reduction in acceleration amplitude with the addition of the stand and found bracing proximal to the wrist reduced tremor amplitude at the finger (Morrison & Newell, 2000b) and it was found to be ideal for fine motor tasks (Coulson et al., 2010). Other ways to support a limb are to brace it against the body and/or involve an additional limb.

The task of shooting a pistol from a standing position requires minimizing the fluctuations in the gun through controlling the motion at the joints and is critical for many law enforcement and military personnel. In order to overcome some of the control issues evident during aiming tasks, various practices such as linking the hands together have been advocated (Department of the Army, 2008; Marine Corps, 2003). Linking the hands together to employ a double hand grip during aiming is believed to provide greater support for holding the mass attributable to the gun. Unlike an external support, however, adding a second limb may lend assistance but also contributes its own tremor to the task. Indeed, the tremor in two limbs is independent of one another, although the properties are similar (Morrison & Newell, 1999, 2000b). Using one limb to support the other could therefore have an additive effect of tremor from both limbs. The second limb also increases the number of degrees of freedom involved in the task, due to the greater number of possible joint motions, which could pose a control problem for the individual (Bernstein, 1967).

Research has indicated that involving a second hand in a task provides additional and beneficial proprioceptive sensory and joint position information (Aruin, 2005) as well as causes a reduction of muscular grip force in the primary hand (Scholz & Latash, 1998) providing the potential for greater control and decreased amounts of muscle activation (Aruin, 2015). Finally, adopting a double handgrip increases the number of degrees of freedom involved, allowing for more options for control that may reduce involuntary oscillations and help perform the task (Morrison & Newell, 1999). Involving more degrees of freedom has been shown to improve performance on a ski simulator and in kicking a soccer ball (Anderson & Sidaway, 1994; Vereijken et al., 1992). Kelleran et al. (2016) examined the effects of a single hand grip versus a bilateral hand grip on tremor during a handgun aiming task. In spite of the additional effort that may be needed to control the second arm and the potential for tremor from the second limb having an additive effect, tremor amplitude was lower in the double limb support condition (Kelleran et al., 2016). The authors suggested that the addition of a second limb may provide a mechanical advantage, additional feedback processes, or greater DOF, allowing for enhanced control of the handgun. Understanding how the second hand contributes to reducing these involuntary oscillations can lend insight to the control of numerous motor tasks impacted by tremor including handgun shooting. In addition, to observing reduced acceleration amplitude with a bilateral handgrip during handgun aiming, Kelleran and colleagues (2016) also observed that the acceleration signal was more irregular (greater Approximate Entropy), suggesting that the involvement of more degrees of freedom may have to led to a greater flexibility of control to minimize fluctuations. However, the second arm also doubles the musculature at the shoulders, arms and hands in controlling the handgun without a concomitant increase in inertia, which could explain the greater frequency of peak power in the 8-12 Hz band and the reduced tremor amplitude (Kelleran et al. 2016).

The current study aimed to determine whether a double handgrip improved shooting accuracy and reduced involuntary oscillations during handgun aiming/shooting greater than a single limb due to additional support (greater musculature) for the load of the gun or enhanced control through the increased sensory and motor degrees of freedom. These hypotheses can be distinguished by determining the interaction effects of unilateral and bilateral handgrip with single weight and double weight handgun conditions. If there is a significant difference between both weight conditions and limb support conditions then further investigation into where the differences are is warranted. For example, if holding a handgun that is double its original weight with a bilateral grip leads to the same tremor amplitude and dynamics as for holding the single handgun weight with a unilateral grip, then the additional limb provides simply a mechanical stabilizing effect. However, if the double limb, double load condition results in a lower tremor amplitude than the single limb, single load condition then we know the second limb provides an additional control benefit (increased sensory feedback and/or ability to utilize more degrees of freedom) rather than simply a mechanical advantage. While studying the accelerations will contribute to our understanding of involuntary fluctuations during aiming, handgun shooting accuracy will also be quantified to determine the effect of accelerations, load and limb support on performance.

Methods

Participants

Twenty healthy volunteers (12 male, 8 female) with handgun shooting experience were recruited; age (28.1±3.9 years), limb dominance (all self-reported as right hand dominant), and shooting experience (8.7±7.5 years) were noted (Table 4.1). For experience volunteers self-reported how many calendar years they had shot a handgun. Anthropometric dimensions were recorded for height (172.5±9.2 cm), weight (78.7±14.6 kg), and arm length. The arm length was measured in a straight line from the acromion to the center of the dorsal aspect of the hand in line with where the thumb and index finger form a "V". All experimental procedures were approved by the university's Institutional Review Board and written informed consent was obtained from each subject prior to testing.

Group	**1**	**2**	**3**	**4**	**5**
Experience (Years)	0	1-3	4-6	7-10	>10
Number of Subjects	0	7	4	2	7

Table 4.1: Classification of handgun shooting experience levels of the participant population

Apparatus

Upper arm, forearm, hand, and the gun barrel tremor were measured using lightweight Noraxon accelerometers (weight 2.8 gm, range ± 2 g) (Noraxon U.S.A. Inc., Scottsdale, AZ). An accelerometer was affixed to both the lateral aspect of the upper arm (UA) approximately half way between the acromion and olecranon process and the dorsal aspect of the forearm (FA) approximately 6 cm proximal to the radiocarpal joint (Fig. 4.1). Arm accelerometers were secured with double sided and Powerflex tape (Andover Healthcare, Inc, Salisbury, MA). A third accelerometer was affixed to a SIRT training pistol (Next Level Training, Ferndale, WA) on the distal, lower portion of the gun barrel (GB). Accelerometers were tethered to the Noraxon TeleMyo 2400T G2 transmitter affixed to the waist of the participant, data were collected at 1000 Hz. Prior to each testing session a calibration trial was collected for each axis of the triaxial accelerometers.

A 20-cm, 5-ring, black and white bull's-eye target was used for all aiming tasks. The target was positioned at a height of 1.55 meters and a distance of 6.4 meters from the participant (Tueller, 1983). For the handgun shooting conditions, shot placement was recorded via laser strike location by a computer based camera system (Laser Activated Shot Reporter, LASR Team LLC., Lincoln, NE). Shots were scored based on distance from center of target. The center was scored as a 0 and each 2.2-cm ring was scored from 1-4 working away from the center point. A score of 5 was a miss.

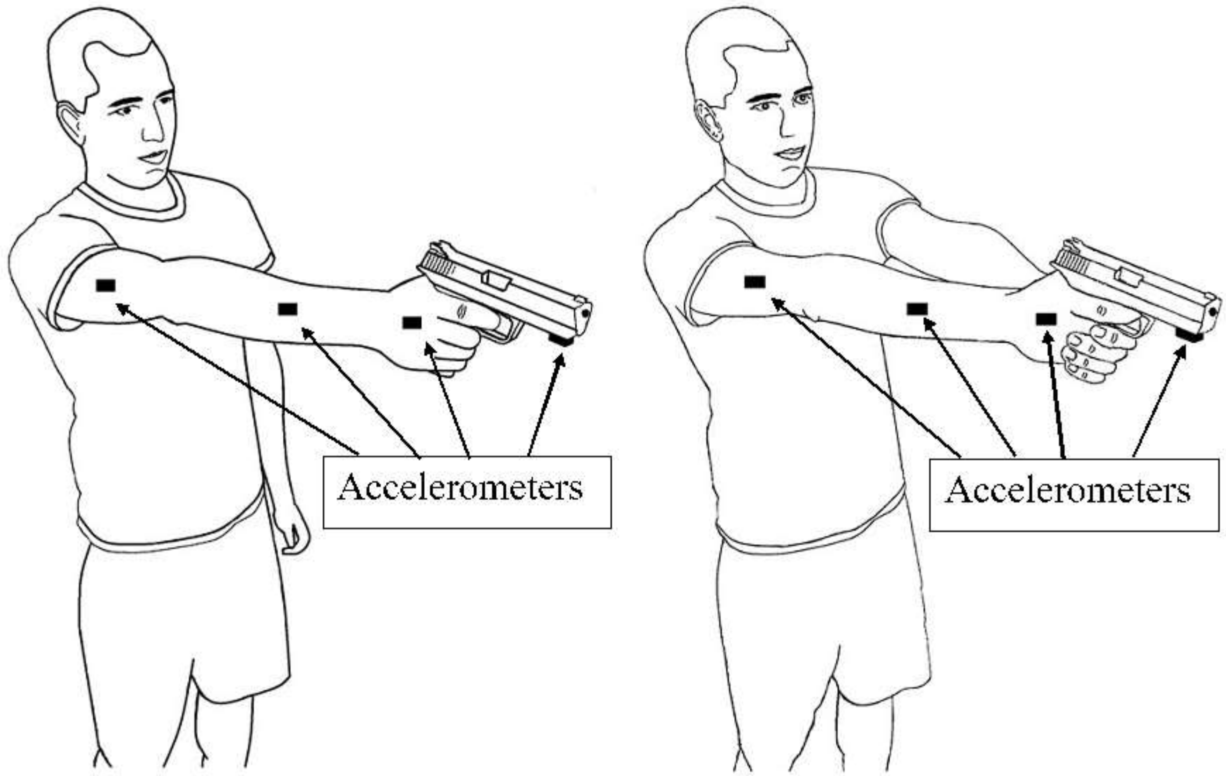

Fig. 4.1: Illustration of accelerometer placement for the unilateral and bilateral conditions

The same four postures were utilized for both the aiming and shooting tasks. For the aiming tasks the subject aimed the handgun at the target for 10 seconds. For the shooting tasks, rather than aiming for 10 seconds, during each 10-second trial the participants took 5 shots as accurately as possible at the target.

Experimental protocol

Participants completed a series of trials that entail two limb conditions and two weight conditions for a total of four combinations: 1) single hand grip/single mass, 2) single hand grip/double mass, 3) double hand grip/single mass, 4) double hand grip/double mass. During single hand conditions, the gun was held in the dominant hand, during double hand conditions both hands held the gun. Weighted conditions utilized the same gun, however, an additional mass was added to the gun for the double mass conditions (single mass 634 g, double mass 1268 g). This weight was verified using an electronic balance (Ohaus Corporation, Parsippany, NJ). All limb conditions were completed in a straight arm position with the shoulder flexed to 90 degrees (arm parallel to the ground), the elbow fully extended, and the wrist and hand rotated medially to hold the handgun in an upright position. The order of the four conditions were counter balanced for each participant. All subjects completed each of the conditions five times, for a duration of 10 seconds apiece. Participants were given 10 seconds of rest between trials.

The participants were instructed to maintain a bilateral stance with their toes behind the 21-foot line marked by a piece of tape. On the command to “aim” the participant raised his or her arm(s) with gun in hand to the pre-determined posture and maintained a steady aim at the target. Once in position the researcher started data collection. After 10 seconds, data collection automatically stopped. At the end of the trial the researcher gave the instruction to “lower your arm” for 10 seconds of rest between trials. This procedure was repeated for each trial under all eight conditions. If the participant held an incorrect posture or another error occurred the trial was repeated.

Data analysis

Accelerations were recorded by Noraxon tri-axial accelerometers and software, then analyzed using custom written Matlab software (R2012A, MathWorks, Natick, MA). Data were down sampled to 100 Hz. A second-order, zero-lag, low-pass Butterworth filter with a 50 Hz cutoff frequency was used to filter the data. Time series analysis included both measures of amplitude and regularity of the recorded data. Tremor data were examined in the ML, and VT axes. Root mean square (RMS) quantifies the average amplitude of fluctuation in the tremor signals to assess the steadiness of each aiming posture (Keogh et al., 2010; Morrison et al., 2013). Approximate entropy (ApEn) was used to assess the regularity, or predictability, of the tremor signal. Specifically, ApEn calculates the probability that a sequence of data points will repeat itself within a given signal. ApEn utilizes a scale of 0 to 2 with 0 being perfectly predictable and 2 indicating a highly complex signal with little repetition of vectors in the data (Hwang et al., 2006; Morrison & Newell, 1996; Pincus, 1991; Pincus et al., 1991). Frequency analysis of tremor was evaluated using Welch's power spectral density estimate within the range of 0-21 Hz. The spectral analysis was performed using a 512-data point length fast Fourier transform, with a 256-data point window size and 128 data point overlap. Three band widths (0-7 Hz, 7-14 Hz, 14-21 Hz) were analyzed, with peak magnitude and its corresponding frequency determined for each band width.

Statistical analysis

Statistical analyses were conducted with SAS software (Version 9.3, SAS Institute Inc., Cary, NC, USA). To determine differences at each segment between conditions each dependent variable was analyzed using a generalized linear mixed model. Significant main effects were further analyzed using the *Tukey–Kramer* method confidence interval adjustment. Data were presented as mean $\pm$ SD unless stated otherwise. The significance for all tests was set at an alpha level of 0.05.

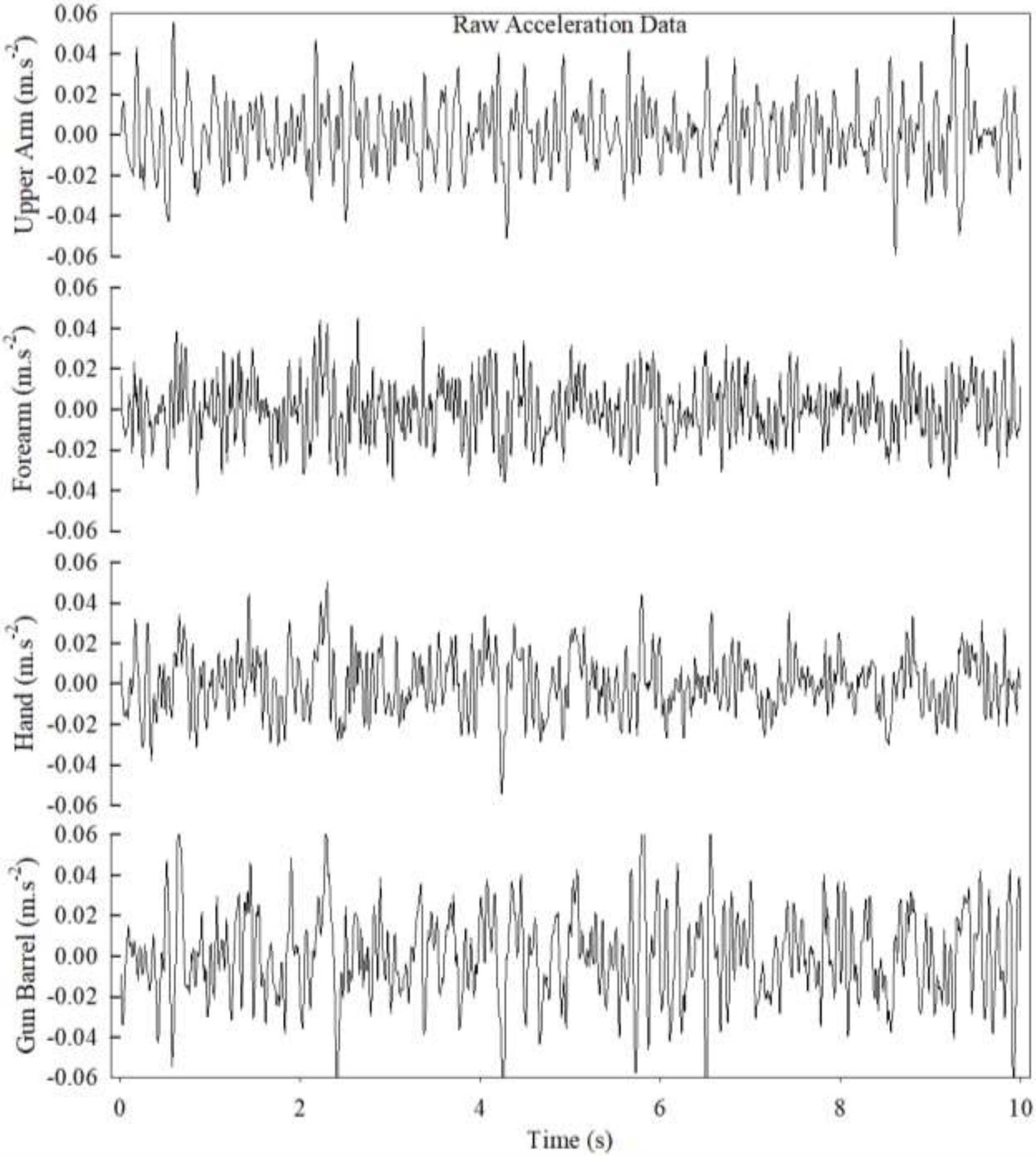

Fig. 4.2: Example of raw acceleration data during handgun aiming at the upper arm, forearm, hand, and gun barrel.

Results

Accelerometry data were collected during handgun aiming and shooting at four segments (UA, FA, HA, GB) and assessed in two directions (VT, ML). These data were collected under two limb support (unilateral, bilateral), and two weight (single, double) conditions. Shooting accuracy was also recorded during each of the limb and weight conditions. Illustrations of example accelerometry graph data for handgun aiming are shown in Fig. 4.2.

Differences in Acceleration Between Bilateral and Unilateral Limb Support

The addition of a second limb significantly altered aiming accelerations of the limb segments (Fig. 4.3). During the aiming conditions a second limb for support decreased the amplitude (VT: $F_{1,19}$ =281.30, $p<0.001$, ML: $F_{1,19}$ =389.77, $p<0.001$) and increased the irregularity (VT: $F_{1,19}$ =314.8, $p<0.001$, ML: $F_{1,19}$ =314.45, $p<0.001$) of the acceleration signal when compared to single arm support conditions. Specifically, amplitude of acceleration at all four limb segments (UA, FA, HA, GB) were significantly reduced during bilateral limb support in both the VT and ML direction (p's<0.001) with the exception of the UA segment in the ML direction, which was not significantly influenced by limb support (p =0.999). Irregularity of the acceleration signal in the VT direction was significantly increased when utilizing a second limb at the UA and HA segments (p's<0.001) segments but no significant changes were observed in the FA (p=0.067) and GB (p=0.295) segments. Irregularity of the acceleration signal also significantly increased with the addition of a second limb in the ML direction for UA (p<0.001), FA (p<0.001), and GB (p<0.001), irregularity significantly decreased for the HA (p=0.037) segment.

Frequency analysis conducted on the accelerometry signal revealed consistent findings for the peak frequency and amplitude across both directions (Fig. 4.4). Frequency analyses of the VT signals found a significantly lower peak amplitude during double arm support for all three frequency ranges (0-7 Hz, 7-14 Hz, and 14-21 Hz) and significantly higher peak frequency (unilateral: 14.9 ± 1.1 Hz, bilateral: 15.1 ± 1.2 Hz) in the 14-21 Hz range (p’s<0.05). VT peak frequency in both the 0-7 Hz and 7-14 Hz were not significantly altered by limb support (p’s>0.05). In the ML direction the accelerometry signals demonstrated a significantly lower peak amplitude (p’s<0.05) and significantly higher peak frequency (p’s<0.05) during double arm support for all three frequency ranges (unilateral: 5.2 ± 1.8 Hz, 9.4 ± 2.3 Hz, 14.9 ± 1.0 Hz, bilateral: 5.4 ± 1.5 Hz, 9.9 ± 2.2 Hz, 15.2 ± 1.2 Hz).

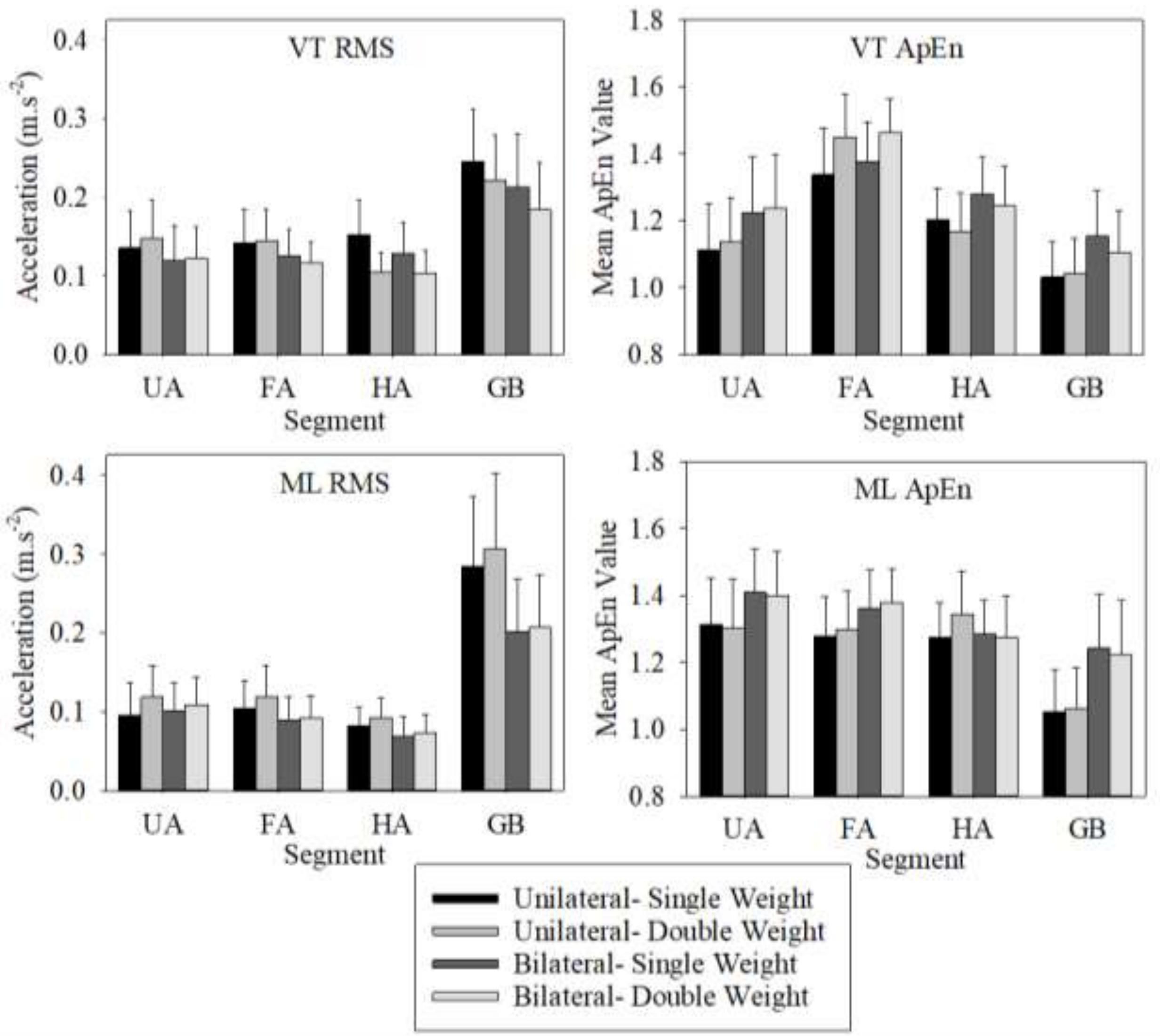

Fig. 4.3: Mean acceleration amplitude (RMS) and regularity values (ApEn) during aiming under both limb support (unilateral, bilateral) and weight (single, double) conditions at each segment of the upper limb (upper arm, forearm, hand, and gun barrel). See text for significant differences. Error bars represent one standard deviation from the mean.

Effect of Different Weights on the Acceleration Signals of Limb Segments

The overall effect of added weight significantly altered the amplitude of oscillations across the limb in the aiming task where single weight led to larger tremor than double weight in the VT direction, $F_{1,19}$ =112.39, p<0.001, while double weight resulted in larger tremor than single weight in the ML direction, $F_{1,19}$ =48.50, p<0.001. Interaction effects for weight and segment were significant in the VT direction (VT: $F_{3,57}$ =56.01, p<0.001) however interactions were not significant in the ML direction (ML: $F_{3,57}$ =1.13, p=0.346). Further examination of the effect of weight at the separate segments revealed in the VT direction there were no significant differences in acceleration amplitude for the UA (p=0.119) and FA (p=0.977) segments but there was a significantly greater amplitude of acceleration during single weight conditions for the HA (p<0.001) and GB (p<0.001) segments when compared to the double weight condition (Fig. 4.3). In the ML direction there were no significant differences in acceleration amplitude for the FA (p=0.124) and HA (p=0.265) segments but there was a significantly lower amplitude of acceleration during single weight conditions for the UA (p<0.001) and GB (p=0.002) segments. The addition of weight during aiming made the signal significantly more irregular across the limb in the VT ($F_{1,19}$ =15.11, p<0.001) but there were no significant changes in the ML ($F_{1,19}$ =3.93, p=0.062) direction. Regularity of the acceleration signal varied by segment based upon weight condition. In the VT direction, no significant differences were found at either the UA (p=0.295) or GB (p=0.348) segments while the FA (p<0.001) was more regular and the HA (p=0.003) was more irregular during the single weight conditions. In the ML direction, no significant differences were found at either the UA (p=0.969), FA (p=0.350) or GB (p=0.999) segments while the HA (p=0.040) was more regular during the single weight condition.

Analysis of the frequency spectrum during the weighted conditions predominately revealed changes in the peak power (Fig. 4.4). The double weight conditions revealed a significantly greater peak amplitude during double limb support for the VT and ML direction in the 0-7 Hz band as well as the ML in the 7-14 Hz band (p’s<0.05). The double weight condition had the opposite effect in the VT direction causing the amplitude of the peak to be significantly reduced in the 7-14 Hz and 14-21 Hz band (p's<0.05). No significant difference was observed between weight conditions in the ML direction for the 14-12 Hz range (p>0.05). Frequency of the peak was significantly increased during the double weight condition in the ML direction for the 0-7 Hz band (p<0.001). Peak frequency for VT in the 0-7 Hz band as well as VT and ML in both the 7-14 Hz and 14-21 Hz band were not significantly altered by weight condition (p's>0.05).

How Limb Support and Weight Conditions Affect Shooting Accuracy

Interaction effects for limb support and weight during handgun aiming accelerometry were not significant in the VT direction (VT: $F_{1,19}$ =0.300, p=0.592), however, interactions were significant in the ML direction (ML: $F_{1,19}$ =16.22, p<0.001). There were significant changes in shooting accuracy due to changes in the number of limbs supporting the gun (Fig. 4.5). Compared to single limb support, bilateral limb support was significantly more accurate (i.e., lower shot score, $F_{1,19}$ =129.05, p<0.001). No significant differences were found in handgun shooting accuracy between the single weight and the double weight conditions ($F_{1,19}$ =1.99, p=0.174). Interaction effects of support and weight on shooting accuracy score were not significant ($F_{1,19}$ =0.01, p=0.947).

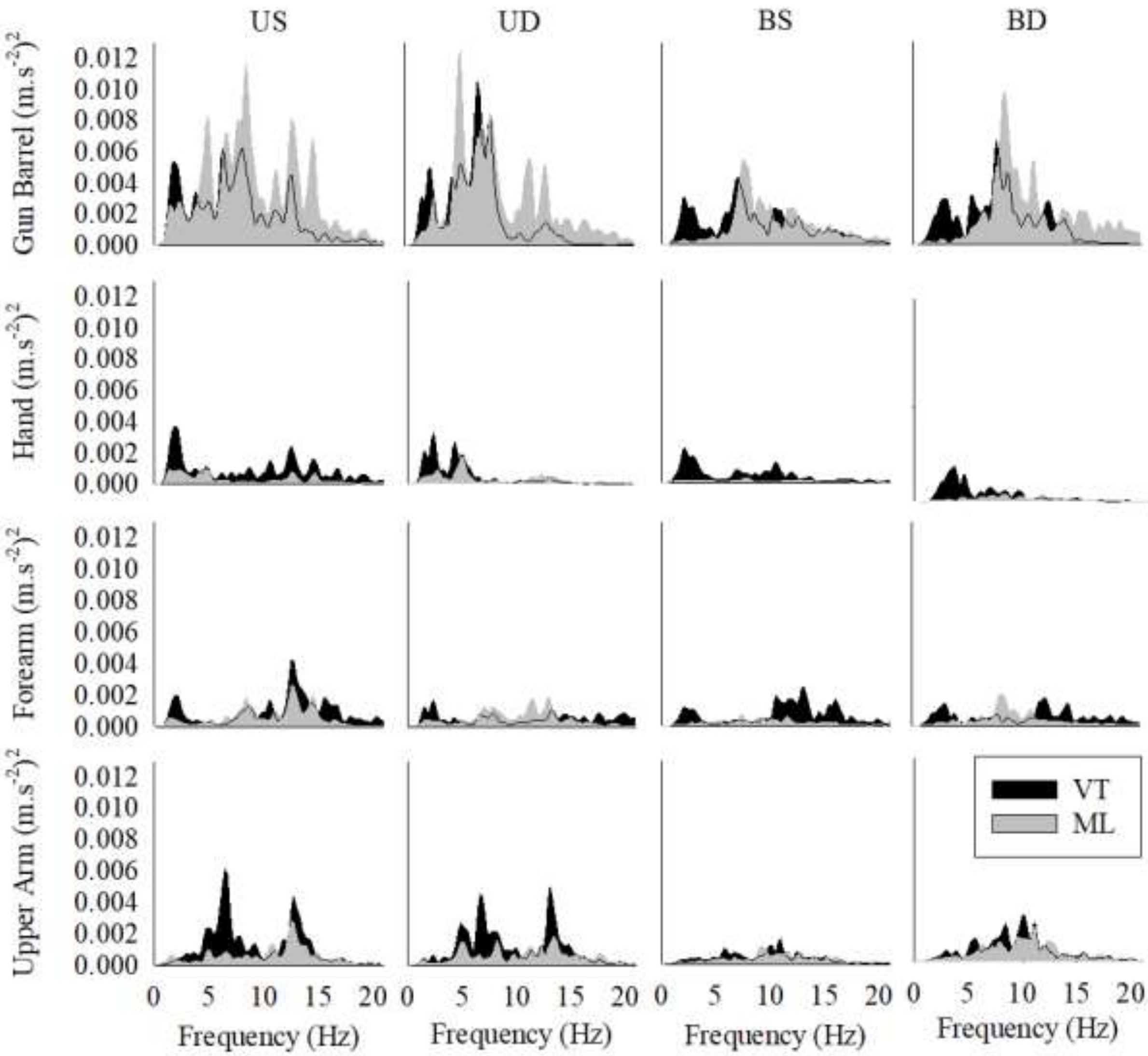

Fig. 4.4: Examples of the spectral frequency analysis (spectrum power) for each segment (upper arm, forearm, hand, gun barrel) and direction (vertical, mediolateral) for each condition (Unilateral- Single Weight [US], Unilateral- Double Weight [UD], Bilateral- Single Weight [BS], Bilateral- Double Weight [BD]) during handgun aiming.

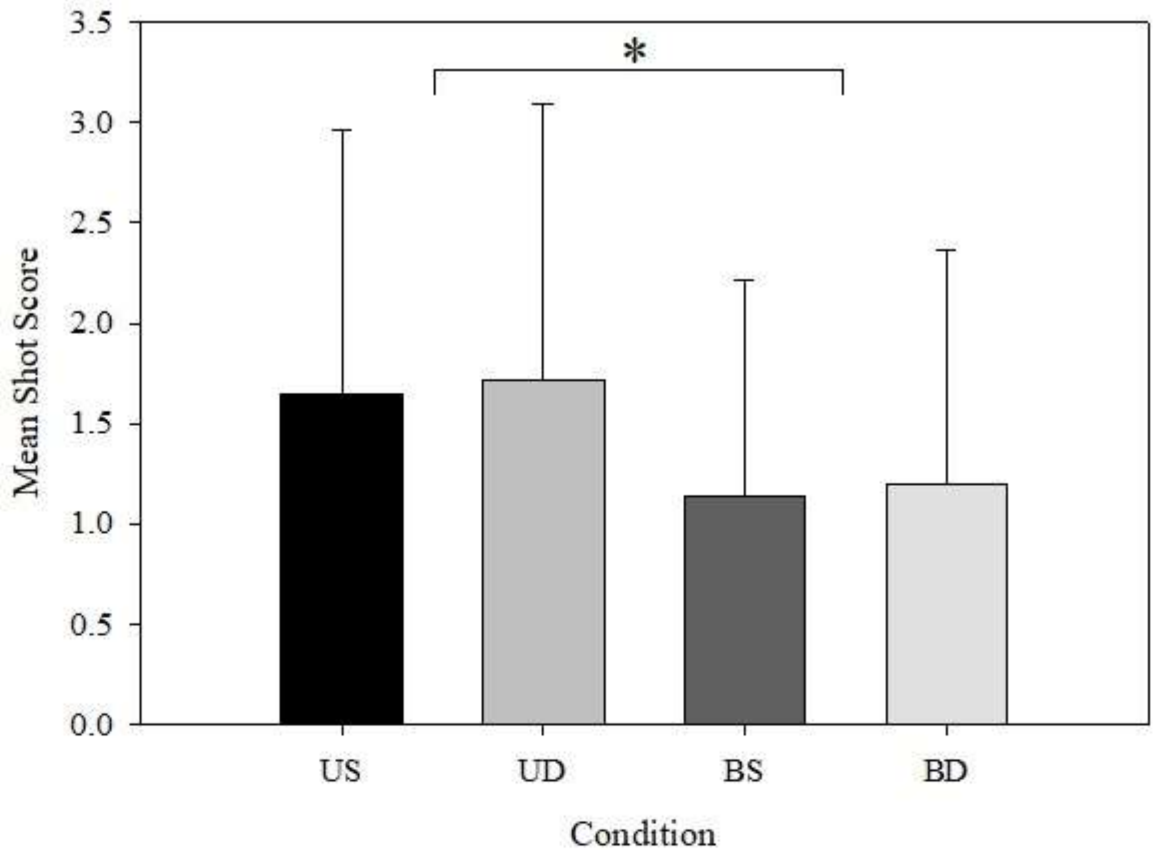

Fig. 4.5: Mean shot scores by condition (Unilateral- Single Weight [US], Unilateral- Double Weight [UD], Bilateral- Single Weight [BS], Bilateral- Double Weight [BD]). Each ring of the target was 2.2-cm wide, scored 1-4 starting with the ring closest to center (score of 0), a score of 5 indicated a miss. *Bilateral limb support was significantly more accurate than unilateral limb support. Error bars represent one standard deviation from the mean.

Discussion

The current study utilized accelerometry to assess movement of the upper limb and gun during handgun aiming as well as a laser to assess accuracy during handgun shooting. These measures allowed the current study to examine the effect limb support and handgun weight have on both involuntary movement of the upper limb and shooting accuracy during the given tasks.

Unilateral vs. Bilateral Limb Support

Research into support of the upper limb during pointing or aiming tasks has mostly been limited to external supports (Coulson et al., 2010; Morrison & Newell, 2000b) or bracing (Morrison & Newell, 2000a). External supports generally reduce the motion about a joint and subsequently degrees of freedom during pointing or aiming tasks. The addition of a second limb allows for a greater number of possible joint motions increasing the degrees of freedom involved in the task (Bernstein, 1967). As previously stated, this could pose a control problem for the individual due to the increased attention demand (Bernstein, 1967) or it may allow for more options for control, which may reduce involuntary oscillations and help perform the task (Anderson & Sidaway, 1994; Morrison & Newell, 1999; Vereijken et al., 1992). Presently, the only study the authors are aware of that address multiple limb support during goal directed handgun aiming tasks is Kelleran et al. (2016). This study included multiple handgun aiming postures including unilateral and bilateral limb support positions. The study did not, however, include a measure of accuracy. The current study aimed to fill that gap by including both aiming and shooting conditions under both bilateral and unilateral conditions. Mirroring previous research (Kelleran et al., 2016), the current study also found a decrease in the amplitude of acceleration (RMS) in both the VT and ML direction under bilateral aiming conditions.

Combining segments at the distal end of the limb to create bilateral support caused a reduction in amplitude of acceleration across multiple frequency bands indicating a dampening across a range of frequencies. This dampening of oscillations, due to bilateral support, extended up the limb from the distal segments all the way up to the UA. While the size of the tremor oscillations were smaller in all dimensions and segments of the arm, they also became more irregular. These findings extended our previous findings from the GB and FA to the HA and UA (Kelleran et al., 2016). Importantly, the bilateral shooting condition demonstrated a clear improvement in accuracy when compared to unilateral conditions. This suggests that the additional DOF supplied by the second limb increased control rather than hindered the task with extraneous available motions. Given that previous research (Chapter 3) found a stronger correlation between ApEn and accuracy than RMS and accuracy, the improvement in shooting accuracy with bilateral support may be more of a function of increased irregularity than a damping in tremor amplitude.

Weight Differences and Accuracy

Different parameters associated with the weight of a handgun have been discussed in the context of personal preference as well as maximum weight limits for some competition pistol shooting events. An unloaded Glock 17 weighs 710 g while a loaded Glock 17 weighs 910 g (GLOCK-Inc., 2017). The simulated Glock laser handgun used for the current study weighed 634 g during the single weight conditions and 1268 g during the double weight conditions. Interestingly, no difference in shooting accuracy was found between the two weight conditions. This finding indicates there should not be a difference between a full magazine and a near empty magazine; accuracy should be consistent as bullets are fired from the magazine. Also, weight of the gun for accuracy measures may play less of a role than anticipated. Previous research has shown that the addition of mass had different effects based upon the duration the limb was maintained outstretched. Mass (1200-1700 g) added to the hand and held for a duration of approximately 60 seconds have shown an increase in the amplitude of oscillation (Takanokura et al., 2007), while mass (500-1000 g) held for approximately 30 seconds had no significant effect compared to unloaded (0 g) conditions (Raethjen et al., 2004). The addition of mass (480-960 g) held for 10 seconds or less has demonstrated a dampening of oscillations (Morgan et al., 1975). The current study found during the double weight (1268 g) condition a significantly reduced amplitude of tremor in the VT direction and a significantly greater amplitude in the ML direction as compared to the single (634 g) weight condition. The attenuation and enhancement of tremor amplitude in the VT and ML direction respectively could be the result of the dampened VT tremor spilling over to the ML direction. Focus on resisting gravity in the VT direction due to the additional weight takes some emphasis off the ML direction resulting in an intensification of ML tremor. The attenuation of tremor amplitude in the VT direction appears to come predominately from the 7-14 Hz range (single weight: 9.7 $\pm$ 2.3 Hz, double weight: 9.6 $\pm$ 2.5 Hz) and 14-21 Hz range (single weight: 15.0 $\pm$ 1.1 Hz, double weight 14.9 $\pm$ 1.2 Hz), while the enhanced tremor in the ML direction came predominately from the 7-14 Hz range (single weight: 9.7 $\pm$ 2.3 Hz, double weight 9.6 $\pm$ 2.3 Hz). The hand, where the weight is applied in this protocol, has a mass component of tremor that naturally oscillates at a frequency between 8-12 Hz as does the neural component of tremor. Therefore, the additional load placed upon the limb may increase peak amplitude of the 7-14 Hz band due to both central neural and mechanical factors of the hand/limb complex. Due to the findings of the aforementioned studies on mass and tremor (Morgan et al., 1975; Raethjen et al., 2004; Takanokura et al., 2007), results pertaining to weight from the current study may be limited by the duration (10 s) of the postural aiming/shooting task.

It is possible that if held for a longer duration amplitude of oscillation and accuracy could be impacted at a greater level.

Control Mechanisms During Bilateral Support

The addition of a second limb for support may reduce the amplitude of acceleration and improve accuracy through either mechanical support, neural feedback, or a combination of both. After Kelleran et al. (2016) demonstrated a reduction in acceleration amplitude during bilateral handgun aiming tasks, examining where these changes came from became essential to understanding the control mechanisms of aiming a handgun. Dissecting the origin of the reduction in accelerations was investigated by comparing unilateral and bilateral postures under different weight loads. Significant differences in acceleration amplitude were seen due to weight. ML accelerations increased with additional weight while VT acceleration amplitudes were reduced. Bilateral limb support demonstrated significant reduction in acceleration amplitude over unilateral support in both the ML and VT directions. If the acceleration amplitude of the single weight unilateral limb support condition were equal to the double weight bilateral limb support condition then we could determine that the effect of limb support were simply mechanical efficiencies. However, the reduction in acceleration amplitude between the limb support conditions were greater than the differences in load conditions indicating more than mechanical support is acting upon the handgun during bilateral limb support conditions. Likely both mechanical support and neural feedback play a role in improving control. As previously suggested, the second hand may contribute to the mechanism of control by both reducing the force of muscular grip by the primary hand while also providing proprioceptive information about movement of the handgun and limbs (Aruin, 2005, 2015; Scholz & Latash, 1998).

Decreased acceleration amplitude coincided with a significant increase in ApEn when utilizing bilateral limb support instead of unilateral limb support. The bilateral posture involves more degrees of freedom due to having joints from both limbs contributing to the task (Bernstein, 1967). This increase in degrees of freedom from the bilateral posture may lead to greater irregularity (more complex) oscillations but results in smaller tremor and improved accuracy (Arutyunyan et al., 1969). The use of two limbs fortunately is a simple intervention that can easily be utilized by most to improve performance. The combination of decreased acceleration amplitude and increase in signal irregularity during bilateral limb support demonstrates significant improvement in handgun shooting accuracy over unilateral limb support conditions. While not yet substantiated, due to the similarities between handgun aiming and finger pointing (Chapter 3), these findings may also translate to other non-handgun specific postural tasks of the upper limb.

Conclusion

The current study sought to examine the effect weight and limb support had on accuracy and accelerations of the limb and gun. Overall the results suggest limb support plays a large role in both accuracy and accelerations at the gun barrel while the weight of the gun impacted accelerations but had a minimal impact on accuracy. Bilateral limb support reduced the magnitude of tremor and increased the irregularity of these accelerations, which resulted in more accurate shooting. Despite significant changes in acceleration amplitude due to the weight conditions, the non-significant changes in shooting accuracy between the weight conditions was startling considering the weight differential between the two conditions. Additional research is necessary to further distinguish the impact of support mechanisms and weight on handgun shooting accuracy.

CHAPTER V

CONCLUSIONS

Everyone has some level of physiological tremor that can be observed at the end of an outstretched upper limb during postural tasks including pointing and aiming. Examined regularly for over a century, tremor is influenced by both intrinsic and extrinsic components related to neural, mechanical, and environmental factors. This tremor and the associated factors can impact various precision-based tasks. For example, the prevalence of motion at the barrel of a gun is ubiquitous and has been suggested to impact accuracy of shot placement. The studies conducted within this dissertation investigated different parameters of oscillatory motion within the upper limb during pointing, aiming, and shooting tasks in an effort to further understand and improve handgun shooting accuracy. The results elucidated from the current studies have furthered our understanding of tremor and examined ways to mitigate tremor during functional tasks.

The experiments 1 and 2 examined tremor in all three directions (VT, ML, AP), experiment 3 studied tremor in the VT and ML direction. Comparable to previous research, the three current studies found there to be a remarkable quantity of tremulous accelerations in the ML direction when compared to the VT tremor. The current studies also found within the ML acceleration signal a significant structure, similar to the structure of the VT tremor, with two distinct peaks and a large overall magnitude. Two of the previous studies to look at tremor in the VT and ML direction were examining tremor during handgun shooting tasks (Pellegrini & Schena, 2005; Tang et al., 2008). Of the few studies to focus on multiple directions, most have found significant tremor in the ML direction (Hong et al., 2008; Hsu & Cooley, 2003; Pellegrini et al., 2004; Pellegrini & Schena, 2005; Tang et al., 2008). Many previous studies on tremor focused upon the VT direction for various reasons previously discussed including equipment restrictions and the importance of resisting gravity during postural tasks (Elble & Koller, 1990; Elble & Randall, 1976; Stiles, 1976). Finding considerable, structured tremor in the ML direction was unique because it was not combatting the force of gravity, bringing to question the origin of this distinct ML motion. Experiment 1 and experiment 2 also examined tremor in the AP direction. Accelerations in the AP direction were approximately half the magnitude of the other two directions (VT, ML) with no discernable structure to the frequency analysis. Fluctuations in the AP direction may be lesser simply because the limb doesn't move as freely in that direction as compared to VT and ML. It could also be argued that fluctuations in the AP direction are of lower importance regarding accuracy during aiming and pointing when compared to deviations off target in the VT and ML direction.

Previous research predominantly focused on tremor of the upper limb when holding an outstretched limb in space or during a goal directed pointing tasks (Elble & Randall, 1976, 1978; Hwang et al., 2006; Morrison & Newell, 1996, 1999, 2000a; Takanokura et al., 2007). A few experiments examined tremor during handgun aiming and shooting tasks (Mason & Bond, 1990; Pellegrini & Schena, 2005; Tang et al., 2008). Experiment 2 also sought to investigate tremor dynamics of the upper limb and link these to handgun aiming. This was accomplished by comparing finger pointing to handgun aiming. Both finger pointing and handgun aiming are goal-directed motor control tasks. These tasks displayed similar structure and amplitude of acceleration signals in the VT, ML, AP directions. This indicated a strong similarity between these tasks from a control perspective.

All three of the current studies demonstrated that tremor increases from proximal to distal segments in a nonlinear fashion similar to the findings of previous research (Hwang et al., 2006;

Morrison & Newell, 1996, 1999). This dissertation then used this information to further study handgun aiming postures. The first study examined different handgun aiming postures in an effort to elucidate which would provide the most stability through a reduction of the magnitude of acceleration. This first study found that bilateral limb support and bending the elbows each reduced acceleration amplitude independently. The magnitude of acceleration was further reduced when combined to a bilateral support posture with slightly bent elbows.

The findings of the first study brought forth the question of whether the second limb under bilateral support conditions simply contributed mechanical support or if additional feedback was provided to enhance the motor control of handgun aiming. By manipulating the weight of the handgun, the third study was also able to determine that the addition of a second limb to the unilateral limb support condition supplied more than simply mechanical support. This was determined by examining the unilateral condition with a single weight and comparing it to the bilateral condition with a double weight. If the reduction in amplitude of acceleration were strictly mechanical the two should have been equal however the amplitude of acceleration during the bilateral support and double weight condition was significantly lower than the unilateral single weight condition. If the reduction in amplitude of acceleration was not entirely due to mechanical support, contributions from neural feedback may have influenced the reduction of acceleration amplitude beyond the extent of the mechanical component. This conclusion is based upon tremor being comprised of two main components, mechanical and neural.

Interestingly tremor amplitude is not particularly ameliorated by experience or skill (moderate correlation). Likewise, a limited relationship (modest correlation) between tremor amplitude and accuracy was found. The correlations for these variables were expected to be higher. Rather, strong correlations were found between handgun shooting accuracy and signal irregularity as well as shooting experience. The strength of the correlation between handgun shooting accuracy and acceleration signal irregularity may indicate accurate shooters are releasing more degrees of freedom resulting in greater complexity of the output as well as improved task performance (Arutyunyan et al., 1968, 1969). Additionally, the current research indicates that the output for experienced shooters may be more complex as well. This increased irregularity may be due to a release of degrees of freedom that comes with practice and enhanced skill (Anderson & Sidaway, 1994; Arutyunyan et al., 1969; Bernstein, 1967; van Emmerik & van Wegen, 2002; Vereijken et al., 1992).

Current strategies for limiting the impact these oscillations have upon shooting accuracy generally focus in increasing support. A long gun such as a rifle is at a distinct advantage over handguns due to a trifecta of contact points for stability. Handguns are limited to one or two contact points depending upon grip type (unilateral, bilateral). The third study further expanded upon this handgun aiming paradigm by comparing limb support and handgun weight. The addition of a handgun shooting condition expanded the application of the project by indicating shooting accuracy for each condition. Bilateral limb support again reduced tremor amplitude and contributed to the new finding of a significantly improved shooting accuracy under bilateral limb support conditions.

In conclusion this dissertation approached a complex task from a novel direction and found ways of not only understanding and improving handgun shooting accuracy but also increased knowledge and awareness of goal-directed tasks of the upper limb. Tremor is ever present during postural tasks. There are postures that appear to mitigate the negative impact of these fluctuations however including bending the elbow and using two hands. Bilateral limb support appears to provide better control potentially through tactial sensation and neural feedback, not simply mechanical support. Experience also helps in this regard. The knowledge garnered form this dissertation can be expanded upon and applied to postural tremor research, improving other precision-based tasks, and potentially even have application in the clinical world.

CHAPTER VI

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