**Experimental Physiology – *Themed Issue Review***

# The influence of muscle tremor on shooting performance

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**Shooting ability is compromised by involuntary movement. Some of this movement is physiological tremor. Tremor size has a demonstrable inverse correlation with shooting performance. Consequently, factors which affect tremor size should affect shooting ability. Adrenaline and local muscle warming markedly increase tremor size, whereas local muscle cooling reduces it. The physiological mechanisms behind these changes are not well understood, but they have the potential to affect shooting performance in subjects who exercise heavily and/or are exposed to extreme environments. The Olympic biathlon is an event in which vigorous physical exercise alternates with rifle shooting and it often takes place in a cold environment. The possible impact of exercise, temperature and other factors on the Olympic biathlete is considered here.**

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Little is known about the physiological limitations of shooting ability. In this review, some of the factors which may impact on performance are considered. Shooting is an example of an activity which requires consistency and accuracy. That is, fired shots must all end up in about the same place, and that place must be the correct one. Accuracy can be improved by training and by choice of equipment. High-quality guns and ammunition are superior in that they produce a precise trajectory of the bullet, and such weapons will have more accurately adjustable sights. Characteristically, shooters will improve their aim with repetition of the activity. Expert shooters practice extensively. The physiological aspects of this form of improvement with learning are at present relatively inscrutable, although sensory aspects (visual resolution and accuracy, and the signal-to-noise ratio of the sensory channel) and motor aspects, such as choice and pattern of recruitment of muscles (both synergists and co-contracting antagonists), undoubtedly play a role. These aspects will not be further considered here.

The enemy of consistency is noise. Noise represents variability in the outcome of an action. Noise may be externally caused; for example, a shooter may be buffeted by gusts of wind. Alternatively, noise may be internally generated. Movements of the body due to breathing or to ballistocardiac recoil or to arterial pulsation are obvious causes. Another form of noise may result from variation in the technique that is used. Most shooters are trained to be very consistent in the sequence of activities that they perform, but even after considerable repetition some variability remains. Less immediately obvious is the inherent 'noisiness' in muscle itself. Muscles are not perfect actuators and they are incapable of maintaining a limb or a held object in a perfectly stationary position. Thus, a successful shooter must seek to reduce the size of the noise wherever possible. A precision activity, such as target shooting, is usually performed in an environment which is thermoneutral and free from other physical stress. The same is true of surgery, micro-dissecting, playing darts and snooker. Soldiers will meet with very different situations. They must shoot consistently in conditions which may be far from thermoneutral, and they may be exposed to extreme physical stress. The Olympic biathlon, which is a sport derived from a military exercise for Scandinavian soldiers, provides an interesting example of an activity which demands consistency in shooting and very heavy physical exercise. Furthermore, in winter conditions the environmental temperature may be very low. In this review, I look briefly at muscle noise, its effect on shooting and ways in which this may be affected by climate, physical exertion and other factors.

## The source of muscle noise

The most obvious manifestation of muscle noise is postural tremor. In maintaining the posture of a limb there is inevitably some positional wobble. Although it

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is not so easily observed, the situation is the same if subjects are asked to maintain a constant force; despite their best efforts there will be fluctuations in the force that is generated. Evidence suggests that the variability in force is proportional to the mean level of force that is being generated, although this relationship may break down at very high and low levels (Schmidt *et al.* 1978; Sherwood *et al.* 1988; Charlton & Newell, 1993). Owing to its proportionality to force, this muscle noise is sometimes described as a 'signal-dependent noise' (Harris & Wolpert, 1998). Signal-dependent noise, like postural tremor, varies greatly in size amongst individuals, and physiological or pharmacological methods cause similar changes in the size of both. There is a clear correlation in the size of tremor measured as a variation in force and as a variation in position in groups of subjects (Fig. 1; Lakie, 1994).

Although the frequency content of postural tremor and signal-dependent noise are very different, it is probably safe to assume that the two share a common origin. The difference in the frequency content is mainly due to the colouration introduced by the dynamics of the moving limb and load when positional tremor is measured, although altered sensory feedback when the limb is free to move may play an additional role. In this review of shooting consistency, tremor will be considered to mean variation in position (or its derivatives, velocity and acceleration) rather than variation in force. Tremor is bound to impact unfavourably on activities where consistency is required. For example, in microsurgery, surgeons adopt elaborate strategies to stabilize their hands (Harwell & Ferguson, 1983). Practical surgical instruments which actively cancel out small tremor-related movements are being actively developed (see for example, Riviere *et al.* 2003). Similarly, 'anti-blur' technology, which cancels out the deleterious effect of tremor on image quality in hand-held digital cameras, is now commonplace. As far as is known, although tremor cancellation of this kind is now commonplace in shooting photographs, it has not been applied to weapons.

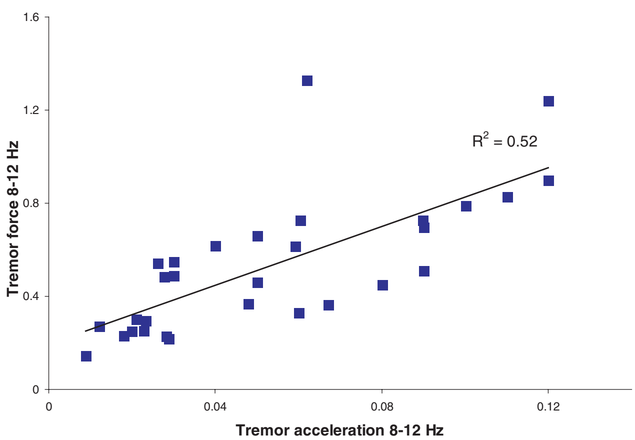


**Figure 1. Comparison of postural tremor size and force fluctuation size**

Postural left hand tremor was measured by an accelerometer on the dorsum and fast Fourier transform analysis used to determine the mean size in the 8–12 Hz band. Isometric force fluctuation was measured approximately 60 s later in the right first dorsal interosseus muscle at a mean force of 5.0 N. The force signals were bandpass filtered between 4 and 14 Hz and the root mean square value recorded. There were 30 subjects (12 men). The units are not directly comparable, but are *g* (the acceleration due to the force of gravity) for postural tremor and grams for force. The positive correlation is significant (ANOVA, $F = 30.915$, $P < 0.001$).

## Physiological tremor

If an outstretched hand is closely observed, it will be seen not to be stationary but to be in a continuous state of minor movement. Instrumental recordings show that there is an apparently random wander in position with no clear peak frequency of the movements. The slowly wandering set-point probably represents the best efforts of the nervous system to regulate position. Simultaneously, there are smaller, higher frequency oscillations. This component is very much more rhythmic and has a maximal size at a frequency between 7 and 11 Hz; it is much more prominent if acceleration is recorded (Elble, 2005). This is physiological tremor. For convenience, acceleration is usually recorded precisely because it emphasizes this clear-cut high-frequency component while minimizing the slower movements. The characteristics of typical postural hand tremor are shown in Fig. 2. The size of physiological tremor in any person varies from time to time, but the frequency content is much more stable.

The cause of the rhythmic acceleration at 7–11 Hz is not entirely settled. In part, the acceleration may result from the repetitive force impulses generated by pulsatile motor unit firing. Even if motor unit activity is entirely unsynchronized, there will always be some tendency for the force modulation to reflect the activity of the largest (that is, the most recently recruited) motor units. The characteristic firing frequency of motor units when first recruited is in this frequency band, and when the frequency becomes higher, 'grouping' into action potential doublets or triplets may keep the principal fluctuation frequency lower (Elble & Randall, 1976; Christakos *et al.* 2009). Random forcing input from motor units may excite internal resonances of the spring/mass, muscle–tendon–limb system, which will cause an oscillation of the limb close to its natural frequency. In part, the rhythmic activity may also result from partly synchronized motor unit firing so that there is an increased likelihood of firing in active motor units at particular intervals. Such rhythmic modulation may in principle be a consequence of central drive or peripheral feedback from the moving limb. There is evidence that both of these mechanisms may operate even in apparently isometric conditions (Christakos *et al.* 2006).

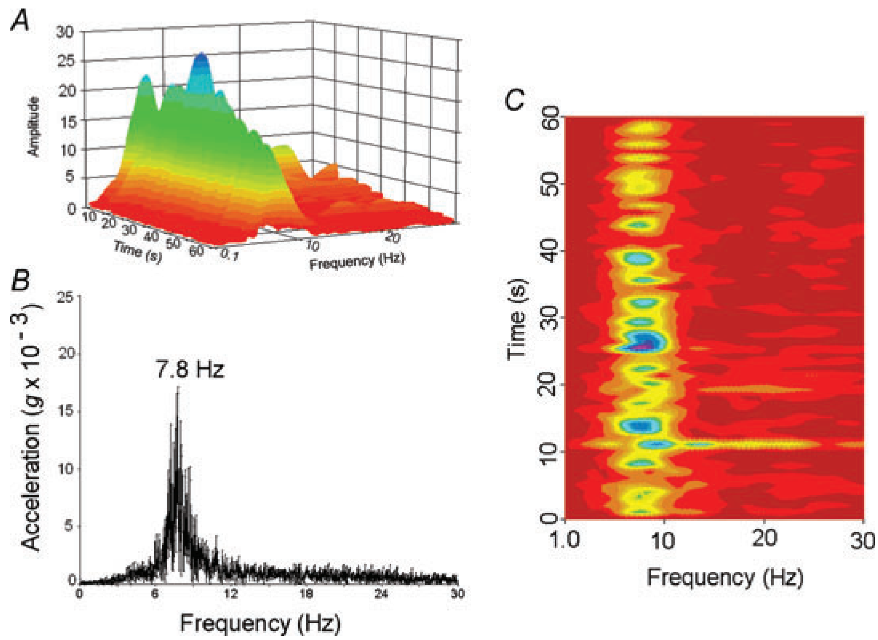


**Figure 2. Right hand tremor measured by an accelerometer in a typical subject**
Tremor was recorded for 60 s. *A* shows the amplitude spectrum over this time period. The averaged spectrum is shown in *B*. *C* shows the spectrogram (plan view of *A*). The key features are the remarkably constant frequency at which the size of the acceleration is maximal and the apparently random variation in the acceleration size with time. (In this example, the frequency is 7.8 Hz and the size ∼17 × $10^{-3}$*g*.)

There is some evidence in support of mechanical, reflex and central mechanisms in tremor generation, and it is likely that all may contribute to some degree (Lakie *et al.* 1986; McAuley *et al.* 1997; Farmer 1998; Durbaba *et al.* 2005). Whatever the cause, there is no evidence that the size of tremor can be controlled by voluntary means. Tremor is a purely involuntary movement. Evidence that the involuntary movement is in any causal way linked to a voluntary one (as might occur, for example, in trigger pulling in shooting) seems weak (Goodman & Kelso, 1983) or absent (Lakie & Combes, 2000).

### Factors affecting tremor

**Frequency.** The frequency of tremor cannot be altered by any known short-term physiological or pharmacological interventions. A study of 245 subjects showed that in most subjects the peak frequency lay between 7 and 11 Hz (Fig. 3*A*; Lakie, 1994). The only known experimental way of changing the frequency of tremor is by mechanically loading a limb. Increasing the inertia will, in general, lower the frequency of tremor (Elble & Randall, 1978; Lakie *et al.* 1986). These observations are compatible with the idea that a limb acts as a resonator or coherer, which tends to oscillate with the largest amplitude at a frequency very close to its natural frequency because it is lightly damped (Lakie *et al.* 1984). The underdamping probably reflects the fact that nature prioritizes speed of movement over stability. There is no obvious mechanistic way in which the frequency of tremor will correlate with the ability to perform precision activities, except insofar as subjects with the largest tremors tend to have slightly lower peak frequencies. The difference in tremor frequencies between subjects is anyway not large. Furthermore, there is no indication that the peak frequency of tremor correlates with measures such as simple reaction time (Lakie & Combes, 2000). Therefore, in shooting or other precision activities no advantage is likely to arise from possessing a particular peak frequency of tremor.

**Size.** If the frequency of tremor is relatively invariant, the same cannot be said for its size. Unlike most other physiological parameters, the size of this oscillation varies very greatly between individuals. Most people will know of at least one individual with a grossly visible tremor. One study showed that the size of tremor in a sample

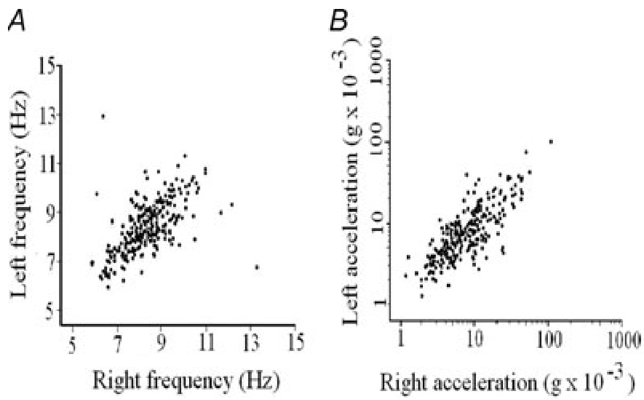


**Figure 3. The hand tremor characteristics of 245 individuals aged between 9 and 91 years**
Acceleration was recorded simultaneously from both hands. *A*, the frequency at which the tremor peaks lies between 7 and 11 Hz in most individuals and is generally similar in left and right hands. *B*, in contrast, the size of tremor can be very different amongst individuals (note the logarithmic scale). The size of tremor is also generally similar in both hands.

of 245 subjects varied by a factor of approximately 100-fold (Fig. 3*B*; Lakie, 1994). Patients suffering from severe essential tremor, who usually have tremors that are even larger, are often unable to draw or write and may have difficulty eating and drinking. This suggests that precision activities may be more difficult for some otherwise normal subjects than for others. In the same study, it was found that tremor size has a clear tendency to increase with age; the oldest subjects had on average 10 times more tremor than the youngest. Tremor size varies spontaneously in individuals, waxing and waning with no clear periodicity. The size of this variability is typically a factor of two to three. A slight diurnal variation has been reported (Tyrer & Bond, 1974; Van Hilten *et al.* 1991), but this may reflect other factors, such as limb temperature, which change tremor size. Many artificial ways exist of increasing or decreasing tremor size. It has long been known that $\beta$-receptor agonists increase tremor levels and that the emotional states of anger or fear can have considerable influence, mainly through their actions in liberating adrenaline. Increased tremor is obvious to speaker and audience when a nervous lecturer uses a laser pointer. The increased tremor of thyrotoxicosis is also well known. Apart from these causes, less is known about other factors influencing tremor size in normal people. Mosso (1896) heated one arm of a subject (his brother), and found that an accentuated tremor of that hand was produced. This finding has been confirmed and, conversely, cooling the arm has been shown to reduce the size of postural tremor and essential tremor (Fig. 4; Lakie *et al.* 1994*b*). Some common factors affecting tremor size are summarized in Table 1.

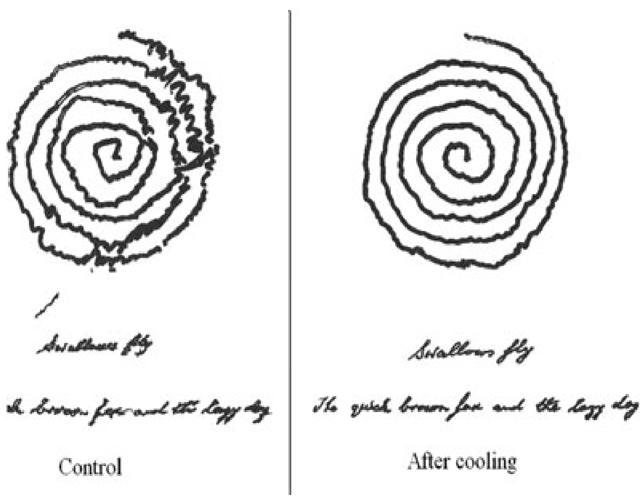


**Figure 4. The effect of muscle cooling on a subject with marked essential tremor**
The subject, a man of 70 with a 40 year history of essential tremor, traced a spiral on an acetate sheet using a felt-tipped pen. A sample of handwriting was also obtained. The results were obtained before and after immersion of the writing arm in water at 10°C for 10 min.

The cause of a change in tremor size may be neurogenic or myogenic. For example, alcohol is known to reduce the size of essential tremor and physiological tremor. It appears that this effect is neurogenic and centrally mediated, because close arterial infusion of alcohol into a limb did not cause a tremor reduction (although there is a question about the adequacy of dosage that was employed (Growdon *et al.* 1975; Lakie *et al.* 1994*a*). The mode of action is not known, although some evidence suggests that alcohol may suppress a thalamic or cerebellar oscillator in the brain (Sinton *et al.* 1989; Boecker *et al.* 1996). Conversely, decreasing limb temperature by immersing a limb in cool water has a myogenic effect, because it decreases the amplitude of the partly fused tetani in active motor units by slowing muscle contraction (and particularly relaxation). Exactly opposite effects are seen with limb warming, which has a strongly tremorogenic effect (Lakie *et al.* 1994*b*). A similar myogenic explanation involving speeded up twitch properties of slow skeletal muscle is generally supposed to underlie the well-known effect of $\beta_2$-agonists, such as adrenaline, on tremor (Foley *et al.* 1967; Marsden & Meadows, 1970). Myogenic factors affect tremor size by changing the bumpiness of the force input to the limb.

It is interesting that many factors influencing tremor size share at least a potential relationship to the blood flow through the muscle. Limb ischaemia causes a rapid and dramatic reduction in the size of its tremor. Size declines within 30 s of a limb being made ischaemic and continues to decrease thereafter. This reduction was at one time attributed to an effect on muscle spindles (Lippold, 1970). However, it has recently been shown that ischaemia does not reduce tremor size if the limb remains passive and relaxed after the application of the cuff (Lakie *et al.* 2004). It appears to be the combination of ischaemia and continuing slight muscle activity that is responsible for the reduction. This strongly suggests that it is the accumulation or depletion of a metabolite in the limb that causes the reduction in tremor size. Lakie *et al.* (2004) tentatively suggested that a locally high extracellular concentration to intracellular concentration ratio for $K^+$ may blunt tremor by a blocking effect on the T-tubules of skeletal muscle. Blocking impairs inward transmission of the action potential, and simultaneous contraction of all parts of the muscle fibre is disrupted, thus reducing the size and sharpness of its force profile. Any circumstances producing an increase in localized extracellular $K^+$ (for example, $\beta$-blocking drugs or reduced washout from the muscles) will decrease tremor size, whereas $\beta_2$-agonists, which promote uptake of $K^+$ into cells, will increase tremor size. A central effect, in the form of a signal sent by the ischaemic limb to the spinal cord, appears unlikely because it has also been shown that a very small 'artificial tremor' induced in an otherwise resting limb by mild percutaneous muscle stimulation is affected in an identical way by

**Table 1. Factors associated with alterations in tremor size**

| Condition | Tremor effect | Treatment (if appropriate) | Explanatory note |
|---|---|---|---|
| Adrenaline and other $\beta_2$-agonists | Large increase | $\beta_2$-Blockers | A |
| Hyperthyroidism | Large increase | $\beta_2$-Blockers | B |
| Raised muscle temperature | Large increase | Not applicable | C |
| Ethanol withdrawal and delirium tremens | Large increase | $\beta_2$-Blockers | D |
| Lithium | Moderate increase | Potassium | E |
| Exercise | Decrease followed by increase | Not applicable | F |
| Ischaemia and muscle activity | Large decrease | Not applicable | G |
| Lowered muscle temperature | Large decrease | Not applicable | H |
| Acute ethanol administration | Large decrease | Not applicable | I |

(A) The peripheral $\beta_2$-receptor associated with tremor is one which controls sodium–potassium exchange (general stimulation of muscle $Na^+$–$K^+$ pumps), rather than one that has a direct effect on the contractile machinery. This hypothesis may explain the delayed tremor response.
(B) Thyrotoxic tremor has been attributed to a synergistic effect of thyroid hormones on adrenaline sensitivity because the tremor is symptomatically 'cured' by $\beta$-blockers. An alternative explanation is that the tremor is a direct consequence of the low plasma $K^+$ caused by the disease. $\beta_2$-Blockers ameliorate the tremor by raising extracellular potassium concentration.
(C) Small increases in muscle temperature greatly increase tremor size. It may be that the changes are partly consequent on temperature-induced changes in blood flow. An increase in muscle blood flow may increase washout of interstitial $K^+$ and keep the concentration low, thus enhancing tremor.
(D) The tremor of delirium tremens is indistinguishable from essential tremor. Three studies have shown that only in patients who developed delirium tremens following alcohol withdrawal was plasma or total body $K^+$ significantly reduced. Resolution of the tremor was accompanied by return of the plasma $K^+$ to normal values.
(E) Postural tremor is a common problem for patients taking lithium. Potassium has been employed successfully to treat these side-effects.
(F) Vigorous exercise results in a subsequent prolonged increase in tremor. This may be attributable to the effects of associated sympathetic release of adrenaline on the $Na^+$–$K^+$ pump, tending to produce a lower interstitial $K^+$ concentration, particularly but not exclusively in the muscles which have been active. However, isometric muscle fatigue generally produces a short-lasting decrease in tremor size immediately on cessation. This would be consistent with a period of $K^+$ efflux from the muscle and reduced or zero perfusion of the active muscle.
(G) Ischaemia only reduces tremor when combined with muscular activity.
(H) As in the case of heating (C), this has been attributed to a direct effect on the contractile apparatus. It is possible that a reduction in blood flow and reduced washout of $K^+$ may also be a contributory factor.
(I) Acute administration of alcohol causes a progressive and profound reduction of both essential tremor and physiological tremor. The effect has been generally held to be a central one. However, particularly in the light of the observations on delirium tremens above, this could be reinvestigated. For further details, see the study of Lakie *et al.* (2003).

ischaemia (Lakie *et al.* 1986). The hypothesis that most tremor size changes have a metabolic explanation remains to be challenged.

The effect of exercise on tremor size is complicated. Exercise of the whole body tends to produce an increase in tremor size. This is probably attributable to liberation of adrenaline, which has strongly tremorogenic $\beta_2$-adrenergic effects. However, although they are potent tremorogens the effect of $\beta$-agonists is invariably delayed, with a delay of 5–10 min between the peak of concentration of the drug in the bloodstream and the peak of the increase in tremor size (Lakie *et al.* 2003). This is the delayed tremor that is experienced after a shock. The effects of localized exercise are different. If the exercise is sufficient to cause a degree of limb ischaemia, then the immediate effect is a considerable decrease in tremor size. Consequently, brief fatiguing isometric efforts tend to be associated with a short-term reduction in tremor size (Arblaster *et al.* 1989). However, dynamic limb exercise where perfusion remains may promote a long-lasting increase in tremor, and it is commonplace that people who wish to perform fine tasks will avoid heavy exercise for a day or so beforehand. There is some evidence for the emergence of a specific form of increased tremor size following fatiguing limb exercise (Furness *et al.* 1977; Gajewski, 2006). A further component of tremor size is the activity of the heart and, to some extent, respiratory movements. Ventilatory movements during and after heavy exercise will be considerable, but can be voluntary suppressed for brief periods if desired. In a relaxed subject, there is a component of physiological tremor which is related to the heartbeat. Each heartbeat produces a transient oscillation of a limb, presumably at its resonant frequency. Such ballistocardiographic tremor is only easily visible in a limb which is relaxed, because as soon as a posture is maintained it becomes ‘buried’ in the postural tremor caused by muscular activity. Its size probably amounts to only 2–10% of the total postural tremor (Marsden *et al.* 1969). However, it can be detected by using an averaging technique. It has two causes. First, there is the arterial pulsation, which is transmitted along the limb. This component can be eliminated by cutting off limb blood flow, for example by cuffing. The second component is the shockwave which is caused by the rapid expulsion of blood from the heart. The recoil from this is transmitted throughout the body, and the thrust causes an acceleration of the body and limbs.

A rise in heart rate will cause an increase in the rate of both of these impulsive inputs. Simultaneously, the considerable increase in pulse pressure and stroke output will increase their size. Accordingly, the size of the ballistocardiac component of tremor will be increased by exertion. However, it remains a relatively minor component, and the frequency of the transient oscillation is not changed because it reflects the properties of the limb (Lakie *et al.* 1986). The same mechanical system is excited by an increased number of larger shocks.

## Association between tremor and shooting

Shooting is a human skill. Ignoring allowances that must be made for the fact that the projectile does not fly in a perfectly straight line and for the effects of muzzle blast and recoil, there are at least two main human aspects to hitting the target. One involves translation of the barrel of the weapon and the other involves rotation. Clearly, the translation aspect is less critical as a target of, say 5 cm in diameter, allows a vertical or horizontal movement of the barrel by 5 cm regardless of its distance away. Rotation is much more stringent. If the 5 cm target is at 10 m distance, a misalignment of the barrel by only 0.3 deg will cause the target to be missed. There have been very few studies of tremor and shooting, and they have only described movement of the weapon in terms of translation, usually of the muzzle, and the more important rotational aspect may have been missed. Aiming skill is similar to that of pointing. Pointing has been extensively studied (see for example, Glencross & Barrett, 1989) and historically is divided into two components: the initial impulse (preprogrammed) and a sensory control phase (current control; Woodworth, 1899). Shooting consistency is probably more allied to the ‘current control’ mode, but shooting involves the important extra feature that the subject must decide when he or she is pointing in the correct direction and commit to this decision by a trigger pull, at that instant using a limb which is also contributing to support of the gun. As far as is known, weapons triggered by voluntary activity in a remote part of the shooter’s body are not practical or safe but they might be theoretically superior.

Rotation of a long object, for example a pointer, is easier to prevent if it is held with the hands well apart rather than close together. Also, the total distance of the hands from the body should be minimized. It is largely these aspects which make it possible to shoot more consistently with a rifle than a pistol. Furthermore, a rifle has a greater mass and a considerably greater moment of inertia, so that its susceptibility to motor noise from the muscles is much less. Studies of tremor applied to shooting have not focused well on that distinction. Similarly, the posture of a shooter is important. A person shooting prone with a rifle is in a much more stable position than a person shooting with a pistol at arm’s length. In the latter situation, the movement caused by postural sway must be added to unwanted movements of the upper limbs. It is clear that in shooting even minor involuntary movement of the limbs or body will have a detrimental effect on consistency.

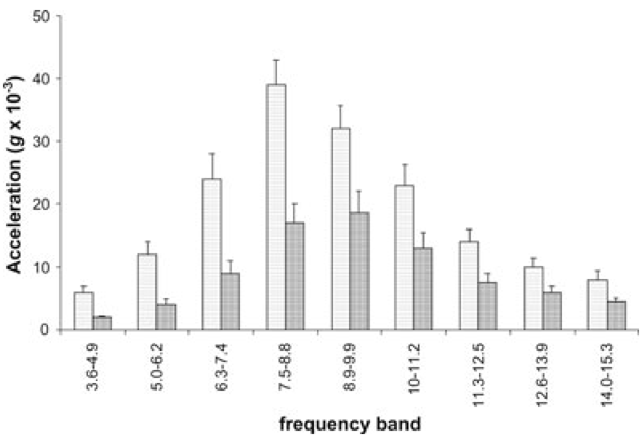


**Figure 5. A comparison of hand tremor in 38 expert shooters and in 120 non-shooting, age-matched control subjects**
The mean (+ S.E.M.) size of the tremor in each of nine frequency bands is shown. All tremor measurements were made at an Olympic training event. The shooters (right-hand bars) had, on average, tremors that were approximately half the size of the control subjects.

## Tremor size in shooters

Bilateral measurements of hand tremor were made in 38 expert shooters at a UK National Championship meeting (Fig. 5). Tremor was measured at various times during the meeting. The tremor size of the shooters was compared with a group of age-matched control subjects. On average, the tremor size was approximately half that of the control subjects, and the difference was very highly significant. The frequency was not significantly different. Unsurprisingly, the expert shooters had small tremors, and this suggests that a small tremor size is a prerequisite for expert shooting or that these expert shooters were somehow able to suppress their tremor. $\beta$-Blockers can suppress tremor size and have been shown to improve shooting performance (Kruse *et al.* 1986). Such drugs are banned in target shooting, and any level detected in the blood during performance is a contravention. Moderate alcohol consumption is also associated in many people's minds with precision sports such as darts or snooker, but this drug too is banned in target shooting.

### The association of tremor size with shooting performance

Spaeth & Dunham (1921) made an early investigation into the association between shooting expertise and steadiness. They assessed tremor by a dexterity test. A strong positive correlation ($r = 0.61$) was reported to exist between steadiness and marksmanship. They suggested that a pretraining screening test of steadiness would be a useful aid in recruiting infantrymen. Very few more recent studies have examined the correlation of tremor size with measured performance. This requires that the tremor of the weapon itself is measured up to the point at which the shot is fired. This has been accomplished by a motion capture system or by attaching a lightweight accelerometer to the gun itself and assessing the performance of the shooter. Pellegrini *et al.* measured tremor in shooters using either a laser pointer (2004) or an air pistol (2005). Their main finding was that in more expert shooters the size of tremor oscillation in the vertical plane was 27% smaller than in non-expert shooters. The range of movement and the frequencies were not different. Tang *et al.* (2008) measured tremor in 10 elite and pre-elite air pistol shooters. They showed that the 8–12 Hz tremor size of the shooters was inversely related to shooting performance and that the elite tremor shooters had a smaller tremor size in the pistol and distal arm segments.

### Factors that will decrease tremor size and improve shooting performance

The small size of tremor measured in expert shooters and the inverse correlation of tremor size with performance suggest that shooting performance might quite possibly be improved by manoeuvres designed to reduce tremor and worsened by factors which increase tremor size. An important point about studies involving skilled performance is that they need to be carefully designed and interpreted. All elite performers are very highly practiced. Any attempt to impose something novel is likely to disrupt performance initially and be counterproductive. It is important in these studies to focus on comparative improvements in groups who have not previously been highly trained in a particular regimen.

Kruse *et al.* (1986) investigated the effect of $\beta$-blockade on shooting performance. In a double-blind crossover study of 33 marksmen (standard pistol, 25 m) the $\beta_1$-adrenergic blocker, metoprolol, was compared with placebo. Metoprolol significantly improved shooting performance by 13.4%. The most skilled athletes demonstrated the clearest improvement. There were no correlations between the shooting improvement and changes in the cardiovascular variables (i.e. changes of heart rate and systolic blood pressure) and no correlation to the estimated maximal $O_2$ uptake. They attributed the improvement to an effect of metoprolol on hand tremor. They measured the score rather than the consistency of performance.

$\beta_2$-Blockers have a more potent tremolytic activity, but they do not appear to have been evaluated in shooting. There are, however, several studies showing that they can have a beneficial effect for musicians playing in public (James *et al.* 1977) or on microsurgeons performing fine dissection (Humayun *et al.* 1997).

Lakie *et al.* (1995) used forearm cooling and heating to change tremor size in a group of six relatively unskilled air pistol shooters. The dispersion of the shots was measured when the subjects shot in normal, heated and cooled conditions, which were presented in random order. A very clear result was obtained (Fig. 6). Cooling improved the grouping of the shots and heating made it worse. This measure of performance correlated highly ($r = 0.776$) with tremor size. Furthermore, there was a small effect on the score gained by these relatively unskilled subjects. Out of a maximum of 200, cooled subjects scored 133, control

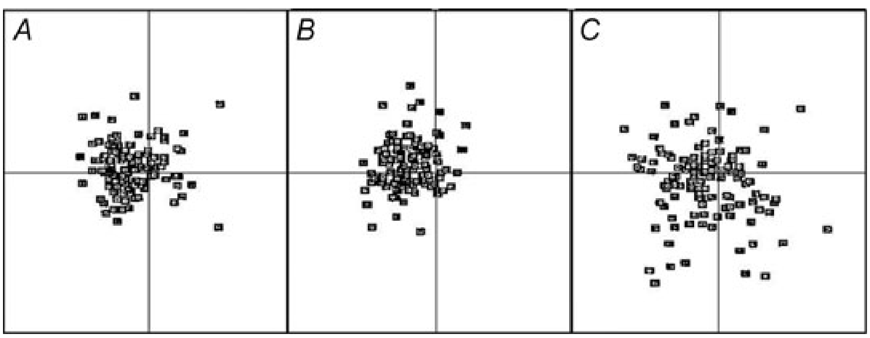


**Figure 6. A comparison of shooting after heating and cooling**
Six subjects each fired 20 shots at a target (10 m distant) using an air pistol in each of three conditions. These were a control condition (*A*), following cooling of the arm in water at 10°C (*B*) and following warming in water at 44°C (*C*). All results are shown in this figure. Each box is 20 cm square. There is greater dispersion of the 120 shots in heated conditions and smaller but significant dispersion in cooled conditions. Adapted from Lakie *et al.* (1995).

subjects scored 126 and heated subjects scored only 101. The improvement was attributed to alterations in the fusion frequency of the forearm muscles; consequently, positional control is smoother in cold rather than warm conditions. It has been shown that with moderate cooling the useful suppression in tremor size lasts for at least 30 min (Lakie *et al.* 1994*b*). In an unpublished study (F. Villagra, L.A. Arblaster & M. Lakie) of cooling applied to shooting, it was found that tremor size was suppressed temporarily in fifteen expert marksmen, but by the end of the contest (on average 90 min) the size had returned to its previous values. Evidently, a means of preventing muscle rewarming would be required for long periods of tremor reduction. Geurts *et al.* (2004) have examined cooling carefully in the human first dorsal interosseous muscle. They concluded that cooling did decrease the tetanic fusion frequency but it did not lead to a smoother voluntary force output. However, their measure of smoothness was the standard deviation of the force, and this is always dominated by low-frequency components, which are not related to higher frequency tremors. Also, as these authors say, their cooling procedure adversely affected cutaneous sensation, which will have impaired the generation of a constant force.

Reading *et al.* (1994) and Tikuisis *et al.* (2002) have also investigated the effect of temperature on shooting performance. These studies did not find the same clear temperature-related effects as the study of Lakie *et al.* (1995). In these studies, however, it was the environmental temperature which was altered. This is a different situation, since any upward or downward shift in environmental temperature is likely to have deleterious effects on sensory performance (as suggested by Geurts *et al.* 2004) and on central processes. With cooling, there is also the possibility of shivering or other involuntary movements. In the study of Lakie *et al.* (1995), temperature change was confined to the forearm itself, and cooling or heating of the hand and trigger finger or the body was minimized.

Another potent tremolytic is the drug ethyl alcohol. Studies have shown that this drug considerably reduces the size of physiological (Landauer, 1981; Lakie *et al.* 1994*a*) and essential tremor (Growdon *et al.* 1975). This suggests that it may have a role in the reduction of tremor in skilled performance. Certainly, the anecdotal association between moderate alcohol ingestion in activities such as golf, musical performance, darts and snooker is well known. Despite this, there appear to be no studies investigating the correlation between alcohol and shooting. This is not surprising, since the combination of a lethal weapon and alcohol is no doubt unwise. None the less, it is likely that moderate doses of alcohol (most studies suggest about 400 mg (kg body mass)$^{-1}$) would have a worthwhile effect of increasing hand steadiness and thus consistency if not necessarily accuracy or judgment.

## Factors that may adversely affect tremor size and shooting performance

There is a widespread belief that caffeine may worsen tremor, and many people (including marksmen) may refrain from drinking coffee before an event. However, evidence for the tremorogenic effect of caffeine is sketchy at best. Most studies show that even large doses of caffeine fail to have a significant effect on increasing tremor size (Koller *et al.* 1987) or awareness of tremor size (Lakie & Combes, 1999). The only exception is a study which investigated the effect of caffeine ingestion in fasted subjects (Wharrad *et al.* 1985). The lack of a measurable tremorogenic effect is probably explained by the fact that caffeine causes a degree of motor clumsiness akin to dyspraxia. The resulting sensation is probably reported by most subjects as an increase in tremor, whereas what actually occurs is a decrease in fine motor skill. Measurements of postural tremor will fail to capture this aspect; however, it seems likely that motor clumsiness will adversely affect shooting consistency.

## What makes the Olympic biathlon possible?

The Olympic biathlon combines severe physical exercise with shooting tasks. There are a number of different events, but they typically involve cross-country skiing for a distance of 7.5–12.5 km and two or four sessions of shooting with five shots in each. Missed targets require a penalty distance to be skied. This is a sport which imposes conflicting demands on the competitors. The physiological adjustments required to perform hard physical exercise are opposed to the adjustments required to perform a precision activity. Pharmacological agents which would improve the accuracy aspects of the sport would impact unfavourably on the physically demanding part of the task. This probably explains why, unlike in target shooting, alcohol and $\beta$-blockers are not formally banned in this sport. It is difficult to see any way in which any minor improvements in shooting consistency would compensate for the inevitable decrease in exercise performance that would result from use of these drugs.

The combination of the two different skills is not impossible, and at least some of the competitors will shoot with 100% success. There are a number of factors which make this sport possible. First, there is the shooting task itself. It is a binary task; targets, which are quite large, are either hit or missed. This, and the fact that an accurate rifle is used, combined at some stages of the event with a prone posture, makes the task simpler. The mass and inertia of the weapon will mitigate the increase in tremor size. The weapon is usually held quite lightly, reducing the transmission of high-frequency tremor. It would be a different matter if competitors were required to undertake a test of accurate marksmanship with a pistol during an extreme physical task of this kind. The competitors shoot when under extreme physical and mental strain. Their levels of adrenaline and tremor will no doubt be high and their heart rate and stroke output also. It appears (J. Carrabre, team physician, British Biathlon Society, personal communication) that the raised heart rate may be an advantage, because it serves to decrease the pulsatile input to the rifle. When the heart rate falls, the stroke volume increases, which increases the rifle deflection when shooting. Increased rifle deflection increases the chance of error. Therefore, high heart rate shooting is not a big problem in biathlon and, counterintuitively, rapid heart rate recovery following heavy exercise performance prior to shooting might be seen as disadvantageous.

It is sometimes said that fast shooting may gain seconds, whereas fast skiing will gain minutes. Moreover, missed shots generate penalties which are time consuming, so it is necessary to be reasonably sure of hitting each target. However, time must not be wasted here, and successful athletes learn to fire rapidly with confidence (as do soldiers), since much time wasted aiming will greatly reduce their chance of victory. It is possible that in this form of rapid-fire shooting the initial preprogrammed impulse is more relevant than the sensory control phase, so that tremor size plays a minor role. The question of how long is necessary to aim accurately has been addressed by Goonetileke *et al.* (2009). This group showed that approximately 2 s was an adequate time for aiming in expert shooters. Their results indicated that the differences occurring with varying levels of experience are due to postural balance and stability and not to the aiming or cognitive component of the task.

The implication of the shooting studies with altered temperature is that limb cooling may be a useful aid to precision performance. However, care has to be taken to avoid undue cooling of the skin of the hand and to avoid central cooling. This might be achieved during target shooting. It is, however, most unlikely to play any role in the biathlon, because the core temperature and limb temperature of the athletes will be high, notwithstanding the often extremely cold climatic conditions.

## Conclusion

Studies have shown that tremor size impacts on shooting consistency. The Olympic biathlon is designed to be very demanding but not impossible. The weapons that are used, the shooting posture, the size and range of the target are all compatible with what will undoubtedly be a greatly increased tremor size in the limbs of competitors. The pragmatic reason is that it is a test of the ability to bring down enemy soldiers at reasonably close quarters between bouts of heavy exercise. Were it a test of extreme marksmanship (or even a task such as threading a needle), much more difficulty would be experienced. Exposure to a cold climate in resting subjects might conceivably improve shooting consistency, but this would only occur if the skin of the hands and the core temperature could be preserved.

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