Please cite the Published Version

Dadswell, Clare Elizabeth (2016) The kinematic factors associated with elite level pistol shooting performance. Doctoral thesis (PhD), Manchester Metropolitan University.

THE KINEMATIC FACTORS ASSOCIATED WITH ELITE LEVEL PISTOL SHOOTING PERFORMANCE

C E DADSWELL

PhD 2016

THE KINEMATIC FACTORS ASSOCIATED WITH ELITE LEVEL PISTOL SHOOTING PERFORMANCE

CLARE ELIZABETH DADSWELL

A thesis submitted in partial fulfilment of the requirements of the Manchester Metropolitan University for the degree of Doctor of Philosophy

Department of Exercise and Sport Science

The Manchester Metropolitan University

2016

Acknowledgements

First, I would like to offer my sincere thanks to Dr Adrian Burden, my Director of Studies for his continued support and guidance throughout my studies. I would also like to thank my supervisors, Dr Carl Payton and Prof. Paul Holmes, for their ongoing help and advice. Their assistance throughout this research has been greatly appreciated.

I would also like to thank Mr John Leighton Dyson whose advice and contributions to the latter studies of this thesis has been invaluable. Thanks also go to Dr Zoe Franklin who contributed many, much-appreciated, hours towards pilot testing and testing weekends. I would also like to thank Mr Garry Pheasey and Mr Jonathan Howell who provided valuable technical support throughout the duration of my PhD, regardless of the task or time of day.

Finally, I would like to express my gratitude to my family and friends for their continual support throughout my research. In particular, I would like to thank my parents for their encouragement and belief, and Casey Osborough, Christine Wilson and Fabia Hully for their help and moral support, which is truly appreciated.

Abstract

This thesis considered the kinematic factors associated with elite pistol shooting performance. The first three studies examined performance in the newly introduced modern pentathlon combined event. Study 1 demonstrated that shooting performances differed significantly between the combined event and the original precision shooting format. Pistol shooters achieved significantly higher scores, and significantly smaller pistol and centre of pressure movements, than modern pentathletes in the precision event ($p<.05$). No significant differences were evident between the groups for combined event shooting ($p>.05$), highlighting that the most successful precision shooters were not guaranteed success in the combined event. Studies 2 and 3 examined how shooting performance changed within and between each shooting series. Aiming time did not change significantly within any series ($p>.05$), and so participants experienced a similar degree of pistol and centre of pressure movement for each shot, and achieved similar scores. No significant differences were evident in shooting performances between each shooting series ($p>.05$), despite the additional 1 km run phases. Thus, each running phase appeared to have little impact on shooting performance. Individual analysis used in each study highlighted the extent of individual variation in shooting performances, and demonstrated that group analysis is not sufficient to reflect the performances of individual participants.

The final two studies examined elite precision shooting performances. Study 4 provided a descriptive analysis of torso, shoulder, wrist and pistol movement during the final second before the shot. Participants produced variable movement patterns for the upper limb, reflecting the principle of abundancy, in order to control the motion of the pistol. The exact patterns varied between participants, further supporting the importance of using individual analysis to examine pistol shooting performance. Study 5 examined the effects of stance position on shooting performance. Changing stance position produced significant differences in the scores achieved by each participant ($p<.05$). The most effective mediolateral and anterior-posterior stance widths, and the mechanisms behind the changes in performance, varied between participants. Thus, it was recommended that pistol shooters should examine stance position in greater detail when attempting to enhance performance.

Research Outputs from the Thesis

Journal Articles:

Dadswell, C.E., Payton, C., Holmes, P. and Burden, A. (2013). Biomechanical analysis of the change in pistol shooting format in modern pentathlon. *Journal of Sports Sciences, 31 (12),* 1294-1301.

Dadswell, C.E., Payton, C., Holmes, P. and Burden, A. (2015). The effect of time constraints and running phases on combined event pistol shooting performance. *Journal of Sports Sciences, 16*, 1 – 7.

Recent Conference Presentations:

Dadswell, C.E., Payton, C., Holmes, P. and Burden, A. (2014). The effect of stance position on elite shooting performance. *World Modern Pentathlon Coaching Conference* (7th – 10th November 2014).

Dadswell, C.E., Payton, C., Holmes, P. and Burden, A. (2014). Movement variability of elite precision pistol shooting. *British Association of Sport and Exercise Sciences: Biomechanics Interest Group Conference* (11th April 2014).

Dadswell, C.E., Payton, C., Holmes, P. and Burden, A. (2013). The effect of changing shooting format on combined event shooting performance. *World Modern Pentathlon Coaching Conference* (8th-10th November 2013).

Dadswell, C.E., Payton, C., Holmes, P. and Burden, A. (2013). The effect of time constraints and running phases on combined event pistol shooting performance. *British Association of Sport and Exercise Sciences: Biomechanics Interest Group Conference* (4th April 2013).

Contents of the Thesis

Introduction to Pistol Shooting and Outline of the Thesis

Common Methods of Evaluating Shooting Performance

Review of the Literature - Factors Affecting Shooting Performance

General Methods for Studies 1 – 3

Research Study 1 – Biomechanical Analysis of the Change in Pistol Shooting Format in Modern Pentathlon

Research Study 2 – The Effect of Time Constraints on Combined Event Pistol Shooting Performance

Research Study 5 – The Effects of Stance Position on Elite Precision Pistol Shooting Performance

Summary of Findings, Practical Applications and Recommendations for Future Research

Reference List

Centre of Pressure Calculations

Combined Event Individual Participant Results

Angle Calculations and Individual Variability Graphs

Shot Score for Individual Participants and Case Study Graphs

List of Tables

List of Figures

Chapter One

Introduction to Pistol Shooting and Outline of the Thesis

1.1 Modern Pentathlon

Modern pentathlon is a multi-event sport in which athletes traditionally competed in five separate disciplines, incorporating 10 m air pistol shooting, fencing, a 200 m swim, horse riding, and a 3 km run. Points were awarded based on performance, with a maximum score of 1000 points available per event. Points accumulated over the first four events were translated into a time-based handicap at the beginning of the 3 km run, meaning that the first athlete to cross the finish line of the run event became the overall competition winner.

In its original format, the modern pentathlon competition began with pistol shooting and ended with the 3 km run. However, a rule change introduced in January 2009 resulted in a merging of these two events. Whilst the fencing, swimming and riding events remained the same, a new event, named the combined event, was created in which athletes complete the following tasks:

20 m Run → Shooting Series 1 → 1 km Run → Shooting Series 2 → 1 km Run →

Shooting Series 3 → 1 km Run

In this format, prior to further changes in 2013, three shooting series existed in place of the previous single round of shooting. During each series athletes were permitted a maximum of 70 s in which to hit each of five targets with a single shot pistol. If an athlete successfully achieved all five hits within the 70 s time limit, they could immediately leave the firing line and proceed to the next running stage. The rules have since been modified further, with athletes required to complete four 800 m running phases interspersed by four 50 s shooting series. Whilst the event has been adapted, the concept of shooting accurately following bouts of exercise remains the same. The combined event now forms the final event of the modern pentathlon competition, and begins with the same style of handicapped start which was previously used for the 3 km run. Thus, the athlete who is the first to complete the final running phase of the combined event becomes the overall competition winner.

1.2 Pistol Shooting

Pistol shooting, as it takes place in modern pentathlon, has changed dramatically following the introduction of the combined event. In its original format, pistol shooting was a precision event with a focus on achieving high scores in a relatively time-unlimited environment. Athletes were required to complete 20 shots, with a maximum of 40 s per shot, at a distance of 10 m from the target. Performance was judged on accuracy, with points awarded based on the distance between the shot and the centre of the target. A hit directly in the centre of the target resulted in a maximum score of 10 points, whilst a hit further from the centre of the target achieved a lower score. Shooting in its original format is termed precision shooting. Throughout this thesis both the precision and accuracy of shooting are discussed. Accuracy is used to represent the shot location on target; a shot which is closer to the centre of the target is more accurate than one which is further from the target centre. Precision refers to the distance between the location of a number of shots on the target. If all shots are located in a similar position on the target, the performance is considered precise. In shooting, this is often referred to as the shot group; a smaller shot group represents a more precise performance.

The introduction of the combined event changed pistol shooting from an accuracy to a speed-based event. Consequently, athletes have been faced with the challenge of adapting from an event were attention is focused on hitting the centre of the target, with few external influences, to an event where attention is focused on hitting the target as quickly as possible. This rule change has introduced additional external influences, such as the effect of exercise on performance and the awareness of other competitors' performances.

Modern pentathletes must now attempt to shoot quickly in order to hit all five targets in the shortest time possible. The ability to shoot quickly is crucial, as an athlete can immediately progress to the next running phase as soon as all five hits are achieved. An unlimited number of shots are permitted within each 70 s shooting series, and a hit is considered successful regardless of the pellet's position on the target. The distance between the athlete and the target remains at 10 m, the same as the original precision format, but the target dimensions have changed. Athletes now shoot at a target of 5.95 cm diameter, in comparison to the precision shooting target, for which the diameter of the 10 ring is just 1.15 cm (Figure 1.1). The combined event target is the equivalent size of the seven ring on a precision target.

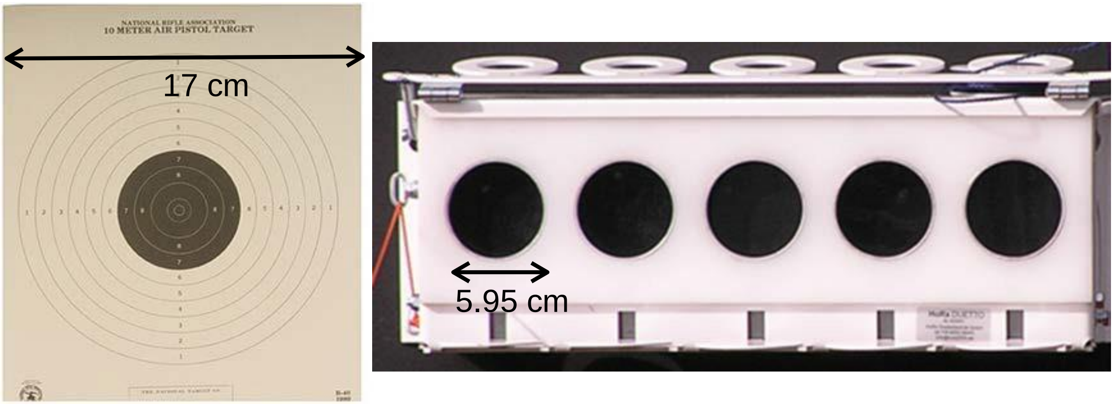


Figure 1.1. A comparison of the change in target, from the original precision format (left) to the combined event target (right).

As the combined event is a relatively new shooting format there is limited existing research on the topic. Investigations into performance in this event are clearly warranted, with the research of Le Meur, Hausswirth, Abbiss, Baup, and Dorel (2010) reporting that combined event performance is more influential on an athlete's final position in the overall modern pentathlon competition than either the swimming or fencing events. Thus, maximising combined event performance will not only improve an athlete's chance of success in the combined event, but also in the entire modern pentathlon competition. Consequently, an understanding of the mechanisms behind a successful combined event performance is critical. The research of Le Meur et al. (2012, 2010) has already gone some way to achieving this. In 2010 they compared the performance of 36 elite modern pentathletes competing in a World Cup competition, investigating the importance of percentage shooting accuracy, time per shot, and running velocity in relation to overall combined event time. By assigning athletes to one of three groups based on their event time, it was possible to identify which factors determined a successful combined event performance. Neither average running velocity nor the time per shot differed significantly between the three groups (*p*>.05). Instead, athletes who completed the combined event in the shortest time required significantly fewer shots to complete a shooting series than the athletes in the two less successful groups (*p*<.05). Thus, it appears that shooting accuracy, rather than the speed at which an athlete can run or shoot, is most crucial in the combined event.

The importance of each shooting series in the combined event was further emphasised by Le Meur et al. (2012), who investigated the effect of pacing strategies within each running phase. Nine elite modern pentathletes completed combined event trials in which the pace of the first two 1 km run phases were manipulated. Three pacing strategies were examined including one fast start strategy, where participants completed the first 170 m at 10% faster than their mean event speed, and two constant strategies. The first constant strategy was completed at 100% of a participants' mean competition speed, and the second at 105%. Pacing had no significant effect on overall combined event time (*p*>.05) and by increasing the pace of the first two 1 km phases, participants took significantly longer to complete the third shooting series (*p*<.05). Thus, any benefits of quicker running phases were negated by an increase in shooting time. These findings are valuable, as they highlight that shooting performance, albeit modified, remains essential to success in modern pentathlon.

The research of Le Meur et al. (2012, 2010) has undoubtedly produced interesting findings regarding the temporal characteristics of performance. It is now important to advance this research area by including the effects of the combined event on kinematic variables associated with shooting. This will make it possible to examine the processes behind a successful combined event shooting performance. A strength of the research of Le Meur et al. (2010) is that it has produced findings which directly represent the performance of elite athletes under competition conditions. Whilst important, this field-based approach cannot produce the more in depth analyses that can be undertaken in a laboratory setting. Laboratory-based analysis can provide detailed information about shooting performance, such as the exact location of the shot on the target, and the area of the target at which the pistol is aimed prior to the shot. The understanding of these processes has previously been achieved for both precision pistol (Ball, Best, & Wrigley, 2003; Mason, Cowan, & Gonczol, 1990) and rifle shooting (Heimer, Medved, & Spirelja, 1985; Tang, Zhang, Huang, Young, & Hwang, 2008) events. The majority of these studies have identified two main variables that affect performance – gun movement and body sway.

1.3 Outline of the thesis

This thesis comprises a further 12 chapters which detail the common methods of evaluating shooting performance, and also provides a review of the literature and includes five research studies which examine different aspects of pistol shooting performance. More information about each chapter is detailed below.

1.3.1 Chapter 2: Common Methods of Evaluating Shooting Performance

A number of methods have been used as evaluators of shooting performance, including shot score and the measurement of pistol and centre of pressure movement. These methods will be described in detail in this chapter prior to discussing their use, and associated findings, in the literature review.

1.3.2 Chapter 3: Literature Review

This chapter provides a detailed, inter-disciplinary, review of current shooting literature. Consideration has been given to research that has examined the biomechanical factors associated with rifle and pistol shooting performance. Physiological factors, for example the effects of exercise on shooting performance, are considered in relation to the rifle shooting sport of biathlon. Finally, research considering psychological factors, which are also likely to influence shooting success, is evaluated.

1.3.3 Chapter 4: General Methods for Studies 1 - 3

The data used for each of the first three studies were collected from the same testing sessions, comprising one precision and one combined event trial per participant. Detailed descriptions of the methods used in each testing session are included in this chapter, and used for reference within the first three research studies.

1.3.4 Chapter 5: Research Study 1

The first three research studies consider shooting performance in relation to the modern pentathlon combined event. The first study was completed following the introduction of the combined event. This examines whether ability level in precision shooting influences shooting performance in the combined event, and identifies the key kinematic variables associated with combined event shooting performance.

1.3.5 Chapter 6: Research Study 2

The second study examines shooting performance within each of the three shooting series. This study uses intra-series comparisons to identify any effects of the time constraints arising from the 70 s time limit by comparing shot score, heart rate and kinematic variables within each shooting series.

1.3.6 Chapter 7: Research Study 3

The third study investigates the effects of each 1 km running phase on shooting performance. Inter-series comparisons compare shot score, physiological and kinematic variables between each shooting series. Comparisons are made between the variables that are significantly associated with shot score in each series to identify any changes in performance.

1.3.7 Chapter 8: Change in Research Focus

The focus of the final two studies changed from combined event to precision shooting. This chapter explains the reasons behind this change and details the links between the first three combined event-based research studies and the final two precision-based studies.

1.3.8 Chapter 9: Review of the Literature

This chapter provides a second literature review detailing the research most relevant to the final two research studies. Existing findings concerning movement variability and coordination are discussed, in addition to the effects of stance position on stability.

1.3.9 Chapter 10: Pilot Testing – Motion Analysis Systems

This chapter describes the pilot testing sessions used to ensure that the motion analysis system had sufficient accuracy and repeatabilit0y to analyse shooting performances. Each testing session, and its corresponding results and conclusions, are described.

1.3.10 Chapter 11: Research Study 4

The final two studies consider elite precision pistol shooting performance. The fourth study produces a descriptive evaluation of elite shooting performance, examining the movement patterns produced when shooting and the variability of body sway and upper limb and pistol movement.

1.3.11 Chapter 12: Research Study 5

The final study investigates the effects of stance position on shooting performance. Shot scores, movement patterns and movement variability are compared between nine different stance positions to examine the effect of stance on shooting success, and to identify the mechanisms behind any changes in scores achieved in each stance position.

1.3.12 Chapter 13: Discussion and Practical Applications

The final chapter provides a summary of the key findings from each of the five studies, and describes the practical applications that arise from each of these conclusions. The applications of these findings to the wider population, beyond the scope of elite level pistol shooting, are also discussed.

Chapter Two

Common Methods of Evaluating Shooting Performance

2.1 Assessing Shooting Performance: Shot Score

The most common method of quantifying performance in shooting events is the use of shot score, which assigns a value to each shot based on the distance of the pellet from the centre of the target (Hoffman, Gilson, Westenburg, & Spencer, 1992; Pellegrini & Schena, 2005; Tang et al., 2008). Higher scores, to a maximum of 10.9 in precision pistol shooting, represent a hit closer to the centre of the target. This method has been used for a variety of performance comparisons, including comparing higher and lower ability shooters, and evaluating the effect of interventions on shooting performance. Examples include Tang et al., (2008) who used shot score to quantify a participants' shooting ability, and thus assign each participant to either an elite or pre-elite testing group, and Hoffman et al. (1992), who used score comparisons to investigate how the performance of a single group of shooters varied following different exercise conditions. Shot score is the customary method of measuring precision shooting performance, but could also prove useful for rapid fire events such as the combined event. Whilst the combined event is not concerned with shot score, an athlete who can consistently shoot close to the centre of the target will have an increased margin for error than one who frequently hits the edge of the target.

2.2 Assessing Shooting Performance: Gun Movement

Another method used to quantify shooting performance, and commonly used by researchers, is the measurement of gun movement (Ball et al., 2003; Hoffman et al., 1992; Mason et al., 1990). This is usually achieved with an opto-electronic shooting system, comprising a frame placed around the target which emits an infra-red signal, and a sensor which is attached to the barrel of the gun. The position of the sensor on the gun in relation to the signals emitted from the target can be recorded before, during, and after trigger pull. This measurement provides information regarding the position of the aim-point of the gun on the target, and how it moves throughout the aiming period. During each shot, the optoelectronic shooting system can provide specific information relating to performance, including:

- Shot Score – the distance between the location of the shot and the centre of the target. Each shot is scored out of a maximum 10.9, representing a hit directly on the target centre.
- Trace Length (mm) – the total distance moved by the aim-point of the gun on the target. Measured during the entire time the pistol is aimed at the target, and can be broken down into time periods, such as 1 s before the shot, and into horizontal and vertical components. Smaller trace lengths have been associated with higher shot scores and increased performance levels (Mason et al., 1990; Zatsiorsky & Aktov, 1990).
- Triggering (mm) – the movement of the aim-point of the gun on the target after trigger release. This represents the recoil of the gun following the shot.
- Aiming Time (s) – the time period from when the aim-point of the gun first aligns with the target to the instance of trigger pull.
- 10 Ratio (%) – The percentage of time spent in the 10 ring of the target whilst aiming.

2.3 Assessing Shooting Performance: Centre of Pressure Movement

Movement of the centre of pressure is another common measure in shooting research, and is often used to represent the amount of body sway produced during the aiming period (Ball et al., 2003; Heimer et al., 1985; Mason et al., 1990). Body sway is considered important due to the extremely small movements that are associated with shooting performances. Any movement from the body can potentially be transmitted to the pistol, and ultimately alter the location of the pellet on the target (Pellegrini & Schena, 2005). Thus, body sway has the potential to affect the scores achieved for precision shooting, or the difference between a hit or a miss in the combined event.

Maintaining an upright, stable posture during simple standing is a demanding task due to the narrow base of support between the feet, and the relatively greater height of the body's centre of mass (Era, Konttinen, Mehto, Saarela, & Lyytinen, 1996). Whilst body sway is an inherent part of all movement, including quiet stance tasks, pistol shooters exhibit a significantly smaller degree of movement than non-shooters ($p<.05$) (Aalto, Pyykkö, Ilmarinen, Kähkönen, & Starck, 1990). Thus, a common consideration for shooting research has been whether the magnitude of body sway also differs between shooters of different ability levels.

A number of methods have been used to record the magnitude and direction of movement of the body in shooting. The majority of investigations have used centre of pressure movements, recorded by a force platform, as an indicator of body sway (Ball et al., 2003; Era et al., 1996; Le Clair & Riach, 1996). Body sway is a general term used to describe movement of the centre of mass; "a theoretical point about which the body's mass can be considered to be equally distributed" (Chapman, 2008, p.23). Although centre of pressure is commonly used to represent the motion of the centre of mass, the two variables are independent. Centre of pressure is calculated as the average location of the vertical forces acting downwards onto the force plate (Winter, 2005). If an individual were to stand with their weight equally distributed under each foot, the centre of pressure location would be located exactly halfway between the two feet.

Movement of the centre of pressure takes place in response to a movement of the centre of mass, and is used to restore the balance of the body (Palmieri-Smith, Ingersoll, Stone, & Krause, 2002). Consequently, whilst centre of pressure movements are not a direct representation of body sway, they are generally considered a reliable indicator of body sway motion. For instance, when the centre of mass moves anterior to the centre of pressure, the plantarflexor muscles are activated to move the centre of pressure forward (Figure 2.1, images 1 and 2). Once the centre of pressure moves anterior to the centre of mass, the body experiences posterior sway, and the dorsiflexor muscles are activated to move the centre of pressure backwards (Figure 2.1, images 4 and 5). Consequently, the centre of pressure and centre of mass are constantly moving, even during quiet stance. Greater centre of pressure movements can therefore be used to reflect greater centre of mass movements and have been used to represent greater levels of body sway (Ball et al., 2003; Era et al., 1996; Nardone, Godi, Grasso, Guglielmetti, & Schieppati, 2009).

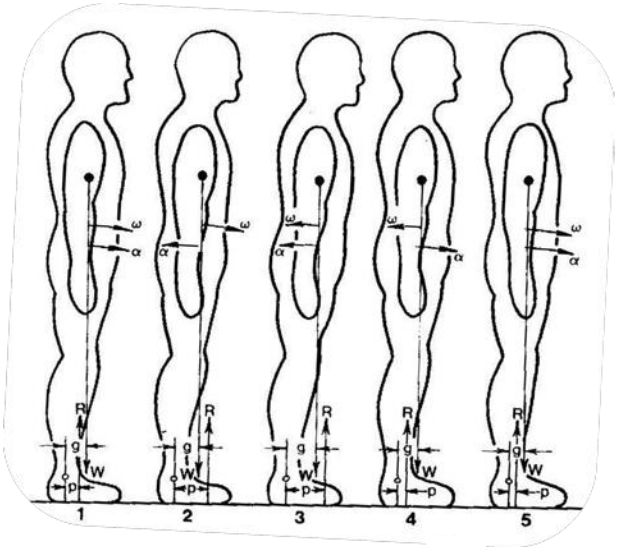


Figure 2.1. The relationship between movements of the centre of mass and centre of pressure during quiet stance (Winter, 2005, p.107). The distance between the ankle joint centre and the centre of mass (g) and centre of pressure (p) are also shown, in addition to the angular acceleration (*α*) and angular velocity (ω) produced for each of the 5 centre of gravity and centre of pressure locations. Weight acting from the centre of mass is represented by "W", while the reaction force is marked as "R" and shown originating from the centre of pressure.

The mechanisms behind postural control are determined by the central nervous system, although the exact mechanisms behind the maintenance of stability are debated in current literature. Components of the musculoskeletal system, such as muscle spindles and golgi tendon organs, provide feedback to the central nervous system regarding changes in muscle and tendon length and position (Kistemaker et al., 2013). The information from the proprioceptors is used by the central nervous system to control muscle activation in an attempt to slow, or reverse, the direction of body sway. Research suggests this is an anticipatory response, with peaks in muscle activity recorded before any changes in muscle length are actually required to prevent a loss of stability (Loram et al., 2005). Whilst this response is adequate to maintain a relatively stable position of the body during quiet stance, Mello, Oliveira and Nadal (2007) reported that under certain conditions, such as when the muscles are fatigued following exercise, these responses could be delayed, resulting in increased movements of the centre of mass.

Numerous research studies have investigated centre of pressure movement in sport, exercise, and clinical settings. A number of different parameters can be derived from the centre of pressure data recorded using a force plate, and investigators have selected the most appropriate variables depending on their aims. Commonly used measures of centre of pressure movement are presented in Table 2.1.

Table 2.1 Variables commonly used in the analysis of centre of pressure movement and examples of their use in previous shooting and quiet stance research.

	Definition	Authors	Main Findings
Range	Difference between the minimum and maximum centre of pressure coordinates. Split into anterior-posterior and mediolateral components	*Shooting Research:*	
		Heimer et al. (1985)	Greater for lower scoring shots
		Ball et al. (2003)	Greater for lower scoring shots
		Quiet Stance Research:	
		Raymakers, Samson, & Verhaar (2005)	Mediolateral range greater for elderly than young participants
Path Length	Total distance moved by the centre of pressure. Split into anterior-posterior and mediolateral components	*Shooting Research:*	
		Era et al. (1996)	Greater for novice shooters than elite
		Ball et al. (2003)	Greater for lower scoring shots
		Niinimaa & McAvoy (1983)	Increased immediately post-exercise
		Quiet Stance Research:	
		Bove et al. (2007)	Increased for 6 minutes post-exercise
		Noda & Demura (2007)	Increased following fatiguing exercise
Speed	Centre of pressure path length divided by the time period over which it was recorded	*Shooting Research:*	
		Era et al. (1996)	Higher for national shooters than elite.
		Hawkins & Sefton (2011)	Not significantly affected by stance angle.
		Hawkins (2013)	Higher for greater stance widths
Velocity	Total displacement of the centre of pressure trace divided by the time period over which it was recorded. Split into anterior-posterior and mediolateral components	*Shooting Research:*	
		Su, Wu, & Lee (2000)	Higher for novice than experienced shooters.
		Quiet Stance Research:	
		Raymakers et al. (2005)	Higher for elderly than young participants
		Derave et al. (2002)	Increased for 2 minutes post-exercise.
		Noda & Demura (2007)	Increased following fatiguing exercise
Area	Area of a square enclosing all data points of the centre of pressure trace	*Quiet Stance Research:*	
		Noda & Demura (2007)	Increased immediately after exercise
Root Mean Square	Square root of the mean squared values of centre of pressure path length	*Quiet Stance Research:*	
		Noda & Demura (2007)	Increased immediately after exercise
Standard Deviation	Standard deviation of all centre of pressure values in relation to the mean location of the centre of pressure. Split into anterior-posterior and mediolateral components	*Shooting Research:*	
		Su et al. (2000)	Greater for novice than experienced shooters
		Quiet Stance Research:	
		Noda & Demura (2007)	Increased immediately after exercise

With multiple parameters available to quantify the level of centre of pressure movement, much research has considered which are the most useful and accurate methods to represent body sway (Demura, Kitabayashi, & Noda, 2006; Le Clair & Riach, 1996; Palmieri-Smith et al., 2002). The consensus is that each variable included in Table 2.1 is a valid measure to represent body sway, with Palmieri-Smith et al. recommending that a combination of variables are used to provide a more in-depth evaluation of postural control. For instance, range of movement examines the amplitude of movement, but relies on two discrete data points to represent movement throughout a trial. Other variables, such as path length, analyse centre of pressure movement throughout a trial, but do not provide specific information about movement amplitude. Le Clair and Riach reported that the optimum time periods used for analysis were 20 s and 30 s. These time periods, have limited relevance in pistol shooting research, particularly for the combined event where time restrictions mean that the aiming period is never more than a few seconds.

Demura et al. (2006) Le Clair & Riach (1996) and Palmieri-Smith et al. (2002) each reported a number of variables that can distinguish between more and less stable participants from the general population. Given that elite shooters produce significantly smaller levels of movement during quiet stance than non-shooters (Aalto et al., 1990; Era et al., 1996; Herpin et al., 2010), there is no guarantee that they can distinguish between different ability shooters. Thus, prior to beginning research into combined event performance it is important to identify which variables have previously been used for shooting analysis, and establish which are sufficiently sensitive to determine between different shooters.

Chapter Three

Review of the Literature - Factors Affecting Shooting Performance

A key focus of previous shooting research has been the identification of the factors that are most important to a successful shooting performance. Two methods have been used to identify these variables, comparing the performances of different participant groups separated by shooting ability, or by comparing the best and worst shots for individual participants. By analysing a combination of shot score, gun movement and centre of pressure movement, it has been possible to determine some of the variables that are key to success in both rifle and pistol shooting events.

3.1 Rifle Shooting Research

The effects of rifle movement on shooting success was examined by Zatsiorsky and Aktov (1990), who recorded the performances of participants in four ability-based groups 1 s and 3 s prior to the shot. The higher ability shooters produced smaller movements of the rifle than the lower ability shooters, particularly in the final second before the shot. Both horizontal and vertical trace lengths were smaller for the higher ability participants. Thus, reducing the magnitude of rifle movement was identified as an important method of enhancing performance.

Further comparisons between different ability shooters were made by Heimer et al. (1985) and Era et al. (1996). Both studies investigated the associations between centre of pressure movement and shot score within a range of rifle shooting abilities. Heimer et al. reported minimal mediolateral movements of the centre of pressure, but anterior-posterior movement varied greatly between participants and in some cases between trials for the same participant, although the extent of these variations were not reported. Negative associations were reported between centre of pressure movement and shot score, indicating that the shots with a greater range of centre of pressure movement resulted in lower scores. Era et al. used different centre of pressure variables to Heimer et al., but came to a similar conclusion, as national and novice shooters produced a significantly faster speed of movement (*p*<.001) and greater path length (p<.001) than elite shooters during the final 1.5 s before the shot. Elite shooters were also able to significantly reduce speed and path length as the instance of the shot approached (*p*<.05). Furthermore, whilst there was a significant difference in centre of pressure movement between the best and worst shots for the national and novice shooters (p<.05), no significant differences were apparent for the elite shooters (*p*>.05).

The research of Heimer et al. (1985) and Era et al. (1996) provides an indication of the effects of centre of pressure movement on shooting performance. However, fundamental differences exist between rifle and pistol shooting, such as stance position and the hold of the gun. Participants in both studies were aiming from a distance of 10 m, as is used in pistol shooting, but targets were of a different size to those used for either the precision or combined event formats. Consequently, whilst the methods and results of rifle shooting research can inform research into pistol shooting events, the conclusions are primarily related to rifle shooters and not necessarily transferrable to other shooting formats.

3.2 Pistol Shooting Research

3.2.1 Pistol and Centre of Pressure Movement

Pistol shooting research has followed a similar path to rifle shooting research, analysing movements of both the pistol and the centre of pressure. An extension to the rifle shooting research is the simultaneous recording of pistol and centre of pressure movements to determine how each variable affects shooting performance (Ball et al., 2003; Mason et al., 1990).

In their analyses of 10 m air pistol shooting, Mason et al. (1990) analysed the performances of 16 elite and junior shooters, each completing 25 shots, whilst Ball et al. (2003) analysed five elite pistol shooters over the course of 20 shots. Mean pistol movement over the final second before the shot was greater for those who took part in Mason's research (108.9 mm horizontal and 89.2 mm vertical) than those used by Ball et al. (76.1 mm horizontal and 70.7 mm vertical). Centre of pressure range over the final second was also greater for Mason's participants (3.1 mm and 3.3 mm in the anterior-posterior and mediolateral directions respectively), than for those who took part in Ball's research (1.9 mm and 1.0 mm). These differences in performance may be a consequence of the ability of the two groups of participants, as higher ability shooters have been associated with greater levels of stability (Era et al., 1996; Zatsiorsky & Aktov, 1990). Thus, the group used by Ball et al., which was composed of entirely elite shooters, would be expected to produce a smaller degree of pistol and centre of pressure movement than the combination of elite and junior shooters used by Mason et al.

In addition to the magnitude of movement produced by pistol shooters, Mason et al. (1990) examined which variables were the most influential to shot score. Regression analysis used for each pistol and centre of pressure variable revealed that horizontal pistol movements had the greatest effect on horizontal accuracy, accounting for 37% of the variability in horizontal shot placement. Vertical accuracy was more sensitive to changes in body sway than pistol movements, as mediolateral centre of pressure movement accounted for 40% of the variability in vertical shot placement, compared to just 13% for vertical pistol movements. Thus, whilst both pistol movement and body sway influence pistol shooting accuracy, each variable appears to have a greater impact on accuracy in one specific direction.

By incorporating regression into their analysis of shooting performance, Mason et al. (1990) highlighted the importance of examining the directional components of each movement, rather than simply using the resultant value. This is particularly important given that mediolateral centre of pressure movements were strongly associated with vertical shot placement, whilst anterior-posterior movements were largely unrelated to shooting performance, accounting for only 8% of changes in horizontal pistol movement. Thus, a more detailed knowledge of shooting performance can be developed by considering the directional components of pistol and centre of pressure movement separately.

A final, and important, issue considered by Ball et al. (2003) was the use of intra-individual analysis to examine shooting performance. Ball et al. reported that the factors affecting shooting accuracy varied greatly between individuals, and so both group and intra-individual analysis methods were used to identify whether group analysis was appropriate for investigations into pistol shooting performance. Correlations, using group data, identified that shot score had a strong, significant, correlation with time spent in the 10 ring of the target (r = 0.95, p<.05), but no significant correlations with either centre of pressure movement or movement of the aim point of the pistol (p>.05). In contrast, intra-individual analysis revealed that three of the five participants experienced significant associations between movements of the aim point of the pistol and shot score. Shots with a greater degree of pistol movement resulted in lower scores. Despite pistol movements accounting for up to 53% of the variation in shot score for three participants, the other two participants demonstrated no significant associations between the same two variables. Centre of pressure movements were only significantly associated with score for one participant, for whom positive correlations indicated that sway movements accounted for 46% of the variation in score. As such, group analysis masked an important aspect of performance for these participants. Furthermore, four participants were identified with significant correlations between body sway and pistol movements, despite the non-significant findings of group analysis. Thus, it seems that group analysis is not sufficient to represent pistol shooting performance, where even small variations between individuals can greatly affect success.

The findings of both Mason et al. (1990) and Ball et al. (2003) clearly demonstrate that pistol and centre of pressure movement can significantly affect the scores achieved when pistol shooting. However, neither the results of Mason’s regression analysis, nor the correlations used by Ball et al. accounted for 100% of the variation in score. Thus, there must be other factors in addition to those considered by these studies which further influence shooting success. With the exception of Pellegrini and Schena (2005), who analysed movements of the upper limb, there is limited existing research considering the additional movements of the body that take place when shooting. Future research must consider other aspects of shooting performance in more detail. This more in-depth analysis, including Pellegrini and Schena's analysis of upper limb movement, will be examined in more detail in a further literature review, and in the final two research studies (Chapters 9 - 12).

The consensus of the majority of pistol and rifle shooting research is that centre of pressure movement has a significant effect on shot score (Mason et al., 1990; Heimer et al., 1985; Era et al., 1996). In contrast, Ball et al. (2003) reported that, at a group level, no significant effects of centre of pressure movement were apparent. Ball et al.'s findings may be somewhat limited by the low number of participants and their similar levels of ability, as all participants scored between 9.2 and 10.0 points for every shot. By incorporating shooters of lower ability into the analysis, greater evidence of associations between body sway and score may have emerged. The difference in findings between those of Ball et al. and the rifle shooting research of Era et al. and Heimer et al. highlight the importance of treating each shooting event separately when considering the variables which most affect performance.

Mason et al. (1990) and Ball et al. (2003) produced interesting findings regarding the influence of pistol movements and body sway on accuracy in precision shooting events. These findings are now less relevant to modern pentathletes competing in the combined event. Whilst shooting stance and posture remain similar to precision shooting, the format of the two events are fundamentally different. Precision shooting places an emphasis on achieving high scores with a relatively long period of time in which to shoot, whilst the combined event requires athletes to shoot quickly and with little incentive to hit the centre of the target. Consequently, research must now focus specifically on the combined event to ascertain whether those factors identified as key to success in precision shooting are also influential to combined event performance. This will not only highlight which variables determine a successful combined event shooting performance, but will also establish how the pistol shooting event has been altered by the rule change in modern pentathlon.

3.2.2 Aiming Time

An additional aspect of shooting performance is the length of time that an athlete spends aiming prior to the shot (Chapter 2, section 2.2). Aiming time reflects the time that an athlete spends sighting the position of the pistol in relation to the target and, whilst less widely reported than other variables such as pistol movement and body sway, it has the potential to influence shooting success. This may become increasingly important with the introduction of the combined event, where shooting performance is now more focused on speed than accuracy.

The relationship between the speed and accuracy of a movement has long been a topic of interest for research into human movement, primarily focusing on pointing movements, rather than shooting performance. Fitts (1954) analysed the performance of three groups of participants, each completing one of three accuracy-based tasks for which either target size or the distance between two targets was manipulated. As target width was increased, thereby decreasing the accuracy demands of the task, participants' speed of movement also increased. More recently, Fernandez and Bootsma (2004) and Berrigan et al. (2006) reported similar findings in the effects of target size on movement accuracy for pointing tasks. Both found that movement time was significantly longer for smaller targets ($p<.01$), Schmidt et al. (1978) attempted to explain these trade-offs between speed and accuracy, suggesting that aiming movements are composed of submovements that are essential for a successful task outcome. They proposed that these submovements are a compromise between a fast, forceful movement to be near the target, and smaller, more time- consuming movements used to ensure that the movement is accurate. Thus, longer aiming times are required for smaller targets, to allow time for both the initial, fast movement and the smaller corrective movements to be produced.

Previous findings indicate that the lower accuracy requirements of the combined event should result in a reduction in aiming times. This may have important implications for combined event performance, with authors such as Beilock et al. (2004) reporting that an increase in time restrictions results in a decline in performance, albeit for a golf-based task. With no prior combined event research, however, the question remains as to whether decreased aiming time will greatly affect shooting performance. Some research has considered the specific effects of aiming time on shooting performance, but not in the combined event. Mason et al. (1990) found that aiming time had a significant positive correlation with accuracy (*p*<.05). Such findings suggest that if aiming time is sufficiently reduced, accuracy may be compromised enough so that an athlete achieves fewer hits on target, and requires more shots to complete each shooting series.

More recent research (Goonetilleke, Hoffmann, & Lau, 2009; Scholz, Schoner, & Latash, 2000) has produced conflicting findings to those of Mason et al. (1990). Scholz et al. analysed the performances of novice shooters, aiming at a target of 3.8 cm from a distance of 3.7 m, and reported no significant correlations between movement time and shot success (*p*>.05). Unlike Mason et al., who recorded the time that the pistol was aligned with the target, Scholz et al. analysed the time from the onset of movement until the instance of the shot. Goonetilleke et al. compared the shooting performances of participants of various ability levels, each shooting at a 22.5 cm target at a distance of 2 m. Each participant completed seven shots with time periods ranging between 0.5 – 3.0 s, in addition to one condition with an unlimited time period. Accuracy increased as aiming time increased up until 2 s for experienced shooters, beyond which there were no significant changes. It was concluded that experienced shooters do not need more than 2 s to view a target before shooting successfully.

A potential explanation for the contrasting findings of Mason et al. (1990) and Scholz et al. (2000) is the lower ability of the participants used by Scholz et al. As such, the correlations presented by Scholz et al. were based on whether a shot was successful or unsuccessful (a hit or miss on the target). Mason et al.'s participants were capable of consistently hitting the target, and so accuracy was examined in more detail by recording shot score. These comparisons suggest that aiming time influences the scores achieved in precision shooting, but it may be less critical in the combined event where athletes are attempting to hit a larger target. This theory is supported by the conclusions of Goonetilleke et al. (2009), whose research was based on a rapid-fire style shooting format. However, both Goonetilleke et al. and Scholz et al. used targets of a different size, and at a much closer distance than those used for either precision or combined event shooting. Thus, whilst it may be possible for a modern pentathlete to achieve a successful shooting performance with a relatively short aiming period, it is yet to be proven. Aiming time should therefore be incorporated into the analysis of combined event shooting to determine whether it is an important consideration for modern pentathletes when training and competing.

3.3 The Effects of Exercise on Shooting Performance

Much research has investigated shooting performance in the precision format, where shooters compete in a controlled and relatively time-unlimited environment. Some has also examined how shooting performance is affected by exercise (Hoffman et al., 1992; Niinimaa & McAvoy, 1983), as encountered in biathlon, where athletes must attempt to hit targets following phases of cross-country skiing. This format, involving shooting series interspersed by bouts of exercise, is the most similar to that which now exists in modern pentathlon. As such, the findings can provide some indication of the effect that each running phase may have on shooting performance in the combined event. Niinimaa and McAvoy (1983) compared the effect of exercise on body sway between novice shooters, biathletes and elite rifle shooters. Centre of pressure movement was recorded for 60 s before and immediately after 4 minutes of cycling at an intensity similar to that required for biathlon (90% of age-adjusted maximum heart rate). Path length of the centre of pressure significantly increased post-exercise for all three participant groups ($p<.05$), indicating that biathletes must shoot with a greater degree of body sway than would be encountered during the traditional, precision shooting format. The finding that centre of pressure movement increases following exercise has since been further supported by other, albeit non- shooting, studies. Noda and Demura (2007) reported a significant increase in centre of pressure movement following an ankle plantar-flexion task designed to induce lower leg muscle fatigue. Such findings suggest that the running phases in the combined event have the potential to affect centre of pressure movement, and potentially influence shooting performance.

Nardone et al. (1997) and Bove et al. (2007) completed similar analyses to those of Noda and Demura (2007), but examined the effects of more intense exercise. Nardone et al. investigated the effects of exercise mode and intensity on centre of pressure movement, reporting that the effects were dependent on both the type and intensity of exercise. Centre of pressure path length significantly increased following fatiguing treadmill exercise (p<.05), whilst no significant differences were recorded following fatiguing exercise on a cycle ergometer (p>.05). Non-fatiguing exercise did not result in any significant changes in centre of pressure movements for either the treadmill or cycle ergometer (p>.05). Bove et al. recorded the time period over which centre of pressure movement returns to a pre-exercise level, and found that movements remain significantly greater than baseline values for 6 minutes post- exercise. As such, any changes in centre of pressure movement are likely to affect modern pentathletes throughout each combined event shooting series, which last a maximum of 70 s.

The effects of exercise on other aspects of biathlon shooting performance has been considered by Hoffman et al. (1992). Shooting performances of elite biathletes were recorded following cycling trials at different intensities designed to recreate those at which an athlete might approach the firing line prior to each shooting phase (130 bpm, 150 bpm, 170 bpm and maximum heart rate). Shot score, shot group dispersion, number of shots, and rifle stability, were all significantly affected by increasing exercise intensity (p<.05). Specifically, an increase in exercise intensity resulted in a decrease in shot score and a reduced number of hits on target, whilst shot diameter and movements of the rifle increased. Thus, it was suggested that slowing down prior to the start of each shooting phase, thereby reducing exercise intensity, could improve a biathlete's rifle shooting performance.

Existing biathlon research (Hoffman et al., 1992; Niinimaa & McAvoy, 1983) provides an insight into the way a modern pentathletes' shooting performance may be affected following each additional 1 km run phase. There are, however, essential differences between rifle and pistol shooting which mean that these findings cannot be directly applied to the combined event. Major distinctions between the two modes of shooting are the difference in the hold of the gun and the stance position, both of which can affect stability. Furthermore, whilst both events include multiple shooting series interspersed by periods of high intensity exercise, the target size and distance to the target differ considerably between the two events. Thus, it is currently unclear whether exercise has a similar effect on shooting performance in the combined event.

Research to identify whether the effects of exercise on combined event shooting performance are similar to those reported for biathlon is clearly warranted. This is particularly apparent from the research of Brown, Tandy, Wulf, and Young (2013) who investigated the effects of exercise on the pistol shooting performance of police officers. Eight participants completed three series of five rapid fire shots, both before and immediately after cycling to volitional exhaustion. No significant correlations existed between heart rate and either shooting accuracy or dispersion of shots on the target (p>.05). It should be noted that participants in Brown et al.’s research shot at a human silhouette, and accuracy requirements were less than those for the combined event, with shots an average of 65 mm from the centre of the shot group.

3.4 Psychological Considerations

The development of the combined event has introduced a new format of pistol shooting, with biomechanical, physiological and psychological factors, each of which have the potential to influence performance. Whilst the main consideration of the current research are the biomechanical and physiological variables affecting performance, the way in which movement and accuracy can be influenced by psychological factors cannot be overlooked. This is particularly important when considering the design of the shooting range, which requires athletes to line up in order, based on their total points score from the previous three events. Once an athlete has completed the five hits required for a series, they immediately leave the range and begin the next 1 km run phase. This means that athletes can be easily aware of how well they are performing in relation to their nearest competitors. A potential effect of anxiety on performance can be explained by attentional control theory (Eysenck, Derakshan, Santos, & Calvo, 2007), which suggests that anxiety can result in a change from goal-focused to stimulus-focused attention, such as an increased awareness of other competitors' performances rather than a focus on the shooting task.

The effect of anxiety specifically on shooting performance was considered by Nieuwenhuys and Oudejans (2010, 2011), in their analyses of police officers' handgun shooting performance. Participants completed two shooting tasks, under low anxiety and high anxiety conditions, whilst aiming at two targets (28 x 28 cm and 12 x 35 cm) at a distance of 5 m. Both studies reported a significant decrease in the percentage of shots which hit the target with the change from low anxiety to high anxiety conditions ($p<.01$). A mental effort scale completed by participants under both conditions, revealed that participants perceived that additional effort was required in the high anxiety condition. Thus, it seems likely that the extreme degree of accuracy required for shooting tasks means that anxiety can have a considerable effect on performance.

The effect of anxiety on shooting performance was further considered by Nibbeling, Oudejans, Ubink, and Daanen (2014), who investigated the interactions between anxiety and fatigue on rifle shooting performance. Twenty two soldiers were separated into two groups, each completing a number of shooting tasks, including an accuracy task shooting at two targets (20 x 28 cm and 28 x 28 cm diameter) at a distance of 3 m. One group completed each task following a rest period, whilst the second completed the tasks following 10 minutes of high intensity running. Both groups completed two trials, one under low anxiety and one under high anxiety conditions. With an increase in anxiety, participants in the non-fatigued group achieved a significantly lower percentage of hits on target ($p<.05$), whilst there were no significant differences in the percentage of hits for those in the fatigued group ($p>.05$). This indicates that the effects of anxiety on shooting performance are reduced once exercise has taken place. This was supported by Lambourne and Tomporowski (2010) who reported that exercise leads to an improvement in cognitive task performance, and that the increased arousal during the time of metabolic recovery can enhance performance. This suggests that any negative effects of anxiety on shooting performance could be counteracted by the effects of exercise. Consequently, anxiety may have less of a negative influence in the second and third series of the combined event, where shooting is preceded by the 1 km run phases.

The findings of previous research concerning the effects of anxiety and arousal on performance in shooting and other cognitive tasks (Lambourne & Tomporowski, 2010; Nibbeling et al., 2014) are somewhat in contrast to those of the biathlon research, which suggests that shooting performance declines following exercise (Hoffman et al., 1992). These discrepancies may result from the tasks used in each investigation, with Nibbeling et al. selecting a shooting task with lower accuracy requirements than is required for biathlon shooting, and Lambourne and Tomporowski's literature review considering cognitive tasks, none of which were reported to be in a shooting based environment. Currently, the question remains as to whether exercise can significantly affect shooting performance in the combined event.

3.5 Research Aims and Hypotheses

Previous research has attempted to identify the factors most influential to performance in precision shooting (Ball et al., 2003; Mason et al., 1990), but has yet to consider pistol shooting as it exists in modern pentathlon. Given that the combined event shooting format is likely to present modern pentathletes with altered biomechanical, physiological, and psychological demands for success, research into this area is clearly required. Research should now examine any fundamental changes that have occurred as a result of the rule change, and investigate the demands of the new shooting format. The overall aims of the first three studies are to:

(i) identify whether precision shooting ability is related to shooting performance in the combined event;

(ii) identify any changes in shooting performance throughout each 70 s shooting series, as the time remaining to complete a series reduces; and
(iii) determine the effect of successive 1 km running phases on combined event shooting performance, where there will be an increasing reliance on anaerobic metabolism.

The first aim is addressed in Study 1, and will be achieved by comparing the performances of both modern pentathletes and elite precision pistol shooters. The inclusion of elite shooters provides a baseline for precision performance against which to compare the modern pentathletes. The criteria for elite pistol shooters was athletes who belonged to a national shooting team, and could achieve scores similar to those achieved by participants classified as elite shooters in previous research. Athletes were selected if they had competed in international shooting competitions within the previous year, and were taking part in regular training and competition. The scores of the selected participants compared well with the scores achieved by elite participants in other research, and so were judged as accurate indicators of elite performances (Table 5.5, page 55). Given that the combined event was only recently introduced, there are no elite performances against which to compare modern pentathletes. Modern pentathletes were therefore classified as elite if they belong to a national modern pentathlon team, or the national development squad. By comparing the performance of each group under precision and combined event conditions it is possible to identify whether precision shooting ability influenced combined event shooting success. Aim two is considered in Study 2 by comparing performances within each shooting series, and the final aim is addressed in Study 3, performance within each shooting series is compared. More specific objectives are detailed in the introduction to each study. The hypotheses that accompany each of the overall aims are:

(i) the variables associated with performance will differ between precision and combined event shooting due to the difference in shooting formats;

(ii) pistol shooters will achieve significantly higher scores and smaller pistol and body movements for both precision and combined event shooting, but both groups will experience significantly decreased scores, and increased pistol and centre of pressure movements in the combined event;

(iii) as the time remaining within a series diminished, shot score and aiming time will reduce significantly, and pistol movements and body sway would increase significantly;

(iv) the variables with significant correlations with shot score will vary between participants for all three series.

(v) shot score will decrease significantly, and pistol movements and body sway will increase significantly with each successive shooting series; and

(vi) the variables associated with performance will differ between each successive shooting series.

Chapter Four

General Methods for Studies 1-3

The first three studies each consider a different aspect of combined event shooting performance. Participants were required to complete shooting trials under both precision and combined event shooting conditions. Data for Study 1 were derived from participants' performances under both shooting conditions, whilst studies two and three focused solely on performance in the combined event. This chapter describes the participants, tasks, equipment and methods of analysis that were common to all three studies. The specific aspects of each participants’ data that have been used for analysis are described in more detail within Chapters 5 - 7.

4.1 Participants

Two groups of participants completed both shooting tasks required for Study 1; seven modern pentathletes from a national development squad (3 male, 4 female) (mean age 17.3 (± 3.1) years, mass 58.6 (±7.6) kg), and three elite pistol shooters (3 female) (mean age 19.3 years (±4.2) years, mass 48.3 (±5.6) kg). Elite pistol shooters were chosen to act as a comparison of elite precision shooting performance of a similar age group. A third group, comprising ten modern pentathletes from a different national development squad, was incorporated into the analysis for the second and third studies (3 male, 7 female) (mean age 17.4 (±2.5) years, mass 60.2 (±11.0) kg). No significant gender differences were apparent for shooting performance in the modern pentathlon group, and so data were analysed as one group for all modern pentathletes. To ensure that group analysis did not overlook any important gender-related differences, both males and females were included in the individual case studies. Written informed consent was obtained from each participant prior to testing and also from participants’ guardians for those athletes under 18 years of age. The study was approved by the Manchester Metropolitan University research ethics committee.

4.2 Tasks

Testing took place in a shooting range, conforming to International Shooting Sport Federation (ISSF) shooting regulations, within the university's biomechanics laboratory. All participants completed each shooting condition using their own pistol (4.5 mm calibre compressed air CO_2 single shot air pistol, weighing less than 1500 g). In both precision and combined event shooting conditions participants stood behind a firing line 10 m from the target (Figure 4.1). A table was positioned in front of the firing line on which participants could rest the pistol and any other equipment they were using. Both conditions were designed to simulate competition settings as closely as possible.

Under precision shooting conditions, participants completed 20 shots, attempting to achieve the highest score possible. Participants aimed at a standard air pistol target (17 cm x 17 cm) and were permitted a maximum of 40 s per shot. An opto-electronic target frame was positioned on the target to allow more accurate measurement of pistol movement and shot score. The commands "Load", "Start", and "Stop" were issued in accordance with modern pentathlon precision shooting regulations.

The combined event condition was completed following the sequence of events detailed by official pre-2013 modern pentathlon regulations, with the addition of blood lactate measurements. As such, participants completed the following tasks:

Blood lactate (1) → 20 m run phase → Shooting series 1 → 1 km run phase (1) → Shooting series 2 → Blood lactate (2) → 1 km run phase (2) → Shooting series 3 → Blood lactate (3) → 1 km run phase (3) → Finish

Each shooting series took place inside the laboratory, and each running section was completed on a sports field directly outside the laboratory, composed of two circuits of a 500 m route marked on grass (Figure 4.1). The route conformed to combined event regulations, although the shape of the course was simpler than those used in many competitions. A combined event target was placed at the end of the 10 m shooting range, with the opto-electronic target positioned in front of the centre target. Athletes were therefore required to aim at only one of the five targets (5.95 cm diameter) so that pistol movement and shot score could be recorded. Once the target was hit, it was reset by pulling a cord attached to the target box. Each shooting series lasted a maximum of 70 s and participants attempted to hit the centre target five times within that period. Once a participant either achieved five hits or reached the 70 s time limit, they immediately left the shooting station and progressed to the next running phase of the event as they would in competition.

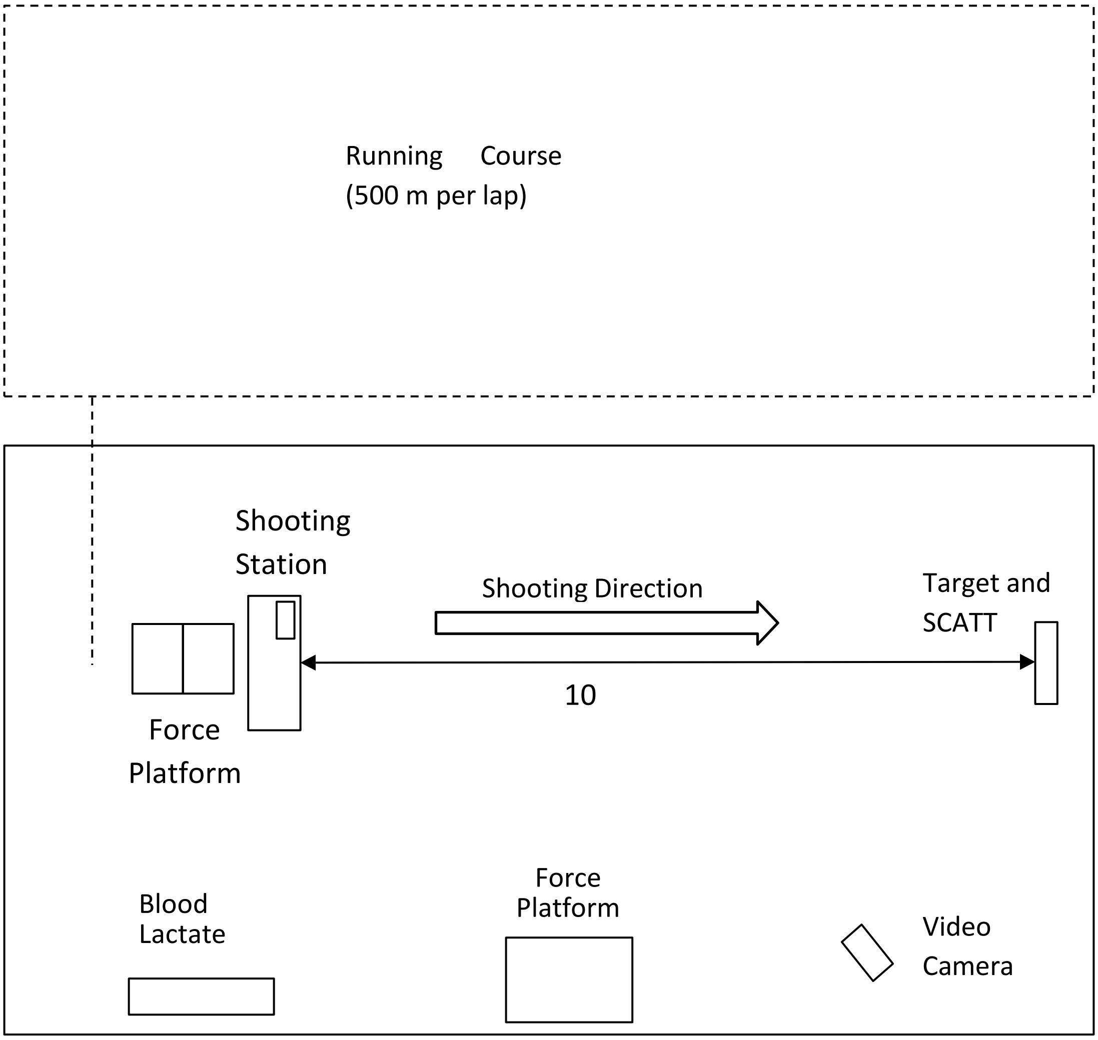


Figure 4.1. Organisation of the course and laboratory for the combined event trials.

4.3 Equipment

4.3.1 Pistol Movement and Shot Score

Movements of the aim-point of the pistol were recorded throughout the aiming period using a SCATT USB opto-electronic shooting system (SCATT, Moscow), linked to SCATT Professional software (version 5.63), operating at 120 Hz. The target was placed in a frame which emitted an infra-red signal (Figure 4.2), which was received by a sensor (7.7 cm, mass 30 g) attached to the cylinder of the pistol. The position of the receiver in relation to the signals produced from the target was recorded by SCATT Professional software, from which the horizontal and vertical position of the aim-point was calculated. Shot score was calculated based on the position of the sensor at the instance of trigger pull.

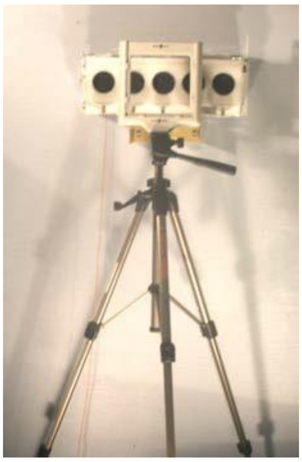


Figure 4.2. Set-up of the SCATT frame in front of the combined event target.

4.3.2 Centre of Pressure Measurements

Two AMTI OR6-7-2000 force platforms, each measuring 46.7 x 51.0 cm, (Advanced Mechanical Technology, Inc. Massachusetts) were used to record ground reaction force data throughout the aiming period of each shot. Each platform (hysteresis ± 0.2%, linearity ± 0.2%) was linked through a DataTranslation 3002 A-D convertor to an RM Expert 3010 computer, using AMTI Netforce (Version 2.1.0, Advanced Mechanical Technology, Inc.) software for data acquisition. Ground reaction force data for all shots were sampled at a frequency of 120 Hz.

For both shooting conditions, participants positioned themselves with one foot fully on each force plate. This made little or no change to their normal shooting stance. Under precision conditions, participants were requested to step off the force plates between each shot so they could be reset, and were given time to reposition themselves before the beginning of each subsequent shot. Under combined event conditions the force plates were reset between shooting series, immediately prior to participants taking up their shooting stance. Following data acquisition, vertical ground reaction force and centre of pressure co-ordinate data from each platform was exported through BioAnalysis software (Biosoft Version 2.3.0, AMTI). Centre of pressure location was calculated for each force plate throughout the aiming period using equations 1.1 and 1.2 in Appendix 1. Data for the centre of pressure equations were derived from each individual force plate, producing centre of pressure values for the forces under each foot. Finally, data were entered into Microsoft Excel to calculate a single centre of pressure position for the whole body during the 1 s prior to each shot (Appendix 1.3).

A microphone located near to the firing line was used to detect the noise from trigger pull. This was amplified to a 9 volt signal, and sent to the A-D convertor, where it was recorded as a pulse on the centre of pressure trace. The pulse was used to identify the instance of the shot, thus enabling synchronisation of the centre of pressure and pistol movement data. In addition, a video camera (Panasonic NV-GS330, shutter speed 1/125th) was used to provide data for temporal analyses.

4.3.3 Physiological Variable Measurements

Under combined event conditions, fingertip blood lactate (BLa) samples were acquired from the fifth digit of the loading hand, and analysed using a YSI 1500 SPORT Lactate Analyzer (YSI (UK) Limited). Samples were obtained on three occasions, as detailed in section 4.2. Activio Sport System (Activio AB, Stokholm), version 2.1, wireless heart rate monitors sampling at 1 Hz were used to identify the heart rate patterns throughout the event.

4.4 Data Analysis

Following data acquisition a number of discrete parameters were selected to represent shooting accuracy and movements of the pistol and the centre of pressure. These were:

Accuracy:

- Shot score. The distance between the position of the shot and the centre of the target (Figure 4.3). Each shot was scored was out of a maximum 10.9, representing a hit directly on the centre of the target.

Pistol movement:

- Trace Length. The distance (mm) moved by the aiming point of the pistol on the target, along the *x* (horizontal), and *y* (vertical) axes. Trace length is demonstrated in Figure 4.3, represented by the green, yellow, and blue lines.

Centre of pressure movement:

- Range of movement (mm) of the centre of pressure along the *x* (mediolateral – perpendicular to the plane of the target) and *y* (anterior-posterior – parallel to the plane of the target) axes. Calculated as the difference between the maximum and minimum co-ordinates of the centre of pressure.
- Path length (mm) along the *x* (mediolateral) and *y* (anterior-posterior) axis. Calculated as the total distance travelled by the whole body centre of pressure along each axis.

Trace length was selected as a variable that has previously been used to accurately discriminate between shooters of different abilities (Ball et al., 2003; Mason et al., 1990). The centre of pressure parameters selected to represent body sway motion have also been previously used to differentiate between shooters of different abilities (Ball et al., 2003; Era et al., 1996; Heimer et al., 1985; Mason et al., 1990). Range represents the amplitude of sway, indicating the extent of centre of pressure movement, and path length provides a measure of the distance travelled by the centre of pressure. The use of both variables examines two aspects of centre of pressure movement. For instance, it is possible for two participants to produce the same range of movement, but for one to produce a greater fluctuation of movement within that range. This additional information would not be apparent if only range were selected to evaluate centre of pressure movement. By measuring both variables a more detailed analysis of the movement patterns of each participant is possible (Ball et al., 2003).

For each kinematic variable, data were calculated for 1 s prior to the shot. This time period has been used in previous pistol shooting research (Ball et al., 2003; Mason et al., 1990), and has been reported as an adequate duration over which pistol and centre of pressure variables can differentiate between different ability shooters. This time period fits within the 1.5 s stated by Era et al. (1996) in which shooters significantly reduce pistol and centre of pressure movements prior to the shot.

Additional variables, representing the temporal aspects of performance were obtained from the video and transferred onto an RM Expert 3020 computer (RM, UK) using Adobe Premier Pro 6.0 (Adobe, California). The time to complete each 1 km run and each shooting series (s) were recorded for each participant.

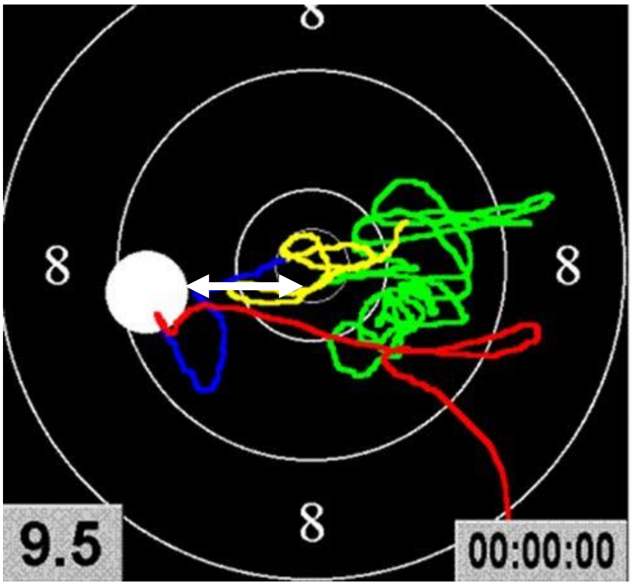


Figure 4.3. Output from the SCATT optoelectronic shooting system.

The white circle indicates the location of the shot on the target. Score is determined by the distance between the inner edge of the circle and the centre of the target (shown by the white arrow). The closer the circle is to the centre of the target, the higher the score. Coloured lines represent the movement of the aim-point of the pistol (Green = movement during the entire aiming period; Yellow = 1 s prior to trigger pull; Blue = 0.2 s prior to trigger pull; Red = after trigger pull). The yellow and blue lines represent trace length.

Chapter Five

Research Study 1 - Biomechanical Analysis of the Change in Pistol Shooting Format in Modern Pentathlon

Published in modified format as:

Dadswell, C.E., Payton, C., Holmes, P. and Burden, A. (2013). Biomechanical analysis of the change in pistol shooting format in modern pentathlon. *Journal of Sports Sciences, 31 (12),* 1294-1301.

5.1 Introduction

The first study investigated how modern pentathlon pistol shooting has changed between its original, precision shooting format, and the new format of the combined event. These comparisons determined whether the most successful precision shooters are also the most successful in the combined event. It was also possible to determine which variables were most influential to success in the new event. Thus, it highlights which aspects of shooting performance modern pentathletes should most consider when training for the combined event. Shot score, aiming time, pistol movements, and body sway were all considered as variables that could influence performance.

Due to the relatively recent development of the combined event there is, as yet, limited research which considers the variables that affect performance. Le Meur et al. (2010) reported that the most successful combined event athletes were significantly more accurate at shooting (p<.05), and completed each shooting series more quickly, than the less successful athletes. Neither shot times nor running velocity differed significantly between athletes, highlighting the relative importance of shooting accuracy to combined event success.

The findings of Le Meur et al. (2012, 2010) indicated the importance of developing a detailed understanding of combined event shooting performance. Previous precision shooting research (Ball et al., 2003; Mason et al., 1990) has demonstrated how a kinematic analysis of precision shooting can determine the variables, such as pistol and centre of pressure movements, which are key to a successful performance. A similar analysis should now be completed for the combined event. In addition, comparisons between performance in precision and combined event shooting will help determine whether the skills previously developed from precision shooting can be directly transferred to the new event.

An additional consideration for combined event research is the individual nature of pistol shooting performance, which has previously been reported for precision shooting (Ball et al., 2003). It is currently unclear whether the same degree of individual variation is evident in combined event shooting, and thus, when attempting to identify the variables most important to performance, both group and intra-individual analysis should be considered.

Given the importance of pistol shooting in the combined event, further analysis of the variables most associated with a successful shooting performance is required. This should examine whether the variables that were previously determined as most influential to precision shooting, are equally important to shooting performance in the combined event. The two objectives of this study, designed to meet the aims outlined in Chapter 3 (Section 3.5), are to:

(i) determine whether the key kinematic variables associated with precision shooting performance correspond with those associated with combined event performance; and
(ii) identify whether precision shooting ability affects shooting performance in the combined event.

To achieve the first objective, correlations are performed between shot score, aiming time, pistol movements, and centre of pressure movements to identify any variables associated with success in either event. The second objective is achieved by comparing participants’ shooting performances under precision and combined event conditions. Comparisons are also made between the performances of modern pentathletes and elite pistol shooters to identify whether the athletes with the greatest precision shooting ability are also the most successful in the combined event. The hypotheses to accompany each objective are:

(i) the variables associated with performance will differ between precision and combined event shooting due to the difference in shooting formats; and

(ii) pistol shooters will achieve significantly higher scores and smaller pistol and body movements for both precision and combined event shooting, but both groups will experience significantly decreased scores, and increased pistol and centre of pressure movements in the combined event.

5.2 Methods

5.2.1 Participants

Seven participants from the first modern pentathlon group and three pistol shooters comprised the two participant groups for this study. More information for each group is provided in the General Methods chapter (Chapter 4, section 4.1). Written consent was obtained from all participants prior to testing, and the study was approved by the Manchester Metropolitan University research ethics committee.

5.2.2 Tasks

Each participant completed trials under both precision and combined event conditions. The format of both conditions are detailed in the General Methods chapter (Chapter 4, section 4.2). The combined event trials required participants to complete the entire event as they would in competition, but data were only analysed from the first series of combined event shooting. This made it possible to assess changes in performance solely due to the change in shooting format, without the additional effects that could be introduced by the 1 km run phases between each series.

5.2.3 Data Analysis

Shot score, aiming time and trace length were recorded from the SCATT optoelectronic shooting system, and centre of pressure range and path length were obtained from the AMTI force plates. Horizontal and vertical trace lengths were used to represent pistol movement, whilst centre of pressure range and path length were used to represent body sway movements. More detail on each variable is provided in the General Methods chapter (Chapter 4, section 4.4). Correlations were performed between each variable to identify any significant associations between kinematic variables and shot score.

Due to small sample sizes, data were found to violate the assumptions of parametric tests, demonstrating a non-normal distribution and heterogeneity of variance. Consequently, non-parametric tests were selected for the statistical analysis of all dependent variables. The performances of the two participant groups, under both shooting conditions, were compared using a Mann-Whitney U test. A Wilcoxon test was performed for each participant group to identify any changes in performance between precision and combined event shooting. For all comparisons, any value below *p*<.05 was considered statistically significant.

Spearman's Rank Order Correlation Coefficients were used for data from both shooting conditions to determine the strength of any associations between variables. Correlations were performed using both group median data and data from selected participants to determine how well the group median reflected individual performances. Due to the high number of correlations between score and the six kinematic variables, Bonferroni corrections were used, and *p*<.007 considered statistically significant.

5.3 Results

Shot score, aiming time, and movements of the pistol and the centre of pressure compared between the two participant groups, and between the two shooting conditions are presented in Tables 5.1 and 5.2 respectively.

5.3.1 Shot Score

Median shot score varied between each of the 20 shots under precision conditions, particularly for the modern pentathletes (Figure 5.1). With the exception of shot 5, the pistol shooters achieved consistently higher scores than the modern pentathletes. Both groups produced median scores greater than 8.0 for all shots, demonstrating that participants were capable of consistently hitting a combined event target, the equivalent of scoring 7.0 or higher on a standard precision target.

Pistol shooters achieved significantly higher scores than modern pentathletes under precision conditions (*p*<.05) (Table 5.1), with median scores of 9.7 (IQR 0.9) and 8.8 (IQR 1.7) points respectively. Scores were significantly lower for both groups when changing from precision to combined event shooting (*p*<.05) (see Table 5.2), with median scores of 8.0 (IQR 2.3) and 7.7 (IQR 1.9) for pistol shooters and modern pentathletes respectively (Figure 5.2). Whilst pistol shooters achieved marginally higher scores in the combined event, the difference between groups became non-significant (*p*>.05) (Table 5.1).

5.3.2 Aiming Time

Under precision conditions, modern pentathletes spent longer aiming than pistol shooters for the majority of shots (Figure 5.3). Median aiming time was 6.1 s (IQR 1.9) for modern pentathletes and 5.1 s (IQR 3.9) for pistol shooters, although this difference was non-significant (*p*>.05) (see Table 5.1).

Both groups experienced significantly shorter aiming times with the change from precision to combined event conditions (*p*<.05) (Table 5.2). Median aiming time decreased by 3.4 s for modern pentathletes, and by 3.7 s for pistol shooters (Figure 5.4), and differences between the two groups remained non- significant (*p*<.05).

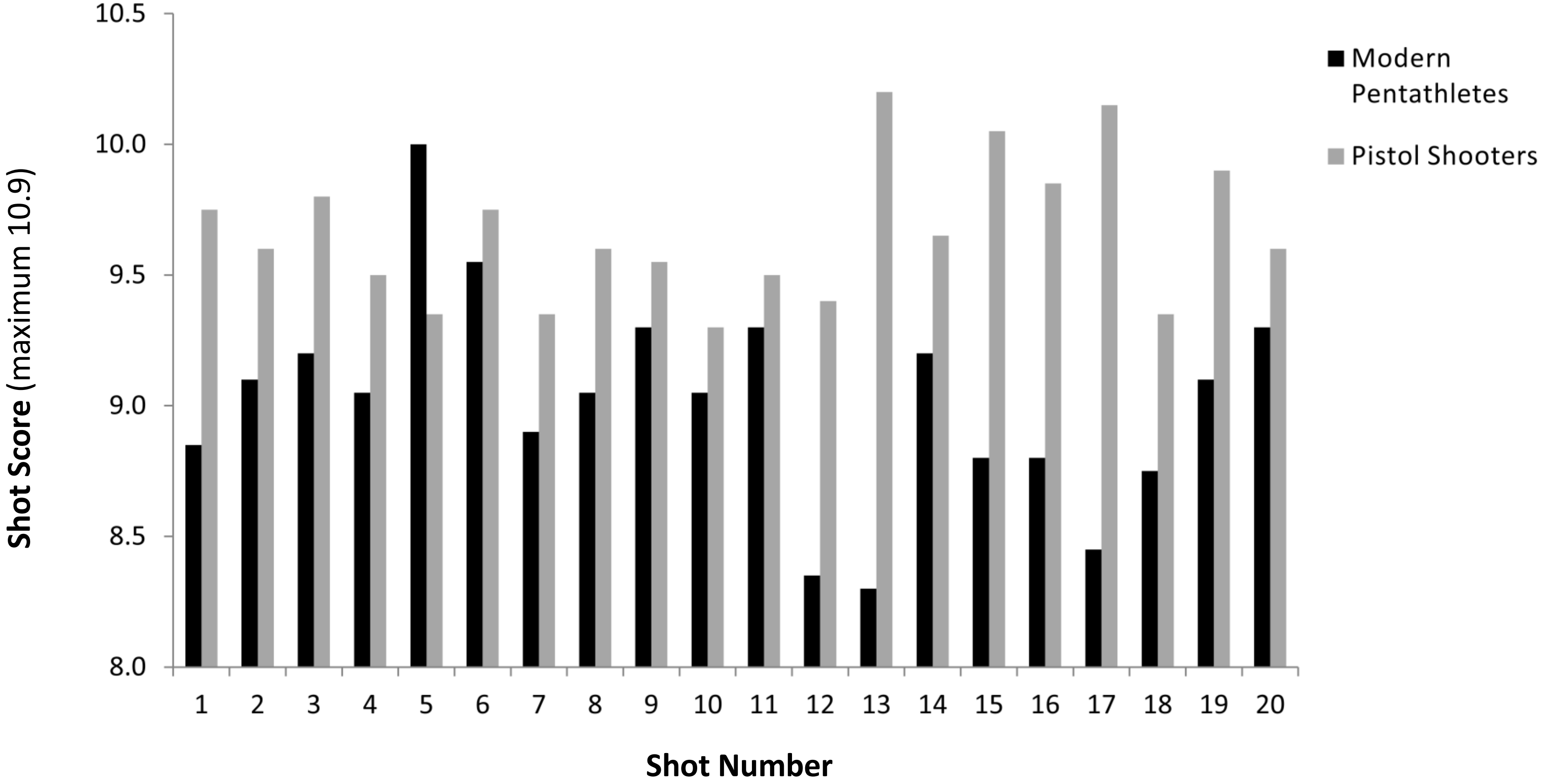
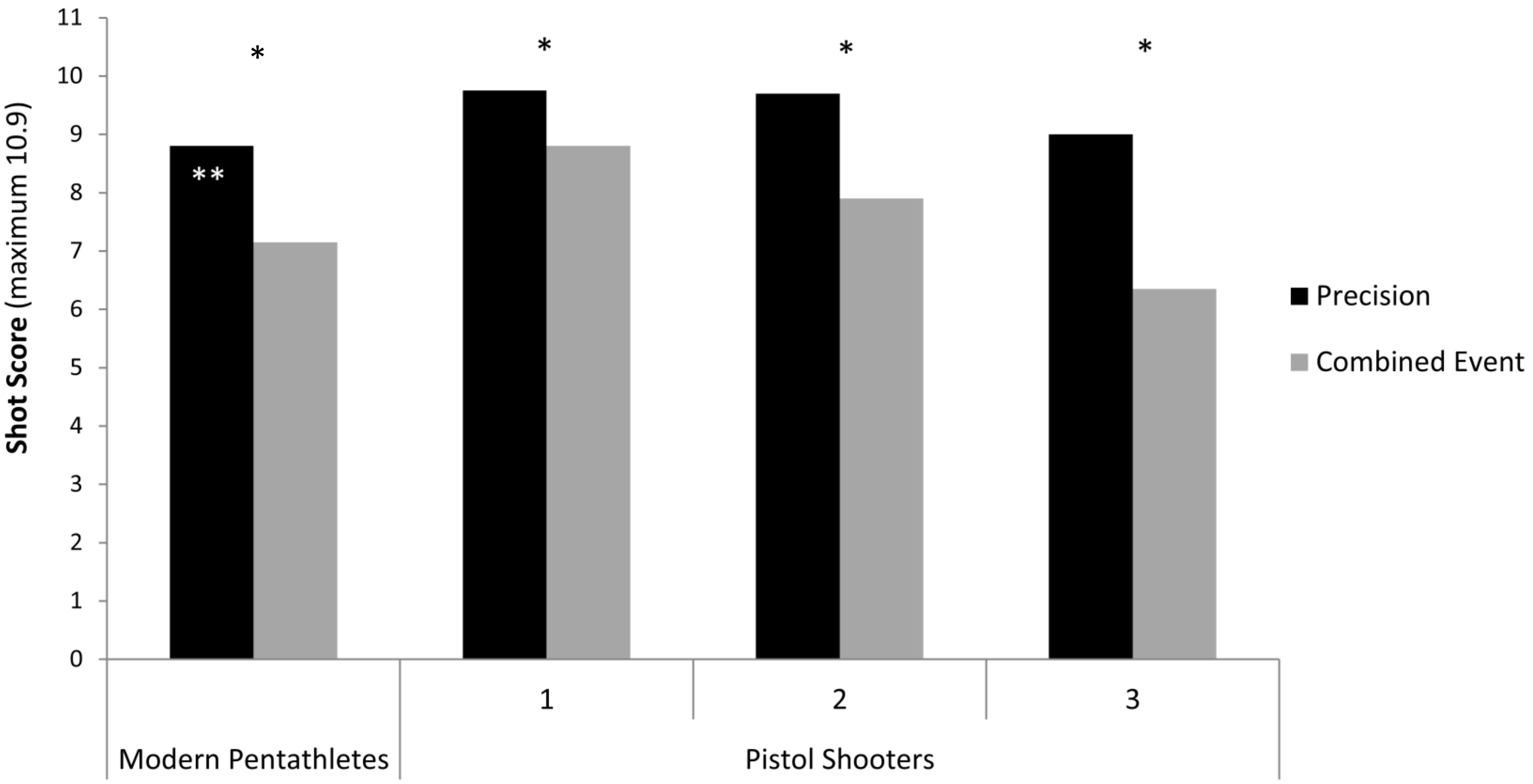


Figure 5.1. Median shot scores for each group under precision shooting conditions.



* significant difference between shooting conditions (*p*<.05)

** significant difference between modern pentathletes and pistol shooters (*p*<.05)

Figure 5.2. Median shot score (± IQR) under precision and combined event conditions. Bars represent all shots in the precision condition and the first combined event shooting series.

Shot score is presented as the median group value for modern pentathletes, and the median individual score for each pistol shooter.

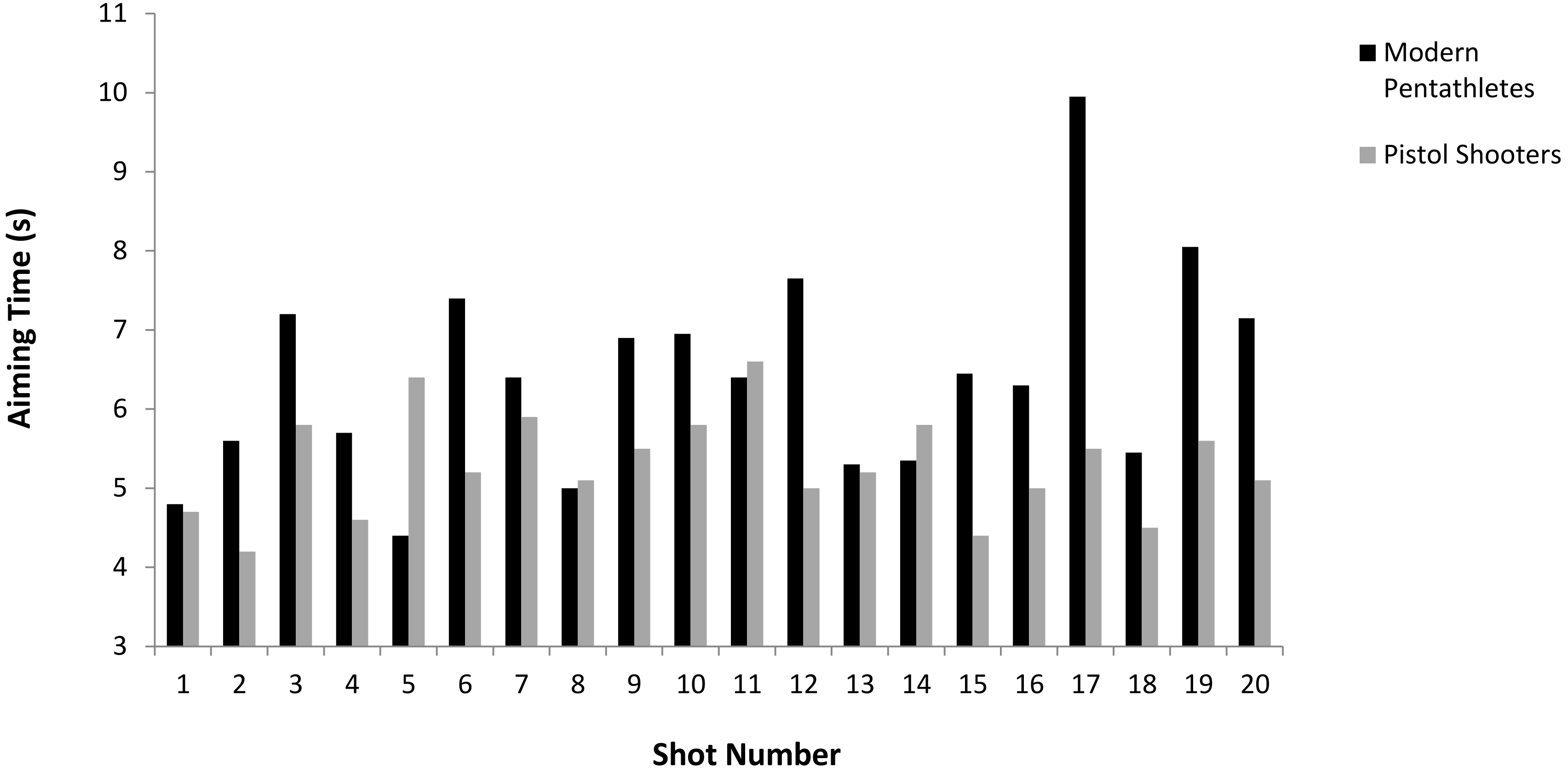
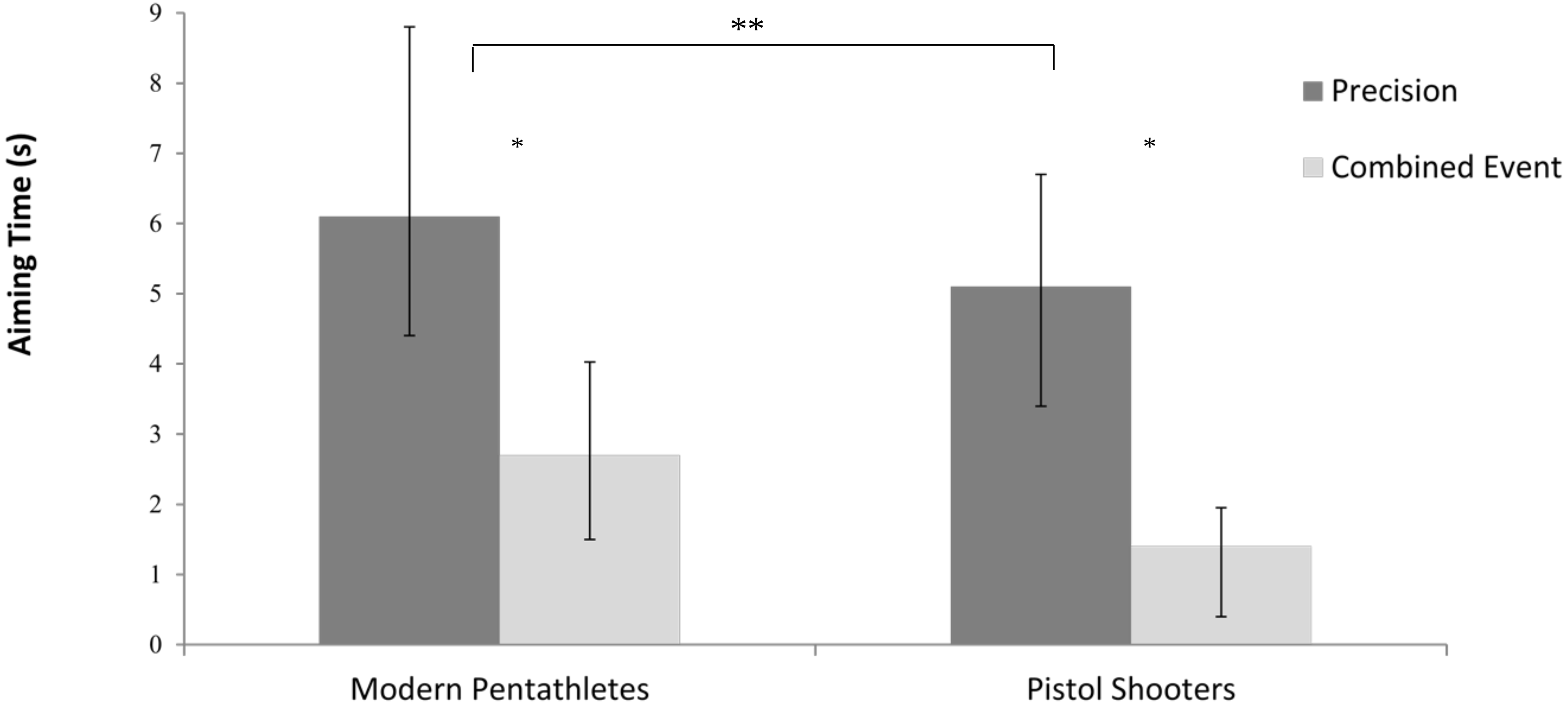


Figure 5.3. Median aiming time per shot for each group under precision shooting conditions.



* significant difference between shooting conditions (*p*<.05)

** significant difference between participant groups (*p*<.05)

Figure 5.4. Median aiming time (± IQR) under precision and combined event conditions. Bars represent all shots in the precision condition and the first combined event shooting series.

5.3.3 Pistol Movements

Median horizontal and vertical pistol movements in the final second before the shot were significantly greater for modern pentathletes than pistol shooters under precision conditions (*p*<.05) (Table 5.1). For the majority of shots, both groups produced greater vertical pistol movements than horizontal pistol movements; a trend which was particularly evident for modern pentathletes (Figure 5.5).

Horizontal and vertical trace lengths were significantly greater under combined event than precision conditions for both groups (*p*<.05) (Table 5.2). Median horizontal trace length under precision and combined event conditions was 115.8 (IQR 18.5) mm and 281.9 (IQR 120.2) mm respectively for modern pentathletes, and 71.2 (IQR 28.8) mm and 190.4 (IQR 52.2) mm respectively for pistol shooters (Figure 5.6). Whilst the difference between groups was greater for the combined event than precision shooting, the greater magnitude of movement experienced in the combined event meant that the difference between groups became non-significant (*p*>.05) (Table 5.1). Median vertical pistol movements under precision and combined event conditions were 132.8 (IQR 29.7) mm and 209.5 (IQR 72.1) mm respectively for modern pentathletes, and 71.3 (IQR 28.8) mm and 209.3 (IQR 50.6) mm for pistol shooters. Differences between groups were again non-significant under combined event conditions (*p*<.05) (Table 5.1).

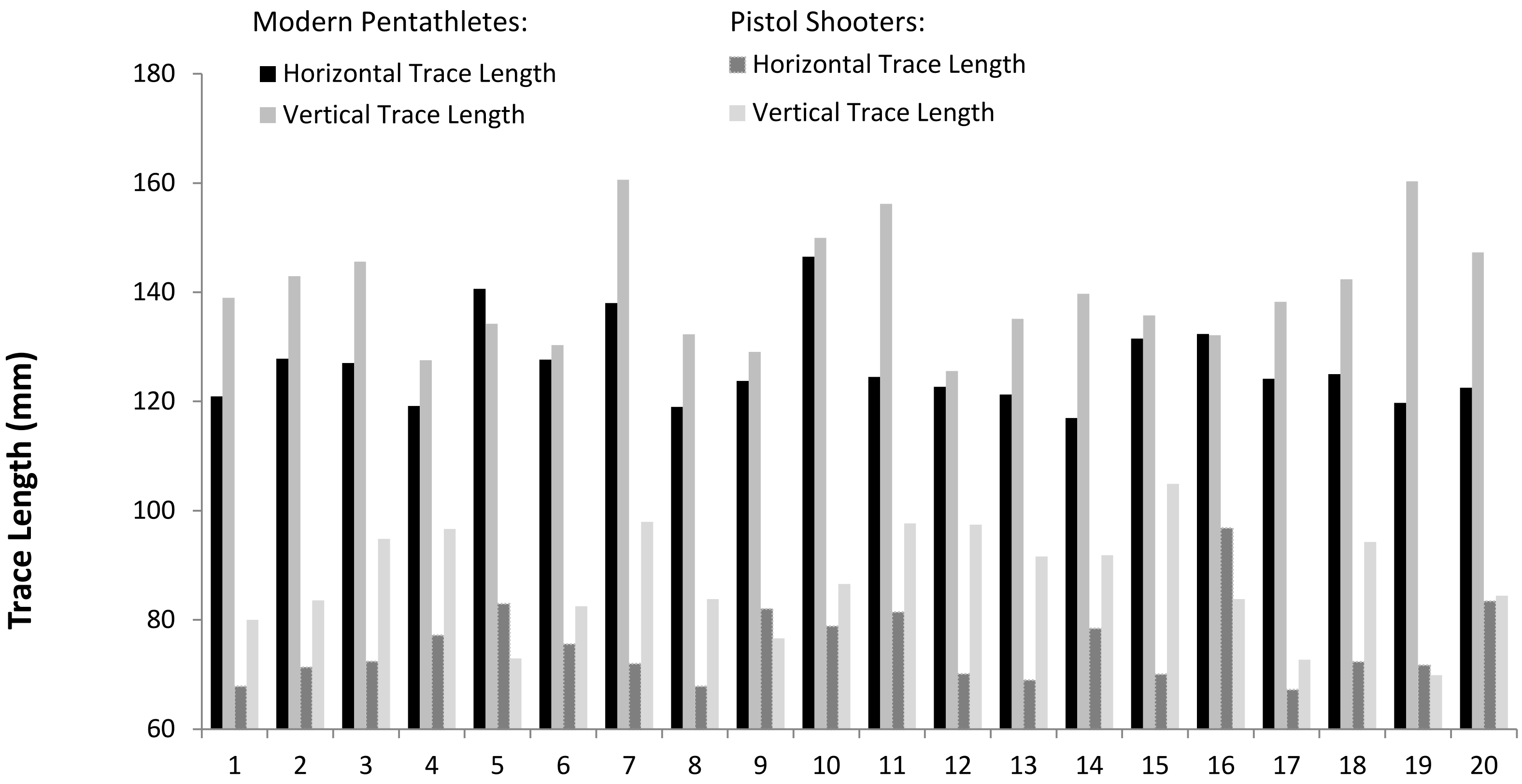
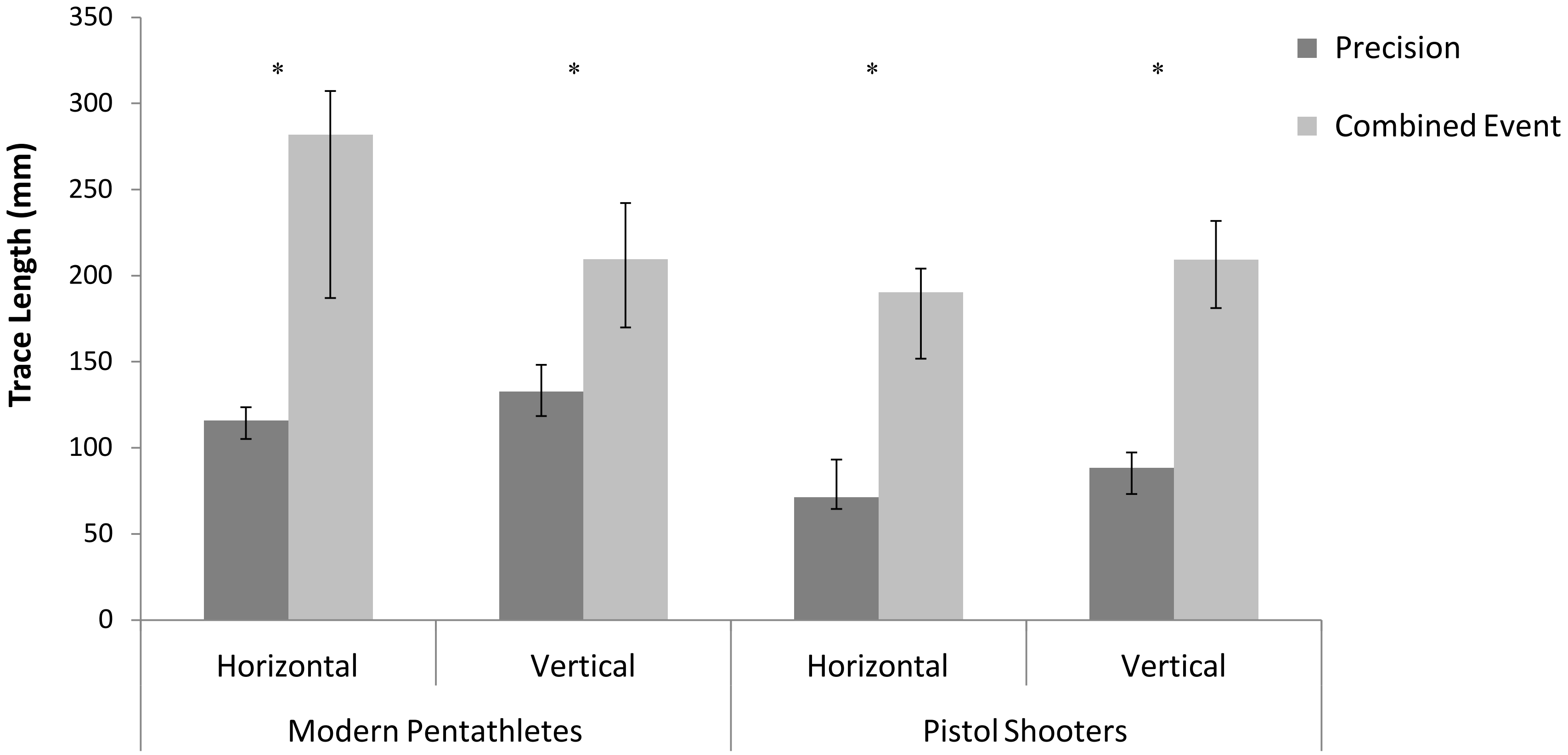


Figure 5.5. Median horizontal and vertical trace lengths for each group under precision shooting conditions



* significant difference between shooting conditions (*p*<.01)

Figure 5.6. Median trace lengths (± IQR) under precision and combined event conditions. Bars represent all shots in the precision condition and the first combined event shooting series.

5.3.4 Centre of Pressure Movements

Both anterior-posterior and mediolateral range were significantly greater for modern pentathletes than pistol shooters, under precision conditions (*p*<.05) (Table 5.1). This was particularly apparent for anterior-posterior range, which was greater for modern pentathletes than pistol shooters for all but two shots (Figure 5.7). Anterior- posterior and mediolateral path length were also greater for modern pentathletes than pistol shooters for most shots, under precision conditions (Figure 5.8), but the differences between groups were non-significant (*p*>.05).

Modern pentathletes' centre of pressure range movement was significantly greater under combined event than precision conditions, (*p*<.05) (Figure 5.9) (Table 5.2). Mediolateral range was 3.6 (IQR 0.7) mm and 5.8 (IQR 0.8) under precision and combined event conditions respectively. Anterior-posterior range was 2.7 mm (IQR 0.8) and 4.6 (IQR 2.8) mm respectively. Mediolateral range was significantly greater for the combined event than precision shooting for pistol shooters (*p*<.05) (Table 5.2), with a range of 8.0 (IQR 4.0) mm and 2.6 mm (IQR 1.1) respectively. Anterior-posterior range was greater, but not significantly, for the combined event than precision shooting, with a range of 4.1 (IQR 6.3) and 1.4 (IQR 0.7) mm respectively. Differences between participant groups became non-significant in the combined event (*p*>.05) (Table 5.1).

Anterior-posterior and mediolateral path length were greater for both groups in the combined event than precision shooting (p<.05) (Table 5.2). Mediolateral path length recorded for the modern pentathletes was significantly greater under combined event than precision conditions (p<.05) (Table 5.2), at 66.1 (IQR 23.0) mm and 75.7 (IQR 28.2) mm respectively (Figure 5.10). Differences in anterior-posterior path length were non-significant (*p*>.05). Differences in both mediolateral and anterior-posterior path length between the two conditions were non-significant for pistol shooters (*p*>.05). Differences between the participant groups were non-significant under combined event conditions (*p*>.05) (Table 5.1).

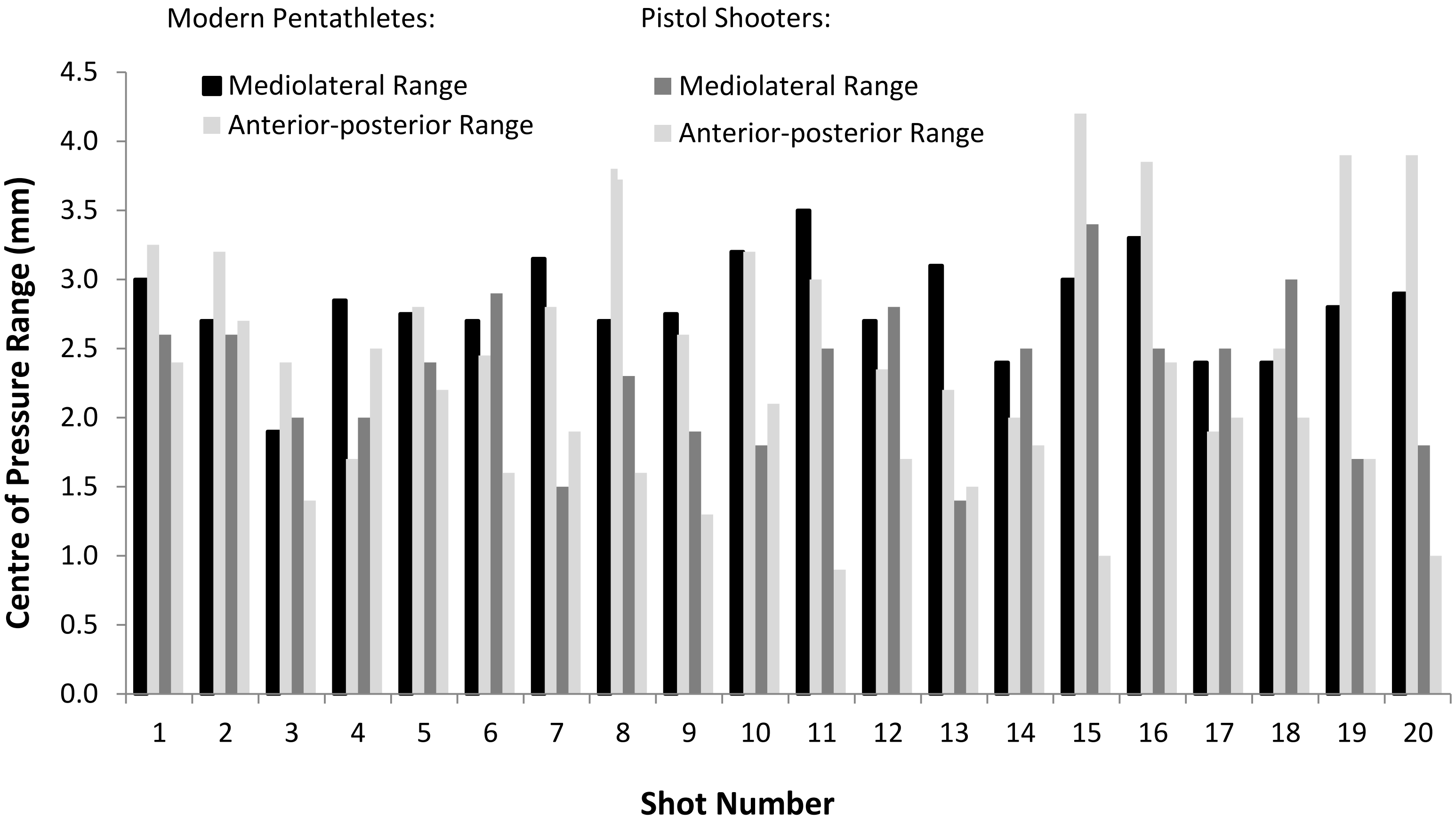


Figure 5.7. Median mediolateral and anterior-posterior centre of pressure range for each group under precision shooting conditions.

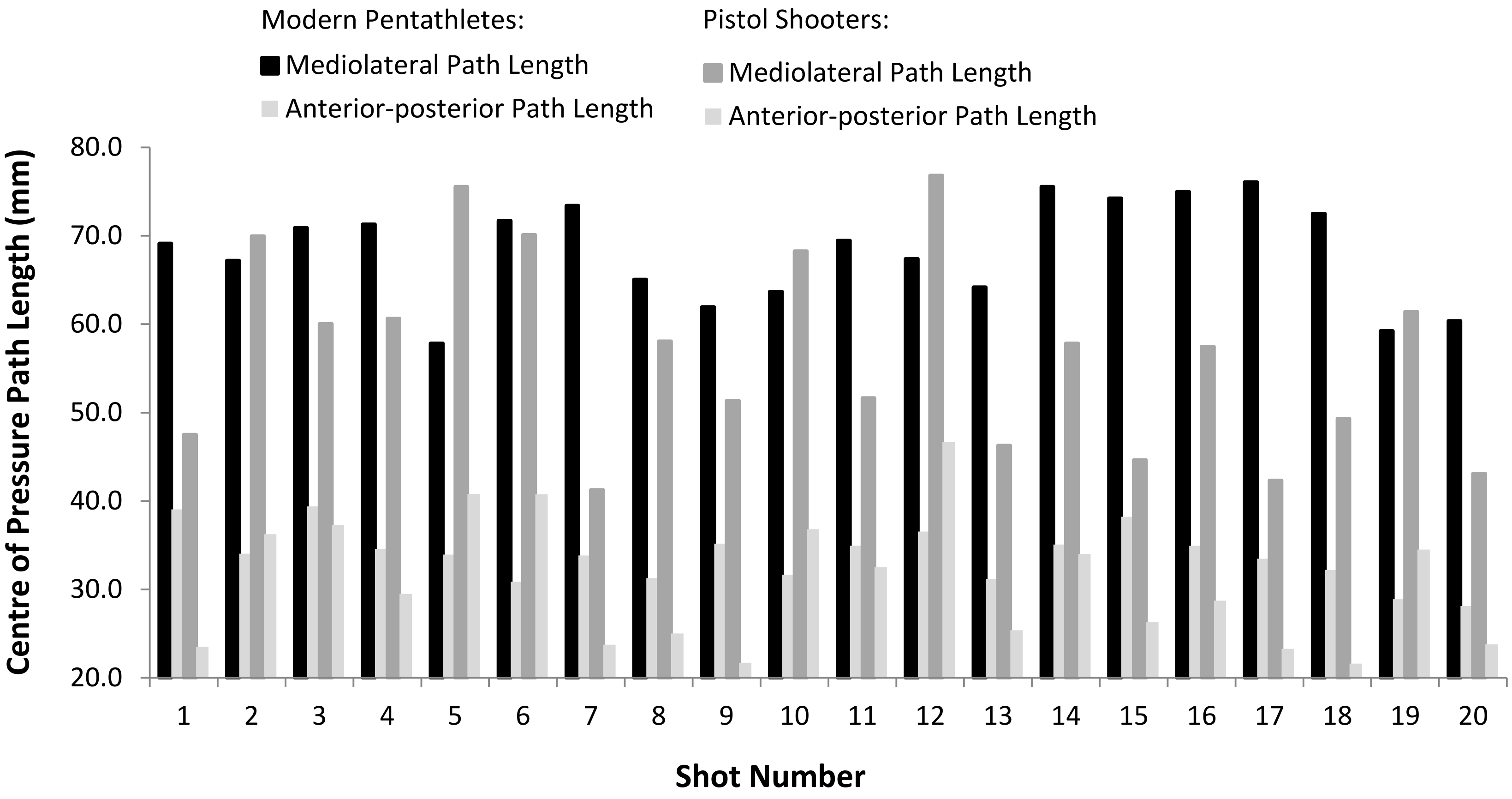
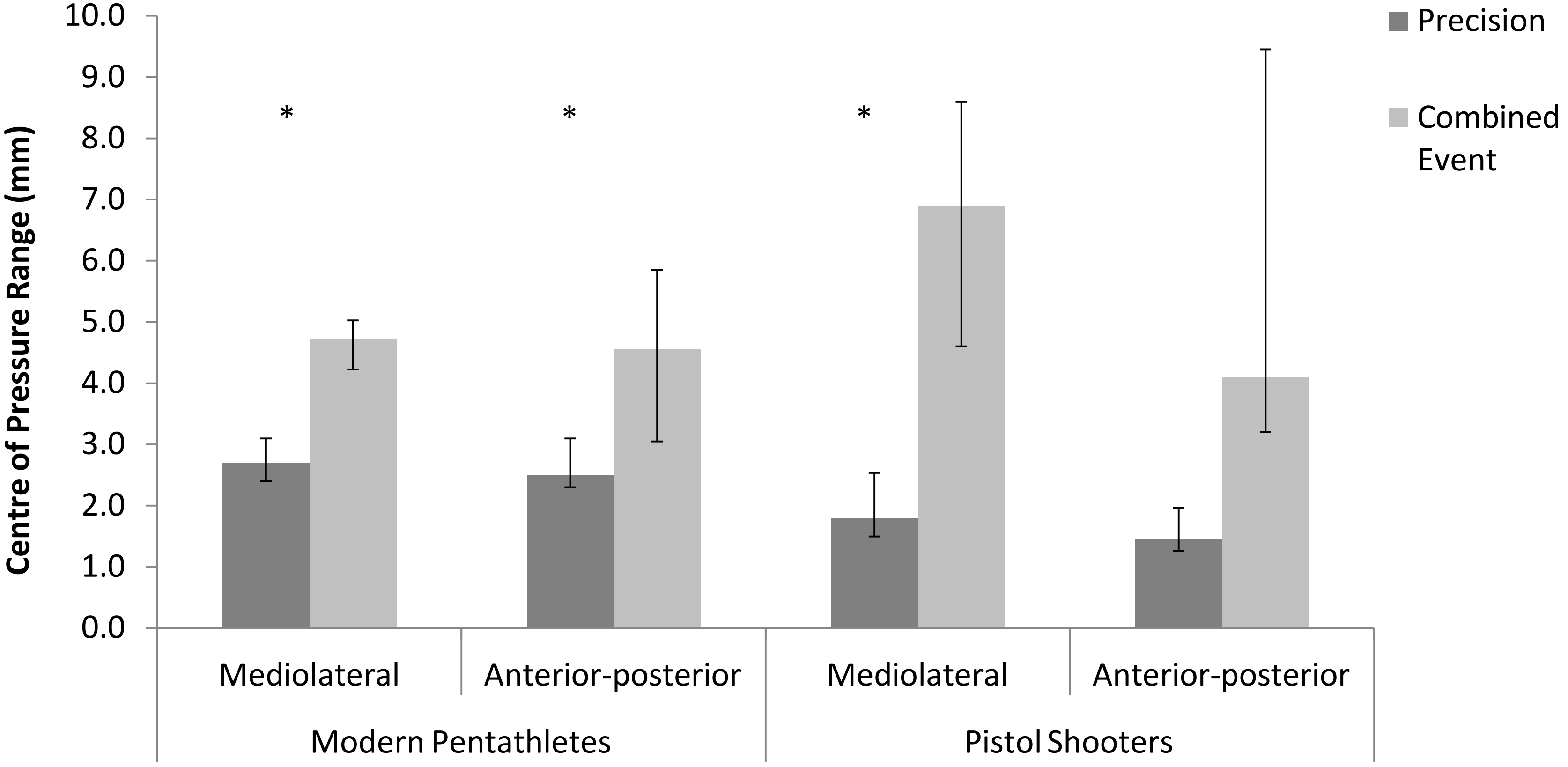
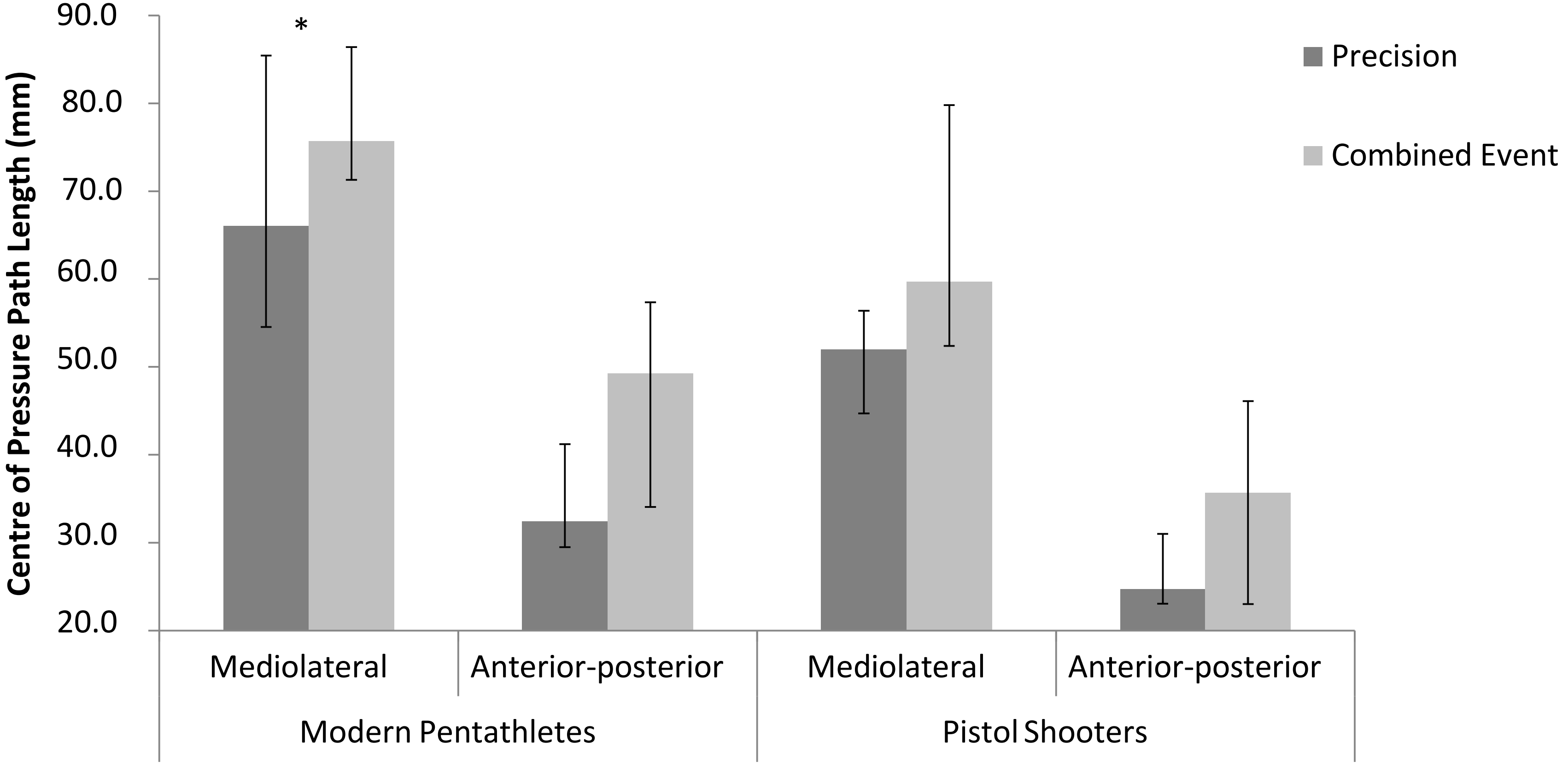


Figure 5.8. Median mediolateral and anterior-posterior centre of pressure path length for each group under precision shooting conditions.



* significant difference between shooting conditions (p<.05)

Figure 5.9. Median centre of pressure range (± IQR) under precision and combined event conditions for both participant groups. Bars represent all shots in the precision condition and the first combined event shooting series.



* significant difference between shooting conditions (*p*<.05)

Figure 5.10. Median centre of pressure path length (± IQR) under precision and combined event conditions for both groups. Bars represent all shots in the precision condition and the first combined event shooting series.

Table 5.1. Statistical comparisons between the shooting performances of each participant group within each shooting condition.

Shooting Condition	**Precision**		**Combined Event**	
	Statistic (U)	*p*	Statistic (U)	*p*
Aiming Time	33.0	0.12	28.0	0.055
Score	8.0	0.00	6.0	0.571
Pistol Movement				
Horizontal Trace Length	24.0	<.001	2.0	0.071
Vertical Trace Length	53.0	<.001	5.0	0.286
Centre of Pressure Movement				
Mediolateral Range	10.0	0.03	2.5	0.060
Anterior-Posterior Range	5.0	0.00	8.5	0.488
Mediolateral Path Length	16.0	0.17	3.0	0.083
Anterior-Posterior Path Length	7.0	0.01	5.0	0.190

Table 5.2. Statistical comparisons of participants' shooting performances between precision and combined event shooting conditions.

	Modern Pentathletes		**Pistol Shooters**	
	Statistic (T)	*p*	Statistic (T)	*p*
Aiming Time	0	<.001	0	0.008
Score	2	<.001	0	0.016
Pistol Movement				
Horizontal Trace Length	0	<.001	0	0.008
Vertical Trace Length	0	<.001	0	0.008
Centre of Pressure Movement				
Mediolateral Range	0	0.004	0	0.016
Anterior-Posterior Range	0	0.004	0	0.016
Mediolateral Path Length	0	0.004	0	0.016
Anterior-Posterior Path Length	8	0.098	0	0.016

5.3.5 Correlations between Score, Aiming Time, Pistol Movement and Centre of Pressure Movement

Group analysis of precision shooting identified no significant correlations between score and aiming time or movements of the pistol or centre of pressure for either group. Intra-individual analysis revealed some significant correlations that were not apparent from the group–based comparisons. Kinematic variables were significantly associated with score for three participants (one modern pentathlete and two pistol shooters) (Table 5.3).

Under combined event conditions, group analysis did not produce any significant correlations between score, and aiming time or kinematic variables. Intra- individual analysis identified only one participant with any significant correlations (Table 5.3). This participant produced significant correlations with score in both events, but the significant associations were with vertical pistol movement for precision shooting, and aiming time for the combined event.

Table 5.3. Significant intra-individual correlations with shot score under precision and combined event conditions (*p*<.007). R^2 values are included in brackets.

MP = Modern pentathletes; Pistol = Pistol Shooters

Event	Group	Participant	Aiming Time	Vertical Pistol Movement	Mediolateral Path Length
Precision	MP	3		.713 (0.51)	
	Pistol	2			-.373 (0.14)
		3			.592 (0.35)
Combined Event	MP	3	.778 (0.60)		

5.3.6 Correlations between Pistol and Centre of Pressure Movements

Under precision conditions, no significant correlations were identified between pistol and centre of pressure movement for either group. Intra-individual analysis identified significant correlations for one modern pentathlete and all three pistol shooters (Table 5.4), each of which contrasted with the non-significant findings of group analysis.

Group analysis of the combined event revealed no significant correlations between pistol and centre of pressure movements for modern pentathletes, whilst pistol shooters produced significant correlations between horizontal pistol movement and mediolateral range (r_s=0.886, $p<.01$, R^2=0.78). Intra-individual analysis identified one modern pentathlete with significant correlations between pistol and centre of pressure movement (Table 5.4), and in contrast to the group result, no significant correlations were identified for pistol shooters.

Whilst few significant correlations were identified for either event, a greater number were apparent for precision shooting. This was particularly noticeable for the pistol shooters, each of whom demonstrated at least one significant correlation under precision conditions, but none when shooting in the combined event. No participant from either group produced significant correlations in both events.

Table 5.4. Significant intra-individual correlations between pistol movement and centre of pressure range and path length under both shooting conditions (*p*<.07). R^2 values are included in brackets.

				Range		Path Length	
	Group	**Pistol Movement**	**Participant**	**Mediolateral**	**Anterior-posterior**	**Mediolateral**	**Anterior-posterior**
Precision	Modern Pentathletes	Vertical	6		-.899 (0.81)		-.899 (0.81)
	Pistol Shooters	Horizontal	1				.438 (0.19)
			2	.522 (0.27)			
			3	.575 (0.33)		.404 (0.16)	
		Vertical	1	.424 (0.18)			
Combined Event	Modern Pentathletes	Horizontal	3				.929 (0.86)

5.4 Discussion

An objective of this study was to identify which kinematic variables were most closely associated with shooting performance in the combined event, and determine any similarities with precision shooting performance. A further objective was to identify whether precision shooting ability could transfer to success in the combined event. Comparisons between the shooting performances of modern pentathletes and pistol shooters examined whether the pistol shooters, who had the greatest precision shooting ability, also achieved greater success when shooting in the combined event.

Scores achieved by the pistol shooters under precision conditions compared well with those recorded for other elite groups used in previous pistol shooting research (Table 5.5), supporting their status as an elite shooting group. Modern pentathletes scored lower than both the pistol shooters in the current study, and other elite groups (Ball et al., 2003; Mason et al., 1990; Pellegrini & Schena, 2005), but higher than groups previously identified as less skilled shooters (Pellegrini & Schena, 2005; Tang et al., 2008) (Table 5.5).

Table 5.5. Comparisons with average shot scores achieved for previous precision pistol shooting research. MP = Modern Pentathletes; Pistol = Pistol Shooters

Current Study		**Mason et al. (1990)**	**Ball et al. (2003)**	**Pellegrini & Schena (2005)**		**Tang et al. (2008)**	
MP	Pistol	Elite and Junior	Elite	More Skilled	Less Skilled	Elite	Pre-elite
8.8	9.7	9.0	9.7	8.8	7.9	9.3	8.3

To achieve the first objective, both group and intra-individual correlations were used to quantify the strength of associations between shot score and aiming time, pistol movements and centre of pressure movements. Group correlations revealed only one significant association, between horizontal pistol movement and mediolateral range for pistol shooters in the combined event. This correlation was not demonstrated by any pistol shooter when using individual analysis, highlighting how group analysis cannot fully reflect any individual's shooting performance. This was particularly evident for the pistol shooters, for whom group analysis identified no significant correlations between pistol and centre of pressure movement for precision shooting, despite each participant displaying at least one significant correlation. The magnitude of the correlations between each variable differed between each participant, supporting the findings of Ball et al. (2003) that correlations vary in both strength and direction between participants for precision shooting. This also reinforces the statements of Scholes, McDonald and Parker (2012) that the use of a group average produces a mythical average participant that does not fully reflect any individual's responses to a particular task. Consequently, the outcomes of intra- individual analysis were considered most appropriate when identifying the key variables affecting a shooting performance.

When shooting under combined event conditions, only one participant demonstrated any significant correlations with score, and as such, no single variable could be identified as most influential to success in the combined event. Two pistol shooters produced significant correlations between score and mediolateral path length. One of these correlations was negative, suggesting that score decreases as centre of pressure movement increases, whilst the other was positive. These opposing correlations have different consequences for the way in which participant can interpret the effect of body sway on performance. Thus, in both precision and combined event shooting, athletes cannot follow one optimal model of technique as a method of improving shooting success. This supports the conclusions of Chow, Davids, Hristovski, Araújo, and Passos (2011), Davids, Glazier, Arújo, and Bartlett (2003) and Langdown, Bridge, and Li (2012) that athletes should not attempt to replicate another individual's technique, but should instead devise their own movement strategies to achieve a successful task outcome.

Given the highly variable correlations between participants, and considering that none of the variables analysed accounted for anywhere near 100% of the variance in shot score, it is clear that variables other than those analysed here must also influence shooting success. One consideration is the position of the aim point on the target before the shot. An athlete who centres the aim point on the 10 zone is more likely to hit a combined event target, than another with movement centred on the 7 zone, near to the edge of the target.

In addition to shot score, correlations between the pistol and centre of pressure varied considerably between participants. Body sway accounted for between 16% and 81% of the variance in pistol movement for precision shooting, and 86% for the combined event. Furthermore, significant correlations were not evident for all participants. This supports the concept of a more complex method of controlling the pistol than the simple transfer of centre of pressure movements through the body to the pistol, ultimately affecting score (Ball et al., 2003; Pellegrini & Schena, 2005). Whilst some significant correlations between pistol and centre of pressure movements were expected, it is unsurprising that these associations were low. Between the centre of pressure at ground level and the hand holding the pistol there are many other potential sources of movement throughout the body. Whilst small, the effect of these movements on the location of the aim-point on the target could be considerable. For example, Pellegrini and Schena investigated the role of upper limb movements when shooting, and reported that vertical movements of the arm increased from proximal to distal segments. This suggests that each successive joint from the shoulder to the wrist introduces more movement to the system that will ultimately affect movement of the pistol. Furthermore, Arutyunyan, Gurfinkel, and Mirskii (1968) reported that pistol movement was not determined solely by postural stability, but was further influenced by the compensatory actions of the joints of the upper limb. Upper limb movements will only be represented by minimal changes in the location of the centre of mass and therefore centre of pressure. Such findings demonstrate that whilst centre of pressure movement has some impact on performance for most athletes, it is not the only variable to influence pistol movement and shot score. As such, it cannot reflect the full extent of the movements produced when pistol shooting.

Correlations between the kinematic variables and score highlighted the individual nature of pistol shooting. No participants produced the same significant correlations for both conditions, indicating that the combined event has placed new demands on athletes’ shooting performance. These findings imply that experience in one event does not guarantee success in the other, indicating the importance of combined event specific training. The absence of matching correlations between the two events suggests that the first hypothesis, that the variables significantly associated with score would differ between the two shooting formats, was correct. However, with a limited number of significant correlations in either event, this cannot be guaranteed. A potential explanation for the limited number of correlations was the low number of participants, particularly for the pistol shooter group. To provide more support for the first hypothesis, future combined event research would therefore benefit from a greater number of participants. This will increase the potential to identify any variables commonly associated with score or pistol movement. Cohen (1988) advises that to achieve the recommended statistical power of 80% with the participant numbers used in this research (10), large effect sizes of 0.70 are required. The correlations both in this research, particularly for the precision shooting condition, and in a previous investigation (Ball et al., 2003) were of medium or low strength, for which over 60 participants are recommended in order to achieve 80% statistical power. Effect sizes recorded for the combined event trials were higher than those recorded for precision shooting and so participant numbers greater than 30 are recommended for research focusing exclusively on shooting in the combined event. However, these numbers are very difficult to achieve when focusing on elite participants, and so, despite the advantages of attaining the recommended number of participants, researchers should ensure that they do not compromise results by including less experienced participants to inflate group size.

This study produced varied results in relation to previous studies (Ball et al., 2003; Mason et al., 1990; Scholz et al., 2000). Correlations between shot score and aiming time are in agreement with Scholz’s pistol shooting research, which reported weak correlations between the two variables. In contrast, Mason et al. stated that score increased as participants spent longer aiming. These differences in results may have arisen from the differences in shooting conditions. Mason et al. investigated precision shooting performance, whilst Scholz et al. introduced time constraints more similar to those used in the combined event condition. Contrasting findings to those of Mason et al. may also have arisen from their greater range in participants' shooting ability. The difference in precision shooting ability between the modern pentathletes and pistol shooters in the current study was reduced by analysing each participant group separately. If all data from the two groups were combined, a significant correlation between aiming time and score was evident.

The extent of the associations between pistol movements and score were not as great as those previously reported by Mason et al. (1990). The differences could again arise from the greater variation in the ability of their participants. Results were more closely in agreement with Ball et al. (2003) who reported that the strength of correlations between pistol movements and score varied between participants. This individual aspect of performance is something that will have been supressed by the group analysis methods used by Mason.

5.4.1 Group comparisons: effect of precision shooting ability on combined event performance

Within each shooting condition, the performances of pistol shooters and modern pentathletes were compared to identify whether the greater precision shooting ability of the pistol shooters was also evident in their combined event performances. The difference in precision ability was evidenced by the significantly higher scores, and smaller pistol and centre of pressure movements of the pistol shooters compared to modern pentathletes. With the change to combined event conditions, both groups experienced significantly decreased scores, which were up to 2.0 points lower than all previous precision results (Table 5.5).

When precision shooting, pistol movements and range of centre of pressure movement recorded for the pistol shooters were again comparable with elite shooters (Table 5.6). Modern pentathletes produced a similar degree of movement to the elite and junior shooters used by Mason et al. (1990). These comparisons support the findings of previous research which demonstrated that greater ability shooters produce smaller gun movements (Zatsiorsky & Aktov, 1990), and established that greater centre of pressure movements are associated with greater gun movements and lower average scores (Ball et al., 2003; Era et al., 1996; Heimer et al., 1985). With the significant changes in performance recorded for the combined event, pistol and centre of pressure movements for both groups were greater than all previous precision findings, including results for unskilled shooters (Pellegrini & Schena, 2005; Tang et al., 2008).

Table 5.6. Comparisons with average pistol and centre of pressure movement recorded for previous precision pistol shooting research.

	Current Study		**Mason et al. (1990)**	**Ball et al. (2003)**
	Modern Pentathletes	Pistol Shooters	Elite and Junior	Elite
Pistol Movement				
Horizontal Trace Length (mm)	115.8	71.2	108.9	76.1
Vertical Trace Length (mm)	132.8	71.3	89.2	70.7
Centre of Pressure Movement				
Mediolateral Range (mm)	3.6	2.6	3.1	1.0
Anterior-Posterior Range (mm)	2.7	1.4	3.3	1.9

The change in performance when shooting in the combined event led to the rejection of the second hypothesis, which predicted that pistol shooters would produce significantly higher scores, and smaller pistol and centre of pressure movements than modern pentathletes, in both events. Whilst the pistol shooters demonstrated the anticipated higher performance levels when precision shooting, there were no notable differences between the performances of the two groups in the combined event. Moreover, mediolateral centre of pressure movement was actually greater for the pistol shooters than for the modern pentathletes under combined event conditions. These similarities in performance under combined event conditions demonstrate that ability in precision shooting does not directly transfer to the skills required to succeed in the combined event.

5.4.2 Event comparisons: effect of changing from precision to combined event shooting

Under combined event conditions, scores were significantly lower and pistol movement and body sway were significantly greater, than for precision shooting. Thus, the third hypothesis was accepted, emphasising the different performance requirements of the combined event in comparison to precision shooting. This is unsurprising given that the change in shooting format has resulted in an increase in target size, meaning that success is now determined by achieving any score above 7.0, significantly lower than all precision scores. The combination of an increase in target size and the altered task requirements to simply hit the target, rather than aim for the centre, means that athletes are now able to shoot more quickly with less consideration given to exact shot placement or the reduction of body sway or pistol movement. Thus, some accuracy may have been sacrificed to increase shooting speed; something which is demonstrated by the significant reduction in aiming time in the combined event.

With a greater emphasis on the speed of shooting, and with the change in target size, a reduction in accuracy in comparison to precision shooting is almost inevitable. Previous research has described the trade-off between speed and accuracy during human movements (Berrigan et al., 2006; Duarte & Freitas, 2005; Fernandez & Bootsma, 2004), consistently reporting that tasks with a greater target size are associated with faster movements. This increase in movement speed has important consequences for accuracy, with Beilock, Bertenthal, McCoy, and Carr (2004) stating that performance declines when participants are instructed to complete a movement at higher speeds. It should be noted that this decrement in performance was only evident for novice, and not experienced athletes. Thus, the speed-accuracy relationship may become a lesser consideration once a modern pentathlete becomes accustomed to the format of the combined event.

The speed-accuracy trade off, as identified by Fitt's Law (Fitts, 1954) means that whilst precision shooters must use slow movements to achieve sufficient accuracy, athletes in the combined event where shot placement is less crucial, can afford to produce faster movements. Whilst the degree of accuracy required for the combined event is lower than that required for precision shooting, the speed-accuracy trade off must remain an important consideration. Le Meur et al. (2010) reported that the most successful combined event athletes have the shortest event times due to greater shooting accuracy, and not because of quicker aiming or 1 km run times. Increased accuracy meant that athletes achieved five hits in fewer shots, and could progress to the next running phase sooner than those who were less accurate. Thus, minimising aiming time may in fact be detrimental to performance. These findings suggest that the less successful combined event athletes need to determine the appropriate level of trade-off between accuracy and speed.

The relationship between speed and accuracy goes some way to explaining the considerable performance differences between precision and combined event shooting. It also presents modern pentathletes with the decision over what degree of accuracy should be compromised in favour of speed. It is important to recognise that the relationship between speed and accuracy has been reported to change with experience (Elliott, Hansen, & Mendoza, 2004). Aiming tasks are generally assumed to have two components; an initial high velocity movement to move towards the target, and a second set of corrective submovements which control the exact positioning on the target (Helsen, Elliott, Starkes, & Ricker, 2000). When learning a task, an individual tends to undershoot a target and require a greater number of submovements. As they become more rehearsed the initial movement tends to end closer to the target, and the corrective process appear to become quicker. Thus, once athletes become more accustomed to the combined event, it should be possible for participants to shoot more quickly than the times reported here and still achieve sufficient accuracy.

An additional consequence of the increased emphasis on speed of shooting in the combined event is a potential change in shooting technique. Typically, precision shooters use a technique of aiming high and moving the pistol down onto the target. However, overshooting a target increases the length of time required for a movement. Additional movement is required, as to correct an overshoot more distance must be covered to reach the target, and the limb must overcome the zero inertia associated with the turning point to move the pistol back down onto the target (Elliott et al., 2004). With the introduction of the combined event, and the need to shoot at greater speeds, many athletes may now favour a technique of aiming below, and moving the aim point up on to the target. Research is yet to consider the change in aiming technique, and evidence is currently anecdotal. Nevertheless, a change in technique may go some way to explaining why the pistol shooters, who were the most successful precision shooters in this study, were not the most successful combined event athletes.

The relationship between speed and accuracy is widely reported, and so the difference in scores achieved between the two shooting events was unsurprising. The significant decrease in aiming time under combined event conditions can also explain the significant increase in centre of pressure movements. Era et al. (1996) reported that elite precision shooters significantly reduced the speed and magnitude of body sway during the final 1.5 s prior to a shot. The considerably shorter time spent aiming in the combined event now means that there is less time available to reduce these movements. This was particularly evident for pistol shooters, who produced a median aiming time of 1.4 s, demonstrating that they spent less time aiming at the target than they would normally spend just on reducing body sway when shooting in the precision event.

Pistol shooters were significantly more successful than modern pentathletes under precision conditions, but there were no clear performance differences between groups when shooting in the combined event. This demonstrates a considerable change to the shooting event in modern pentathlon, with the implication that an athlete who was previously successful at precision shooting is not guaranteed success in the combined event without specific training. It is important to acknowledge that the differences in performance may also be related to participants’ experience in each event. All pistol shooters had taken part in precision shooting for a longer period of time than the modern pentathletes, whereas neither group had any prior experience of shooting in the combined event.

Future research should consider similar performance comparisons once athletes have become more familiar with combined event shooting. This would establish whether the ability demonstrated in precision shooting also becomes apparent in the combined event following training. Additional associations between score and kinematic variables may also become apparent with greater experience. Research could also establish the differences in performance between combined event shooters of different abilities. This has already been achieved for precision shooting (Ball et al., 2003; Mason et al., 1990), and could provide an indication of the performance characteristics that modern pentathletes must aim to achieve in order to be successful.

5.5 Conclusion

This study attempted to identify the performance implications of the introduction of the combined event to modern pentathlon. Intra-individual correlations highlighted that whilst pistol movements and body sway can both influence shot score, the strength of each association can vary between individuals. Both the magnitude and direction of each correlation varied between precision and combined event shooting, clearly emphasising the different performance requirements for the two events. This is further supported by the absence of any significant difference when comparing the performances of modern pentathletes and pistol shooters under combined event conditions. Ability in precision shooting does not guarantee a similar level of success when shooting in the combined event. This has important implications, as athletes who were successful under the old rules must now find ways to adapt to the new demands of combined event shooting in order to remain successful in modern pentathlon.

Chapter Six

Research Study 2 - The Effect of Time Constraints on Combined Event Pistol Shooting Performance

Published in modified format as:

Dadswell, C.E., Payton, C., Holmes, P. and Burden, A. (2015). The effect of time constraints and running phases on combined event pistol shooting performance. *Journal of Sports Sciences, 16*, 1 – 7.

6.1 Introduction

The first study compared the performance requirements of precision and combined event shooting to identify whether the skills acquired in the original shooting event would transfer to those required for the combined event. This analysis, whilst providing a clear comparison between the two events, did not evaluate any changes in performance within each 70 s shooting series. This is an important consideration, given the increased time pressures which are placed on athletes when shooting in the combined event in comparison to the relatively time-unlimited environment of precision shooting. This chapter examines how performance varies within each series, with particular consideration given to whether performance alters as the time remaining to achieve five hits on target diminishes.

The effect of imposing time constraints on accuracy-based tasks has already been examined (Berrigan et al., 2006; Fernandez & Bootsma, 2004; Fitts, 1954; Schmidt et al., 1978). The consensus is that faster movements are accompanied by a reduction in accuracy, indicating that if athletes attempt to shoot more quickly as the time remaining within a series diminishes, they may become less accurate and achieve fewer hits on target. Much of this research has examined performance during pointing tasks, which do not demand the same degree of accuracy as pistol shooting. Thus, the findings cannot be directly applied to the combined event, but can still indicate how shooting performances may be affected by the greater speeds at which modern pentathletes may choose to shoot.

Findings from Study 1 demonstrate that modern pentathletes must now shoot with a significantly reduced aiming time in comparison to the previous rules. Research suggested that the faster an athlete shoots, the less accurate the performance, but the current findings give no indication as to how fast movements can be before accuracy is compromised. Furthermore, whilst previous studies have analysed accuracy, there are crucial differences between pointing tasks and pistol shooting. Research is required to identify how the time spent aiming can specifically affect a combined event shooting performance. Study 2 will examine the extent to which aiming time varies within each series of the combined event, and whether the difference between the quickest and the slowest shots is enough to affect the degree of accuracy. Study 1 provided clear evidence that the variables most influential to shooting performance in series one vary between participants. This study will examine whether these individual aspects of performance are continued through series two and three. The specific objectives of this study are to:

(i) identify how heart rate, shot score, aiming time, pistol movements, and centre of pressure movement change within each shooting series; and
(ii) identify the kinematic variables most closely associated with shooting performance within each of the three shooting series.

To achieve the first objective, each variable is compared between the first six shots within each series. Any significant differences indicate adaptations in performance as the time remaining to achieve five hits diminishes. To achieve the second objective, correlations are performed between each variable to identify the variables significantly associated with shot score. The hypotheses to accompany each of these objectives are:

(i) as the time remaining within a series diminished, shot score and aiming time will reduce significantly, and pistol movements and body sway will increase significantly; and

(ii) the variables with significant correlations with shot score will vary between participants for all three series.

6.2 Methods

6.2.1 Participants

The participants whose performance was analysed for Study 1 were also used for this study. This included the first modern pentathlon group and the pistol shooter group. Additional participants from the second modern pentathlon group identified in the General Methods chapter (Chapter 4, section 4.1) were incorporated into the analysis. In Study 1, neither accuracy nor pistol or centre of pressure movement differed significantly between the modern pentathletes and pistol shooters, and so data were analysed as one group for all participants.

6.2.2 Tasks

Each participant completed a combined event task designed to replicate competition conditions, the full format of which is detailed in the General Methods chapter (Chapter 4, section 4.2). Data from all three shooting series were analysed to identify any performance changes within each series. Activio heart rate monitors were used to demonstrate how heart rate varied between the beginning and end of each series. Aiming time, shot score and pistol movement data were all obtained from the SCATT optoelectronic shooting system (Chapter 2, section 2.2). Centre of pressure range and path length data were recorded using the AMTI force platform (Chapter 2, section 2.3). Definitions of each variable are in the General Methods chapter (Chapter 4, section 4.4).

6.2.3 Data Analysis

Each shooting series was analysed separately, to compare how each variable changed between the beginning and the end of a series. The format of the combined event allows athletes to take an unlimited number of shots in their attempts to achieve five hits within the 70 s time limit. As such, participants took a varied number of shots within each series (Series one: 5 – 11 shots; Series two: 6 – 11 shots; Series three: 6 - 11 shots). Statistical analysis was therefore based on the first six shots in each series to ensure that data were appropriate for group comparisons. In addition to group statistical analysis, data from selected participants were plotted to determine how closely the group median reflected individual performances, and whether this varied between the participants who required fewer than, or greater than, the six shots used for group analysis.

Due to small sample sizes, data were found to violate the assumptions of parametric tests. The Kolmogorov-Smirnov test reported that data differed significantly from a normal distribution, and Levene's test revealed heterogeneity of variance. Thus, non-parametric statistical tests were selected for intra-series comparisons of group medians for each dependent variable. Wilcoxon tests compared maximum and minimum heart rate within each series, and Friedman's ANOVA tests were used to identify any significant changes in aiming time, shot score, pistol movements and centre of pressure movements between the first six shots within each series. One participant who required only 5 shots in series one was excluded from group analysis to ensure that the data used for each shot was produced from the same group. For all comparisons, $p<.05$ was considered statistically significant. Wilcoxon Tests using Bonferroni corrections were used for post hoc analysis of any significant results, with $p<.016$ considered statistically significant.

In addition to identifying changes in performance within each series, Spearman's Rank Correlation Coefficients were used to identify any significant associations between shot score, aiming time, and pistol and centre of pressure movements. In Study 1 the variables that were significantly correlated with score differed between participants, and so both group and intra-individual correlations were used. Due to the high number of correlations between score and the six kinematic variables, Bonferroni corrections were used, and $p<.007$ considered statistically significant.

6.3 Results

6.3.1 Heart Rate

Each participant experienced similar heart rate patterns throughout the event (Figure 6.1), which increased during each 1 km run phase then significantly decreased within each shooting series (*p*<.05) (Table 6.1). In series one, heart rate increased at the beginning of a series, and decreased towards the end. In series two and three maximum heart rate occurred at the start of a series, and minimum heart rate was recorded at the end, immediately prior to beginning the next running phase.

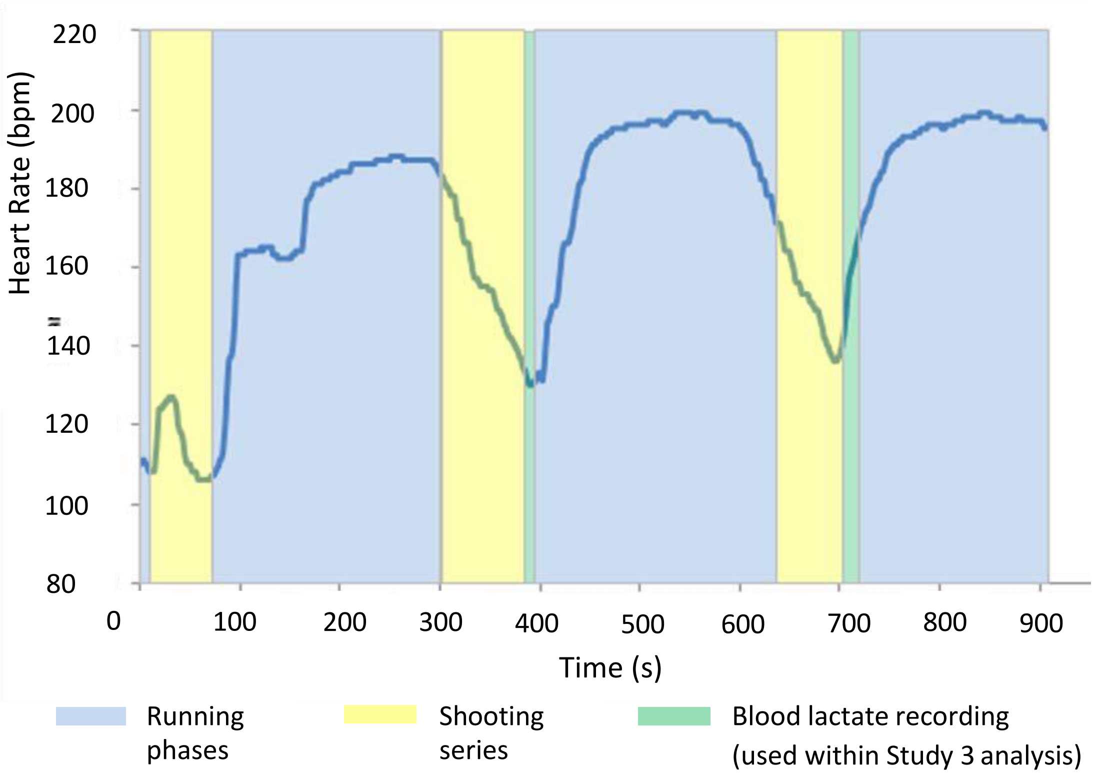


Figure 6.1. Heart rate from one participant throughout the combined event. This pattern is representative of the heart rate pattern for all participants.

Table 6.1. Intra-series comparisons of group median heart rate within each shooting series (IQR in brackets).

		Series 1	**Series 2**	**Series 3**
Heart Rate (bpm)	Minimum	112 (±39)	153 (±28)	150 (±25)
	Maximum	142 (±15)	181 (±13)	185 (±9)
	T	0 ($p<.001$)	0 ($p<.001$)	0 ($p<.001$)

6.3.2 Shot Score, Temporal and Kinematic Variables

Shot score, aiming time, pistol movements and centre of pressure movements were each compared between the first six shots within each shooting series. Results of these comparisons are presented in Table 6.2.

Table 6.2. Comparisons between the first six shots within each shooting series for all dependent variables.

	Series 1		**Series 2**		**Series 3**	
Dependent Variable	χ^2	p value	χ^2	p value	χ^2	p value
Score	7.61	0.268	3.83	0.574	9.59	0.088
Aiming Time	4.95	0.422	2.12	0.833	9.53	0.09
Pistol Movement						
Horizontal Trace Length	0.76	0.985	4.57	0.495	1.62	0.917
Vertical Trace Length	4.47	0.513	2.19	0.848	0.67	0.990
Centre of Pressure Movement						
Mediolateral Range	6.51	0.260	5.07	0.408	3.81	0.577
Anterior-posterior Range	1.74	0.884	5.02	0.413	5.75	0.331
Mediolateral Path Length	3.09	0.685	4.37	0.498	5.06	0.409
Anterior-Posterior Path Length	5.39	0.370	3.59	0.610	8.75	0.119

Median aiming time did not change significantly within any of the three shooting series (Table 6.2). The difference between the shortest and longest time spent aiming was 0.3 s, 0. 5 s, and 0.4 s for series one, two, and three respectively (Figure 6.2). Each shot was completed within 0.9 s - 1.5 s (Figure 6.2), and in series three, whilst not significant, there was a progressive decrease in median shot time between shot 1 (1.3 s) and shot 4 (0.9 s). Although the group median indicated little change within any series, individual data showed greater changes, with up to 4.3 s between the longest and shortest aiming time for individual participants.

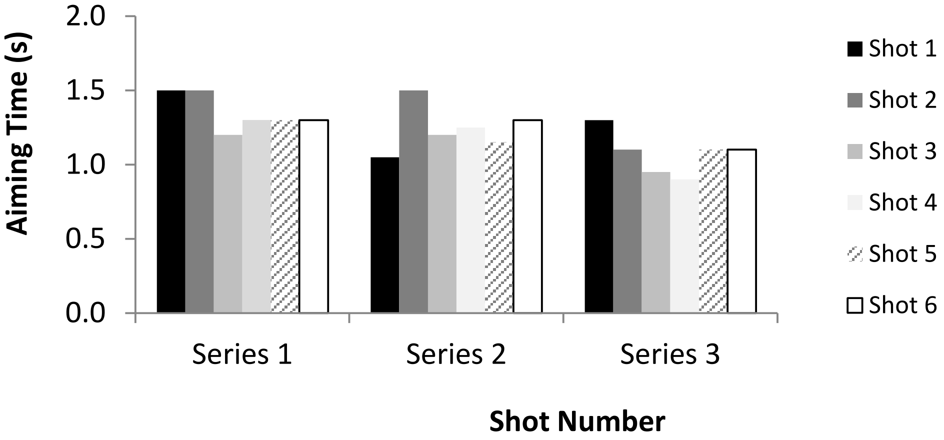


Figure 6.2. Median aiming time for shooting series 1, 2, and 3.
IQR shots 1 - 6: Series 1 (1.5; 1.2; 0.4; 1.4; 1.1; 0.8)
2 (1.1; 0.8; 0.9; 1.1; 0.5; 1.4)
3 (1.2; 0.9; 0.8; 0.7; 1.5; 1.6)

No significant changes in shot score were recorded within any of the three shooting series (Table 6.2), and there was no evidence of a pattern towards decreasing scores as the series progressed (Figure 6.3). This was particularly evident in series three where, despite the progressive decrease in aiming time between shots 1 and 4, there was no corresponding decline in the scores achieved. Instead, score fluctuated between successive shots, with a range of 1.7, 1.1 and 2.6 points for series one, two, and three respectively. No series had median scores consistently above 7.0; the score that represents a hit on the target.

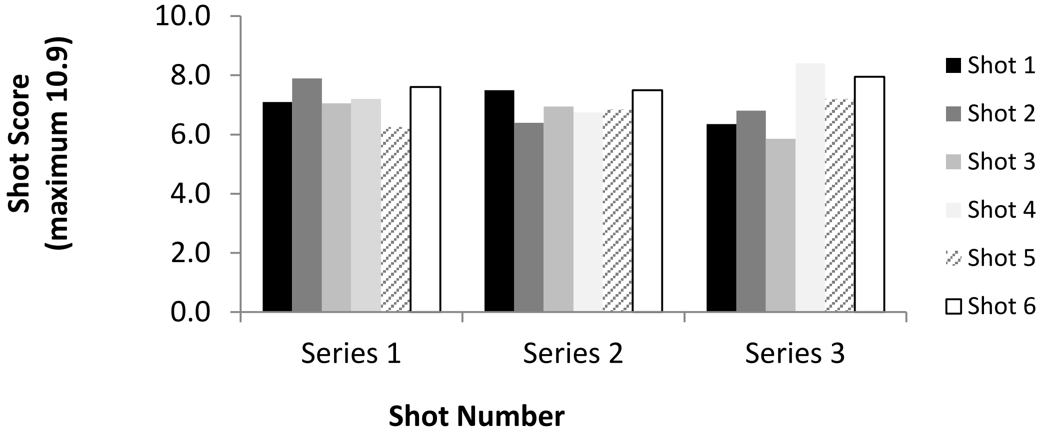


Figure 6.3. Median shot scores achieved for shooting series 1, 2 and 3.
IQR shots 1 - 6: Series 1 (1.1; 4.5; 2.9; 2.7; 4.1; 3.2)
2 (3.1; 3.2; 3.6; 4.2; 3.1; 3.9)
3 (3.1; 2.9; 3.7; 3.1; 2.8; 2.5)

Neither horizontal nor vertical pistol movement changed significantly within any series (Table 6.2). Whilst non-significant, both movement components varied greatly between shots. Horizontal pistol movement range was 30.7 mm, 59.9 mm, and

56.7 mm within series one, two, and three respectively (Figure 6.4a). More variation was evident for vertical pistol movements, with a range of 50.6, 80.3 and 57.6 mm in each successive series (Figure 6.4b).

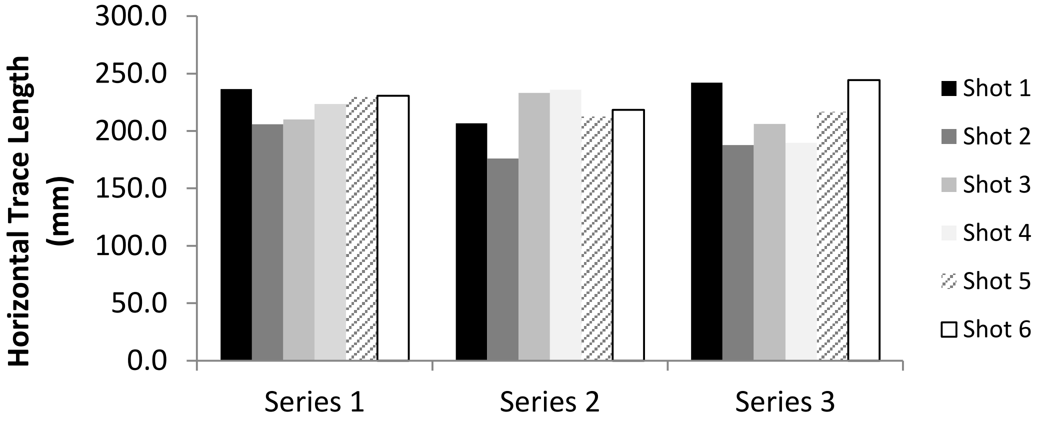


Figure 6.4a. Median horizontal pistol movement in shooting series 1, 2, and 3.
IQR shots 1 - 6: Series 1 (176.3; 173.1; 123.1; 157.8; 172.3; 117.8)
2 (151.5; 340.9; 199.9; 168.2; 177.3; 78.4)
3 (135.0; 36.9; 120.7; 118.0; 198.8; 127.6)

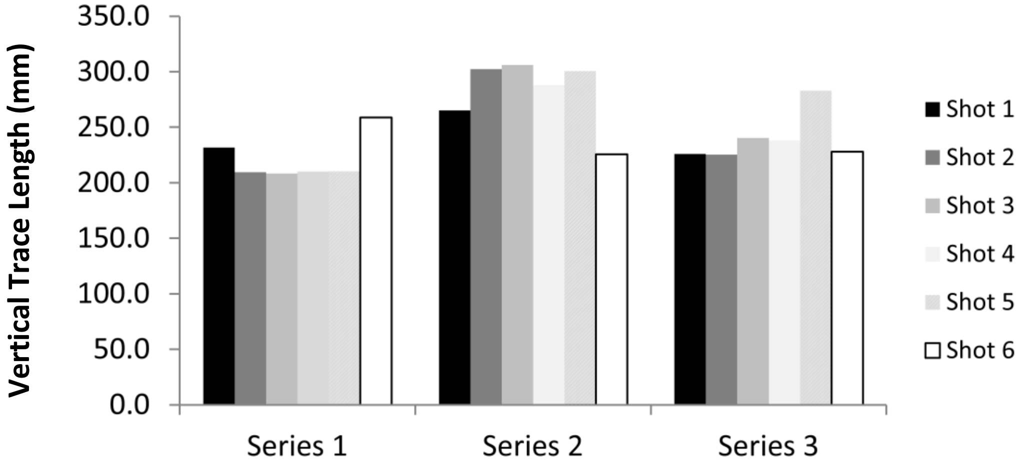


Figure 6.4b. Median vertical pistol movement in shooting series 1, 2, and 3.
IQR shots 1 -6: Series 1 (84.9; 61.1; 78.1; 120.3; 126.3; 95.5)
2 (131.6; 161.5; 188.8; 183.0; 217.9; 121.3)
3 (139.2; 36.9; 120.7; 118.0; 198.8; 127.6)

Neither centre of pressure range nor path length changed significantly between shots for either anterior-posterior or mediolateral movements (Table 6.2). Although non-significant, both movement components varied within each series (Figures 6.5a and 6.5b). The greatest mediolateral movement was produced at the end of each series, with a range of 2.3, 2.0 and 2.2 mm within each successive series (Figure 6.5a). Greater variation was evident for anterior-posterior movement, of 1.9, 4.7 and 3.7 mm, although no patterns were evident for when the greatest or smallest movements were produced.

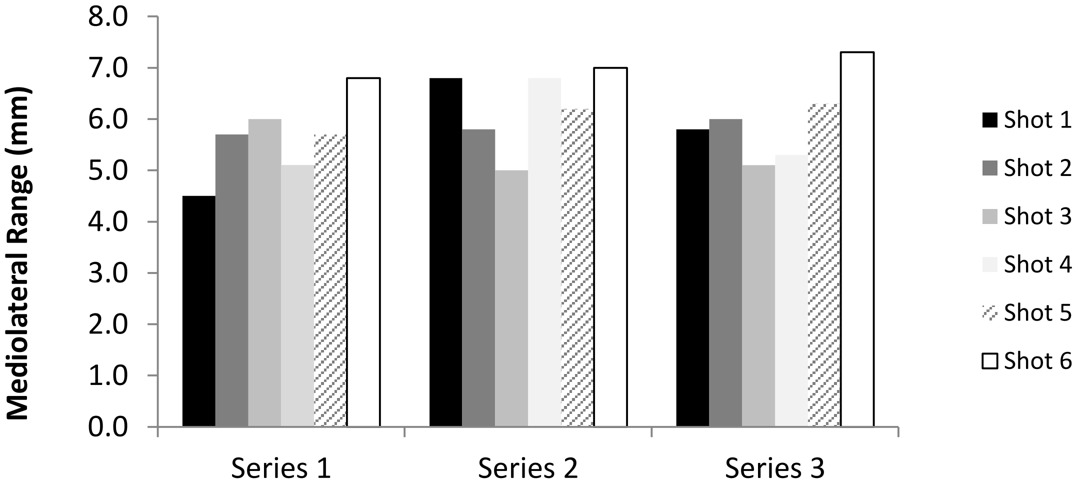


Figure 6.5a. Median mediolateral range for shooting series 1, 2, and 3.
IQR shots 1 - 6: Series 1 (4.8; 3.8; 3.8; 2.7; 5.1; 3.8)
2 (4.2; 7.5; 4.2; 5.6; 6.5; 7.8)
3 (1.2; 3.4; 3.4; 3.3; 5.5; 6.7)

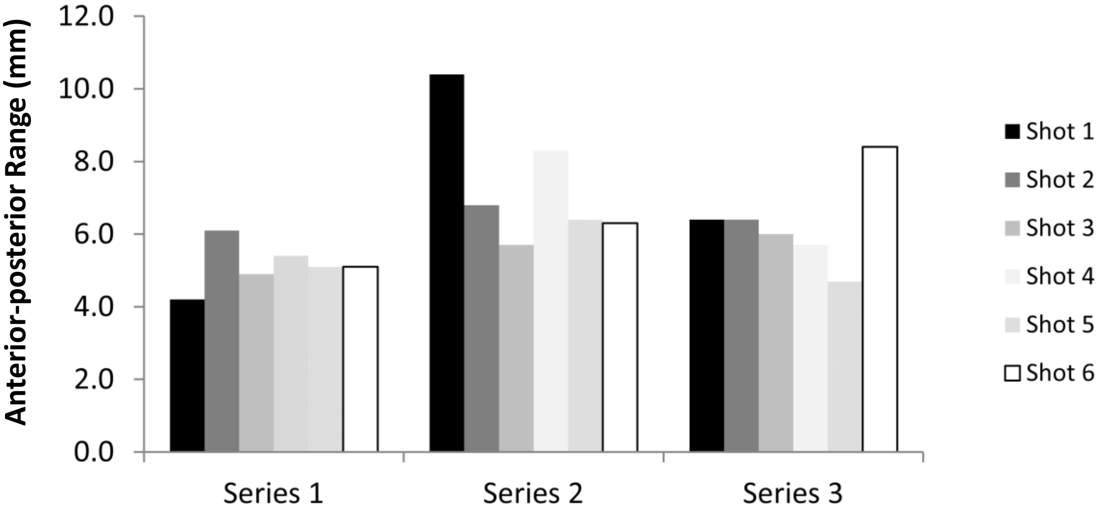


Figure 6.5b. Median anterior-posterior range for shooting series 1, 2, and 3.

IQR shots 1 - 6: Series 1 (4.5; 8.2; 5.2; 2.9; 4.6; 3.5)
2 (5.2; 5.2; 5.5; 7.0; 5.8; 3.3)
3 (9.7; 6.0; 4.2; 4.1; 3.7; 6.0)

Mediolateral path length in series one also showed variation within each series, and was more variable in series two and three (Figure 6.6a). The range in path length within a series was greater for mediolateral movements (7.9 mm, 15.6 mm, and 11.9 mm) than anterior-posterior movements (3.2 mm, 5.9 mm, and 5.0 mm) (Figure 6.6b) for all series.

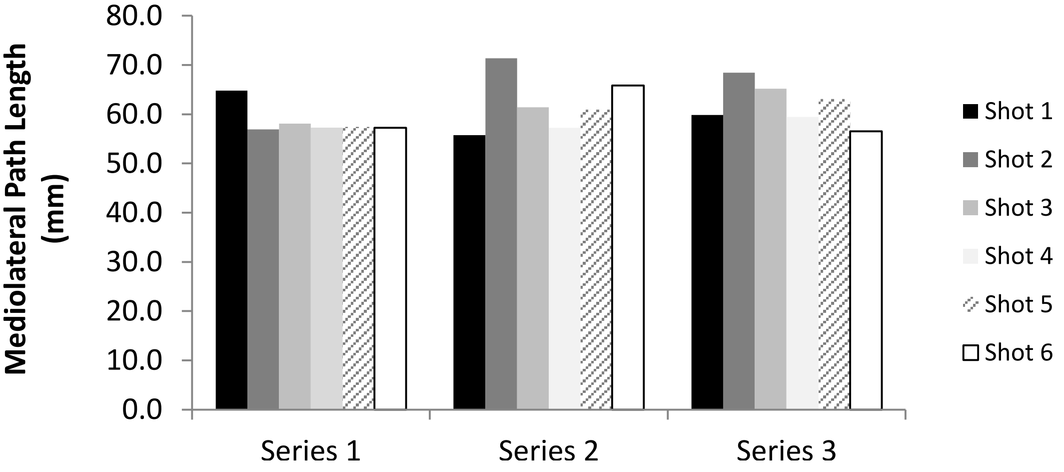


Figure 6.6a. Median mediolateral path length for shooting series 1, 2, and 3.

IQR shots 1 - 6: Series 1 (30.3; 15.9; 22.0; 28.2; 22.2; 19.9)
2 (23.9; 40.9; 19.1; 21.7; 48.6; 38.3)
3 (33.7; 26.0; 25.6; 29.0; 13.7; 24.9)

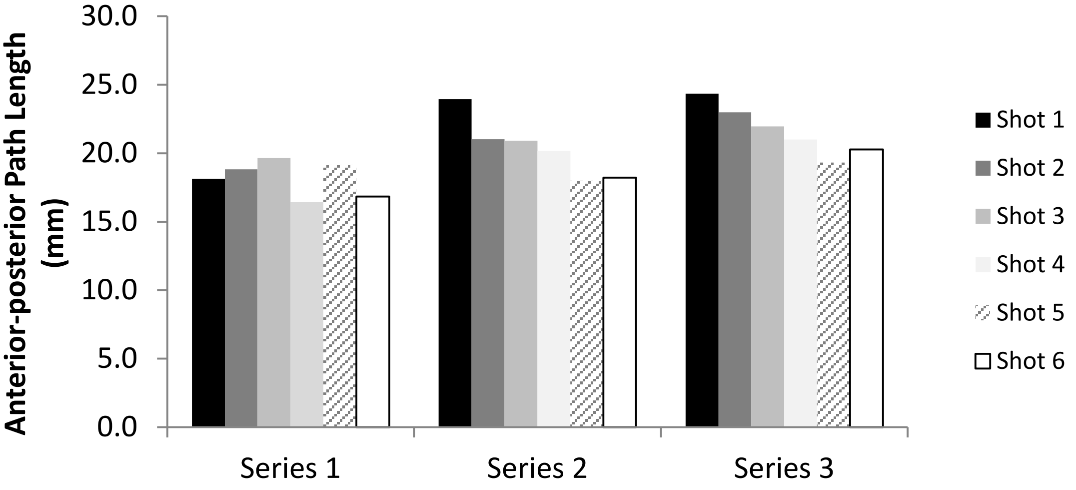


Figure 6.6b. Median anterior-posterior path length for shooting series 1, 2, and 3. IQR shots 1 -6: Series 1 (9.5; 7.3; 8.0; 8.9; 4.8; 5.3)
2 (12.8; 7.1; 7.9; 11.8; 13.1; 12.6)
3 (17.4; 12.0; 7.8; 10.6; 10.7; 8.8)

Participant 1 (Shots in each series: 5; 6; 11)

Series 1, 2 and 3 were each completed before the 70 s time limit, in 26 s, 28 s and 68 s respectively. Aiming times for this participant varied considerably between shots, ranging from 0.7 to 3.8 s (Appendix 2.1a). This variability was greater than that recorded for the group median, even in series one where this participant was most successful. Shot scores also varied more than indicated by the median, and were higher than the group value for series two and three. Pistol movements were more varied, and mostly greater than the median for series one and three, but were similar to the median in series two. Some differences were also evident for centre of pressure movements (Appendix 2.1b), such as mediolateral range which showed little resemblance to the group median in series two. Path length results were more aligned to the group result than any other variable.

6.3.3.1 Participant 5 (Shots in each series: 7; 6; 6)

Each series was completed within the 70 s limit, in 56 s, 49 s and 47 s for series 1, 2 and 3 respectively. Aiming times and shot scores in each series were more aligned to the group median than those recorded for participant 1 (Appendix

2.2a). The time spent aiming was also less variable, ranging between just 0.3 and 1.0 s for series two. Greater differences were evident between pistol movements and the median, particularly for horizontal pistol movements in series one and two, and vertical movements in series one and three. Centre of pressure movements were often similar to the group result (Appendix 2.2b), particularly for mediolateral and anterior-posterior range, for which only one shot in each series deviated greatly from the median. Mediolateral path length was similar to the median in series two and three, whilst anterior-posterior path length was consistently greater than the group result.

6.3.3.2 Participant 14 (Shots in each series: 11; 11; 11)

Participant 14 did not achieve five hits in any of the three series, and so each series lasted the full 70 s. Aiming times varied more between shots than the group median, particularly during series one and two (Appendix 2.3a). Score varied greatly between shots, particularly in series two, where scores ranged between 0.0 and 8.1 points. Pistol movement was consistently greater than the median, and centre of pressure movements were all more variable than the median (Appendix 2.3b).

Intra-individual performance comparisons clearly demonstrate differences between the group median and individual participant performances. An important finding is that none of the three participants produced the expected changes in score alongside changes in aiming time, such as reduced scores with shorter aiming times. As such, the group data does reflect individual performance to some extent, but cannot fully reflect all unique aspects of a performance.

6.3.4 Correlations with Shot Score

When correlations were performed using group data, no variables were significantly associated with score in any series (*p*>.007). Thus, all further analysis centred on intra-individual correlations. Few participants demonstrated significant correlations between kinematic variables and score. Aiming time produced a significant positive correlation with score for one participant in series one

(Participant 3: *r* .778, *p*<.007), whilst another participant experienced a significant negative correlation between the same variables in series two (Participant 9: *r* -.882, *p*<.007). Two other participants presented significant negative correlations between score and horizontal trace length in series three (Participant 8: *r* -.970, *p*<.007; Participant 10: *r* -.753, *p*<.007). Each variable accounted for between 57% and 88% of the changes in score, but no other participants demonstrated any significant correlations. No centre of pressure variables produced any significant associations with score.

6.3.5 Correlations between Pistol and Centre of Pressure Movements

Only four participants were identified with significant correlations between pistol and centre of pressure movements in any series (Table 6.3). One (participant 3) produced a positive correlation between horizontal pistol movement and anterior-posterior path length in series one. Two participants (5 and 16) experienced significant correlations within series one and three. For participant 5, vertical pistol movements were significantly associated with anterior-posterior range in series one, and with mediolateral range in series three. For participant 16, significant correlations were between vertical pistol movements and anterior-posterior range in series one, and between vertical pistol movements and both mediolateral and anterior-posterior range in series three. Anterior-posterior movement was more commonly associated with changes in pistol movement, and although the correlations reported were high, accounting for between 49% and 97% of the variation in pistol movement, correlations only achieved significance for a few participants (3, 5, 16 and 14).

Table 6.3. Significant intra-individual correlations between pistol and centre of pressure movements for each series (*p*<.013). R^2 values are included in brackets.

Series	Pistol Movement	Participant	Mediolateral	Anterior-posterior	
			Range	Range	Path Length
1	Vertical	5		-.886 (0.78)	
		16		-.838 (0.70)	
	Horizontal	3			..929 (0.86)
3	Vertical	5	.986 (0.97)		
		16	-.800 (0.64)	-.767 (0.59)	
	Horizontal	14			.700 (0.49)

6.4 Discussion

The first objective of this study was to identify any changes in shooting performance within each series as the time remaining to achieve five hits gradually diminished. To achieve this objective, shot score, aiming time and pistol and centre of pressure movements were compared between the first six shots within every shooting series.

The first hypothesis, that scores would reduce, and pistol and centre of pressure movement would increase as the time remaining in a series diminished, was rejected. The time remaining to complete a series appeared to have little impact on shooting performance, with no significant changes in either aiming time, score, pistol movement or centre of pressure movement within any series. This was particularly evident from the individual analysis (Figures 6.7a - 6.9b) as some participants' performances varied between successive shots, with no predictable change between the start and end of a series. This first hypothesis was based on the assumption that as the time remaining to achieve five hits reduced, participants would shoot more quickly, thereby reducing aiming time and leaving less time to complete any aiming routines. Elite shooters reduce the amount of movement over the final second before a shot (Era et al., 1996), and so it was expected that decreased aiming times within a series would leave less time for reductions in pistol and centre of pressure movement to take place. However, with no evidence of decreased aiming time, the participants in the current study were able to reduce pistol and centre of pressure movements to a comparable degree for every shot. This was unsurprising for some participants, such as participant 1, who required less than 30 s to complete a series. With considerable time remaining in each series, this participant would not be expected to demonstrate great changes in aiming times. Others, such as participant 5 who completed each series in 47 s – 56 s and participant 14 who required the full 70 s for each series, were expected to show a greater change in aiming time as the pressure to complete a series increased. However, intra-individual analysis demonstrated that the anticipated reduction in aiming time was not apparent even for those participants who were shooting until the series time limit. Consistent aiming times also meant that there were no negative effects of the speed-accuracy trade-off, as discussed in Study 1.

Shooting performance did not appear to be greatly affected by the significant changes in heart rate within each shooting series. In series 2 and 3 this potentially reflects the effect of exercise on anxiety. Nibbeling et al. (2014) stated that exercise can counteract the negative effects of anxiety on performance, indicating that the high heart rates recorded at the beginning of each shooting series would not necessarily hinder shooting performance. A different heart rate pattern was evident in series one, where heart rate increased during the beginning of the series. Oudejans and Pijpers (2010) stated that an increase in heart rate can potentially reflect a response to anxiety. According to attentional control theory, anxiety can result in a change in attention (Eysenck et al., 2007) which can potentially be detrimental to performance. Consequently, future research should examine the specific effects of each exercise phase on performance by comparing shooting performances between each of the three shooting series.

The second objective of this study was to determine which kinematic variables are most closely associated with shot score, thereby identifying the variables that athletes must consider when training for the combined event. Few significant associations were identified with score for any series and, as such, no variables were identified as a key influence to combined event shooting success. In addition to limited correlations with score, few correlations between the movements of the pistol and centre of pressure achieved significance. This provides further support to the findings of Study 1 that there must be other performance variables not considered here, such as body movement and the location of the aim point on the target, which must also influence performance. This also supports findings from previous research (Arutyunyan et al., 1968; Ball et al., 2003; Mason et al., 1990; Pellegrini & Schena, 2005; Tang et al., 2008).

Findings meant the second hypothesis, that the variables associated with score would differ between participants, was accepted. For instance, participants 5 and 16 both produced significant correlations between vertical pistol movement and mediolateral centre of pressure range in series three. An increase in centre of pressure movement was accompanied by an increase in pistol movement for participant 5, but a decrease in pistol movement for participant 16. Thus, whilst participant 5 experienced greater pistol movement when body sway increased, participant 16 appears to counteract this increase in sway by reducing the amount of pistol movement. These unique aspects of performance are masked by the use of group analysis, and could be important to individuals. Understanding these individual performance traits could be particularly important for the less successful participants, for whom understanding how their performances differ from the better participants could provide crucial information in the ways in which they can improve. The individual nature of shooting was further demonstrated by the performances of the four participants selected as case studies. The changes in each variable within each series differed between participants, even when two participants completed a series in the same number of shots. This further supports the conclusions of both Study 1 and previous research (Ball et al., 2003; Mason et al., 1990) that pistol shooting performance varies considerably between individuals. Thus, the importance of using individual analysis when investigating pistol shooting performance is clear.

Individual analysis has highlighted how one variable can greatly influence performance for one participant, but have either no effect, or the reverse effect, for others. It is clear that simply promoting one technique as a method of enhancing combined event performance would provide few benefits to the majority of modern pentathletes. This supports the findings of Chow et al. (2011), Davids et al. (2003) and Langdown et al. (2012), who suggest that athletes must develop their own technique to create a successful performance, rather than recreate the movement strategies of others. Furthermore, whilst aiming time, pistol, and centre of pressure movements were not strongly correlated with score for most participants, consistency of technique could be as important as the magnitude of movement. This is particularly apparent in Figures 6.8a, where the pistol movement for participant 5, who required only 6 or 7 shots to complete each series, was less variable between shots than for participant 1, who required between 5 and 11 shots for each series, and participant 14 who took 11 shots in every series. Thus, consistency of performance may be influential to shooting success. Further research should consider whether a more consistent performance could help enhance success when shooting.

This study revealed the limited effect of time pressures on shooting in the combined event, but it should be acknowledged that there were some limitations. Whilst all participants had experience in pistol shooting, some had no prior experience of shooting in the combined event format. Potentially with further experience, an athlete's performance could change, including their response to the time restrictions associated with combined event shooting. However, although not reported here, results for only those participants with experience of the combined event were also considered. No variable changed significantly within any series, supporting the findings for all participants. An additional consideration should be the success of other athletes during competition, something which could have a considerable impact in the combined event. The testing format required participants to shoot whilst standing on force plates, meaning that each participant had to complete the trial individually, albeit with a large audience that included the experimenters, coaches and other participants. All other technical aspects of the event were identical to those in competition, but future research in which participants compete alongside other athletes would be useful to investigate direct competition effects. A final consideration is the format of the shooting series, which means that whilst some participants took up to 11 shots to complete a series, most only required between six and eight. Thus, only six shots were used for analysis. Future research in which participants take a greater number of shots using the combined event shooting format could increase the likelihood of uncovering correlations between different variables. This would further enhance the understanding of the factors most critical to combined event shooting success. This would, however, require consideration of an appropriate method in which to maintain validity.

6.5 Conclusion

Shooting performance did not change significantly between the first six shots within any shooting series. The consistent aiming times produced throughout a series meant that participants could produce a similar degree of pistol and centre of pressure movement, and achieve similar shot scores, for every shot. Few significant correlations were identified between score, pistol movement and centre of pressure, and the few correlations that achieved significance varied between participants. Thus, intra-individual analysis is essential when developing methods of enhancing performance for modern pentathletes. Future research is now recommended to investigate additional factors affecting combined event shooting, and to determine the speed at which modern pentathletes can shoot before accuracy is compromised. Understanding this trade-off between speed and accuracy will help to reduce the amount of time spent in each shooting series.

Chapter Seven

Research Study 3 - The Effect of Running Phases on Combined Event Pistol Shooting Performance

7.1 Introduction

Studies 1 and 2 considered two important issues related to combined event pistol shooting; the change in performance requirements in comparison to the previous precision shooting format, and the effect of the time restrictions associated with each 70 s shooting series. An additional issue, which provides a clear distinction between the combined event and other pistol shooting formats, is the 1 km running phases between each shooting series. Given that biathlon is the only other sport with these specific requirements, there is currently little information available to modern pentathletes concerning how their shooting performances may change in the second and third shooting series.

Whilst limited research has considered the effect of exercise on shooting performance, a greater deal of consideration has been given to the effect of fatigue on centre of pressure movements. Nardone et al. (1997), and Bove et al. (2007) both reported that centre of pressure movement during quiet stance significantly increased following fatiguing treadmill and cycling exercise ($p<.05$). Thus, exercise clearly has the potential to affect body sway in the combined event. Bove et al. also indicated that centre of pressure movements remain significantly greater than baseline values for up to six minutes post-exercise. As each combined event shooting series lasts a maximum of 70 s, these findings indicate that modern pentathletes may have to develop the skills to shoot with significantly increased centre of pressure movements for the duration of series two and three. However, the tasks used to induce fatigue and the quiet stance tasks are different to the running phases and shooting series that are completed in the combined event. Research needs to identify whether the combined event running phases produce a similar effect on centre of pressure movement, and how this may influence shooting success.

Some research has considered performance in biathlon (Hoffman et al., 1992; Niinimaa & McAvoy, 1983), which is of a similar format to the combined event, with shooting series interspersed by bouts of exercise. Niinimaa and McAvoy reported that mediolateral and anterior-posterior path length significantly increased following exercise ($p<.05$), providing further support to the notion that modern pentathletes may experience increased body sway when shooting in series two and three of the combined event. Hoffman et al. (1992) reported that shot score significantly reduced and shot dispersion and rifle movements significantly increased following exercise ($p<.05$). Given that biathlon is based on rifle shooting, a similar effect of exercise on combined event shooting performance is not guaranteed. Thus, research must investigate the specific effects of exercise on combined event performance.

Study 1 considered the effect of biomechanical variables on shooting performance in the first series of the combined event. The effects of each running phase on performance in each of the three shooting series has yet to be examined. Therefore, the specific objectives of this study are to:

(i) identify any changes in score, aiming time, pistol movement and centre of pressure movement between each shooting series; and

(ii) identify whether the variables most closely associated with performance differ between each shooting series.

In order to achieve the first objective, median shot score, aiming time, pistol movements and centre of pressure movement are compared between each shooting series. Comparisons are made for both group median data and individual participant data. The second objective is based on the outcome of the correlations presented in Study 2. Any participants who produced significant correlations in more than one series will be selected, and comparisons made between the variables that are most strongly associated with score and pistol movement.

There are two hypotheses to accompany these objectives:

(i) shot score will decrease significantly, and pistol movements and body sway will increase significantly with each successive shooting series; and

(ii) the variables associated with performance will differ between each successive shooting series.

7.2 Methods

7.2.1 Participants

The performances of the same nineteen participants who took part in Study 2 were analysed, comprising those from the first modern pentathlon group, second modern pentathlon group and the pistol shooter group (Chapter 4, section 4.1). With the exception of the blood lactate values recorded following the third shooting series, there were no significant differences between the three groups for any of the physiological, temporal or kinematic variables in any series ($p>.05$). Consequently, in accordance with Study 2, data were analysed as one group for all participants.

7.2.2 Tasks

The order of events undertaken by each participant were as detailed in the General Introduction (Chapter 4, section 4.2), with data from all three shooting series used for analysis. Data were derived from the same trials as those used for Study 2, where participants ran 20 m, then completed alternating 70 s shooting series and 1 km running phases. Participants were instructed to complete each running phase at a pace similar to that which they would use in competition.

7.2.3 Data Analysis

Score, aiming time, and pistol and centre of pressure movement was compared between each of the three shooting series. Additional comparisons were made for any participant who was identified in Study 2 with significant correlations between variables in more than one series. These comparisons were used to identify any changes in the variables which had the strongest associations either with score or pistol movement. Aiming time, shot score and pistol movement were obtained from the SCATT optoelectronic shooting system, and centre of pressure range and path length were recorded from the AMTI force platform. Explanations of how each variable was recorded are in the General Methods chapter (Chapter 4, section 4.4).

Heart rate was recorded throughout each trial, using an Activio Sport System wireless heart rate monitor. This demonstrated how heart rate changed between each running and shooting series. Three fingertip blood lactate samples were obtained, one at the beginning of the event, and two others immediately following completion of the second and third shooting series. Blood lactate concentration was used to indicate the reliance on anaerobic metabolism throughout the event. Each sample was taken from the 5th digit of the loading hand, and analysed using a YSI 1500 SPORT Lactate Analyzer.

Due to small sample sizes, data were found to violate the assumptions of parametric tests. The Kolmogorov-Smirnov test reported that data differed significantly from a normal distribution, and Levene's test revealed heterogeneity of variance. Non-parametric statistical tests were therefore used for the inter-series comparisons of group medians for each dependent variable. Wilcoxon tests were used for the comparison of maximum and minimum heart rate within each series, and Friedman's ANOVA was used to compare median group aiming time, shot score, pistol movement, and centre of pressure movement between each series. For all comparisons, any value below $p<.05$ was considered statistically significant.

7.3 Results

Both heart rate and blood lactate changed significantly throughout the combined event. Despite these changes, no temporal or kinematic variables changed significantly between series (Table 7.1).

7.3.1 Physiological Variables

Maximum and minimum heart rates were significantly greater for the second and third shooting series compared to series one ($p<.016$) (Table 7.1). No significant differences were recorded between series two and three, despite the 1 km running phase that separated the two series. Between the final two series, maximum heart rate increased by only 4 bpm and minimum heart rate decreased by 3 bpm. Despite no significant changes in 1 km run time ($p>.05$), blood lactate concentration significantly increased between each series ($p<.016$), rising from 1.1 $mmol \cdot L^{-1}$ prior to series one, to 5.9 $mmol \cdot L^{-1}$ and 6.7 $mmol \cdot L^{-1}$ at the end of series two and three respectively.

7.3.2 Shot Score, Temporal and Kinematic Variables

No significant changes were recorded for aiming time between any series (Table 7.1), as the group median decreased by just 0.1 s between successive series. Shot score also changed little, and non-significantly between series, with only 0.2 points separating each series' median score. The median scores achieved in each series ranged between 7.0 and 7.2, due to a high number of shots that scored below the success criteria of 7.0 points. IQR increased with each successive series as the success of participants varied more widely in series two and three.

Neither horizontal nor vertical pistol movements changed significantly between series (Table 7.1). Some, albeit non-significant changes were evident as horizontal pistol movements decreased by 44.6 mm between series one and two, and increased by 20.2 mm between series two and three. Opposite changes were recorded for vertical pistol movement, which increased between series one and two (42.3 mm) and decreased between series two and three (16.4 mm).

None of the centre of pressure variables changed significantly between series (Table 7.1). Although non-significant, median range of movement varied by 1.2 mm and 1.1 mm for mediolateral and anterior-posterior range, respectively. Some change was evident for mediolateral and anterior-posterior path length, which varied by 4.5 mm and 2.2 mm respectively.

Table 7.1. Comparisons of dependent variables between each shooting series.

	Median group values (± IQR)						
	Series 1		**Series 2**		**Series 3**	χ^2	**p**
Maximum Heart Rate (bpm)	142 (15.5)	*	181 (13.0)		185 (9.3)	18.1	<.001
	†		†		†		
Minimum Heart Rate (bpm)	112 (39.0)	*	153 (28.5)		150 (25.5)	12.8	.002
Blood Lactate (mMol·L^{-1})	1.1 (1.3)	*	5.9 (2.6)	*	6.7 (2.8)	26.5	<.001
Aiming Time (s)	1.4 (0.1)		1.3 (0.1)		1.2 (0.1)	5.3	.070
Shot Score	7.2 (0.5)		7.0 (0.6)		7.2 (1.3)	0.9	.711
Pistol Movement (mm)							
Horizontal Trace Length	272.6 (16.9)		227.9 (21.1)		248.2 (42.0)	2.2	.403
Vertical Trace Length	238.5 (16.8)		280.9 (31.1)		264.4 (13.3)	5.6	.062
Centre of Pressure Movement (mm)							
Mediolateral Range	5.4 (0.7)		6.4 (0.9)		5.2 (0.8)	0.8	.714
Anterior-posterior Range	5.8 (0.4)		6.5 (1.6)		5.4 (0.6)	1.1	.607
Mediolateral Path Length	56.1 (13.1)		55.1 (13.9)		59.6 (18.4)	0.5	.866
Anterior-posterior Path Length	17.5 (7.2)		18.8 (7.6)		19.7 (9.5)	4.8	.098

† = significant reduction in heart rate within series ($p<.05$)
* = significant difference between series ($p<.016$)

7.3.3. Intra-Individual Performance Analysis

The format of the combined event meant that not all participants completed the series in the six shots used for statistical comparisons in Table 7.1. Individual data from four participants were plotted to identify any performance changes for participants who experienced varied levels of success when shooting. Data for these same four participants will be presented for every variable to represent any individual changes in performance.

Aiming time demonstrated some variations between participants (Figure 7.1a). With the exception of participant 14, participants spent a marginally longer time aiming in series one than series two or three. Only one participant (participant 8) demonstrated the anticipated decrease in aiming time with each successive series, with a decrease of 1.5 s. Aiming time changed little for other participants, particularly participant 14, for whom there was only a difference of 0.4 s between series.

Individual analysis demonstrated greater variations in score than was implied by the group median (Figure 7.1a). This was particularly apparent for participant 1, who required only five shots to complete series one in comparison to 11 shots in series three. Median scores for this participant were greater than 9.0 for series one, but below the 7.0 criteria for success in series three. Participant 14 also demonstrated the expected decline in each series, whilst participant 5 produced a similar pattern to the group median.

Pistol movement differed considerably between group and individual analysis (Figure 7.1a). The group result indicated that a decrease in horizontal pistol movement was accompanied by an increase in vertical pistol movement, whereas each of the four participants produced either an increase or a decrease in both movement components (Figure 7.3). Only one participant (participant 1) produced the same change between series as the group median for horizontal movements, and none demonstrated the same pattern for vertical movements.

Centre of pressure movements provided a further indication of individual variation in performance (Figure 7.1b). No participant produced the same change in mediolateral range between series as the group median. Two (participants 1 and 5) followed the same pattern as the group result for anterior-posterior range. The other two participants (8 and 14) produced the opposite results to the group, as anterior- posterior path length decreased between series one and two, and increased between series two and three.

Greater changes were also evident for individual analysis of path length in comparison to the group median (Figure 7.1b). Participants 8 and 14 produced greater changes between series than participants 1 and 5, particularly for anterior-posterior path length which increased by 24.4 and 9.2 mm for participants 14 and 8 respectively.

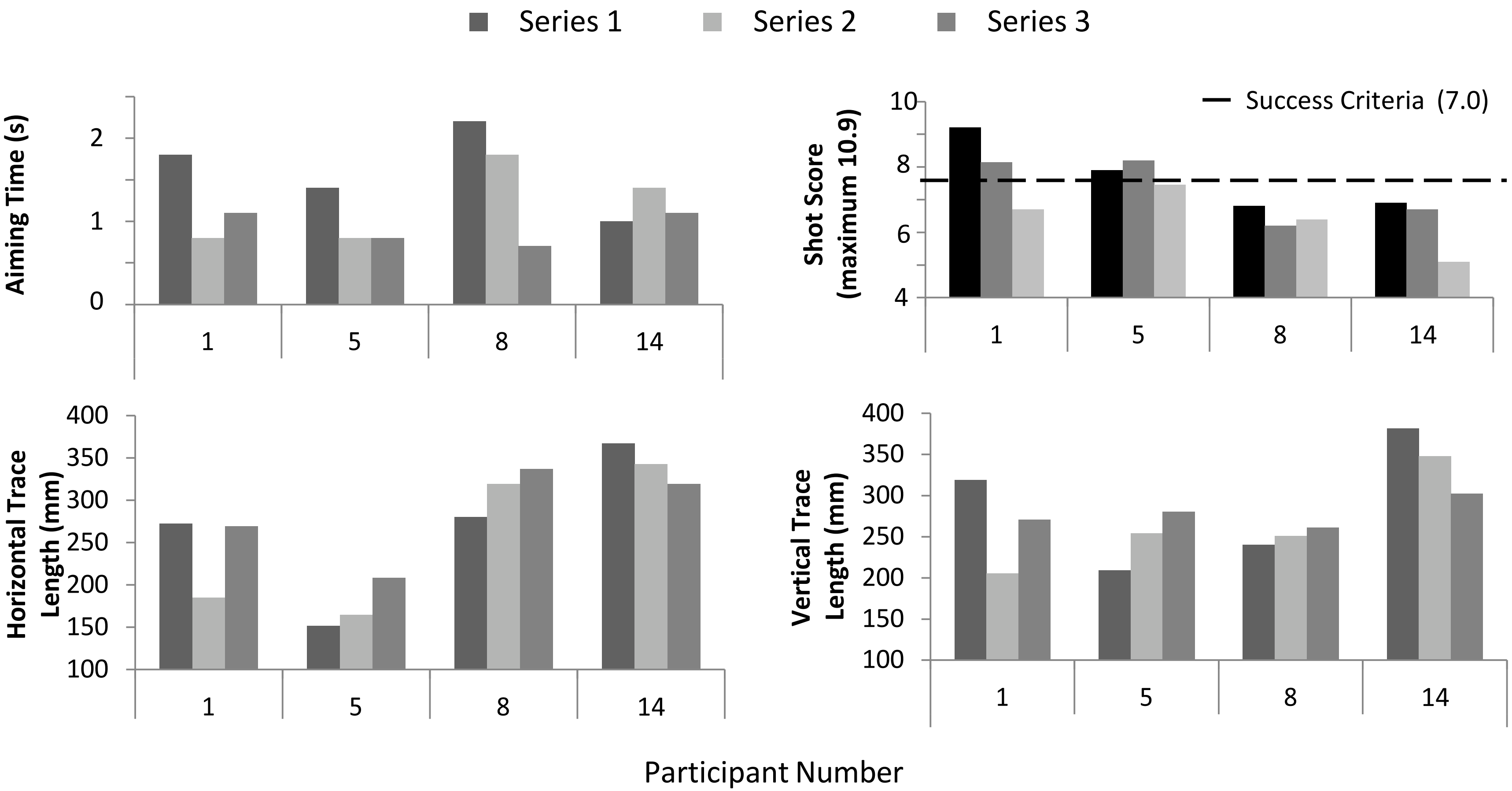


Figure 7.1a Intra-individual analysis of median aiming time, shot score and pistol movements for selected participants.

Number of shots required for series 1, 2 and 3 respectively were:

Participant 1: 5 \ 6 \ 11	Participant 5: 7 \ 6 \ 6
Participant 8: 8 \ 8 \ 10	Participant 14: 11 \ 11 \ 11

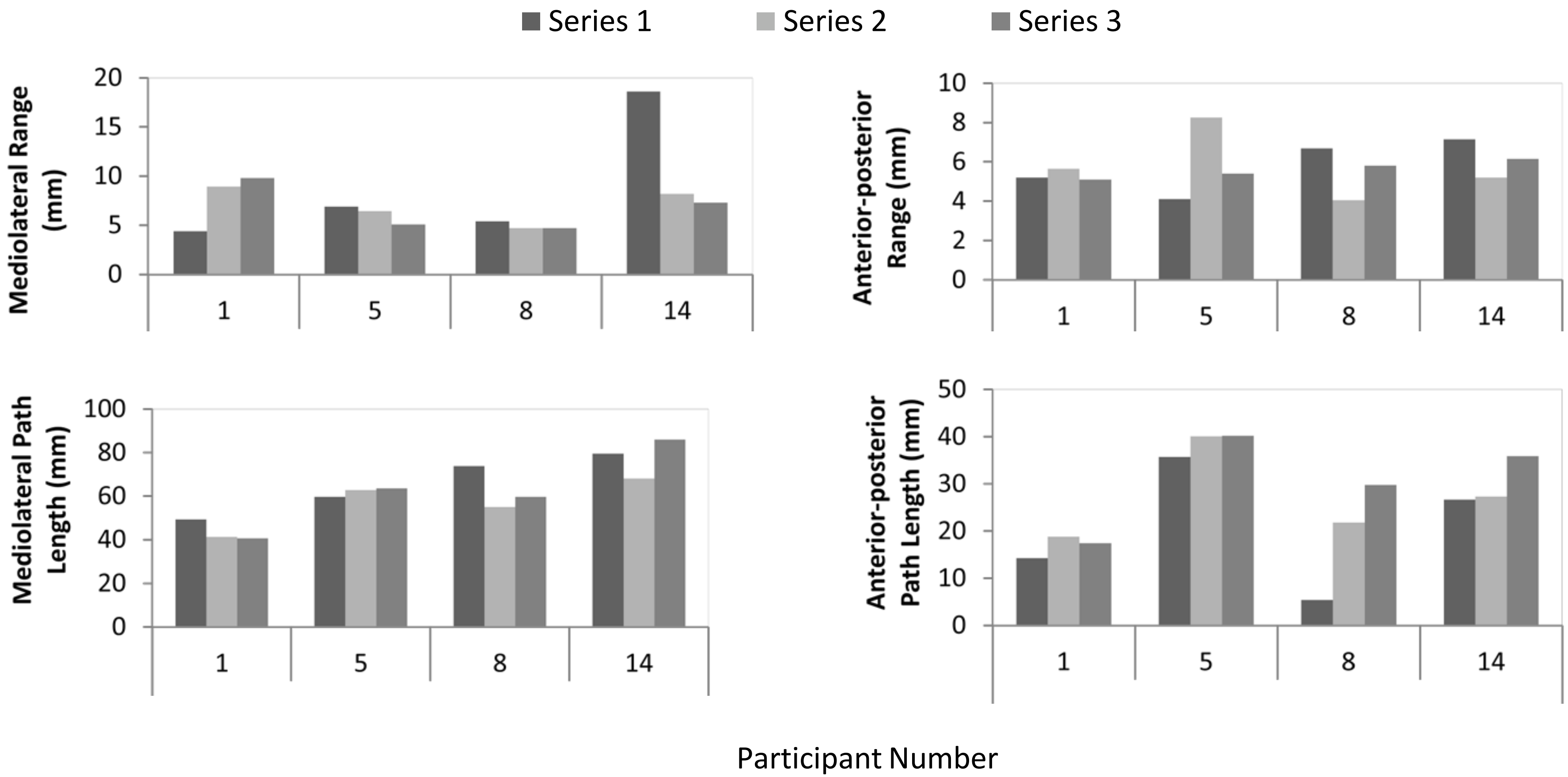


Figure 7.1b Intra-individual analysis of median centre of pressure movements for selected participants.

Number of shots required for series 1, 2 and 3 respectively were: Participant 1: 5 \ 6 \ 11 Participant 5: 7 \ 6 \ 6 Participant 8: 8 \ 8 \ 10 Participant 14: 11 \ 11 \ 11

7.3.4 Intra-Series Correlations

Two participants produced significant negative correlations between score and horizontal trace length in series three (Participant 8: *r* -.970 *p*<.007; Participant 10: *r* -.753, *p*<.007). A third participant produced a significant negative correlation with aiming time in series two (Participant 9: *r* -.882, *p*<.007). Whilst each variable accounted for between 57% and 88% of the changes in score, the same correlations did not achieve significance in any other series for these participants. Furthermore, none of the remaining 16 participants demonstrated any significant correlations. With these limited numbers of significant correlations it was not possible to determine any changes between series in the variables that were most influential to performance.

7.4 Discussion

This objective of this study was to identify any changes in shooting performance between each of the three series. Neither score, pistol movement nor centre of pressure movement changed significantly between series, leading to a rejection of the first hypothesis. Thus, despite an increasing reliance on anaerobic metabolism throughout the event, shooting performance remained similar. Whilst these findings fail to support the hypothesis, they do support the research of Le Meur et al. (2010) who reported no significant change in shooting success or time per shot for any series in the combined event (*p*>.05). As such, shooting performance following 1 km series running appears similar to performances achieved following only 20 m of running.

A potential explanation for the similarities in shooting performance across the three series is the increase in arousal associated with exercise. In their analysis of fatigue and shooting performance, Nibbeling et al. (2014) reported that an increase in arousal has the potential to reduce the effect of anxiety. Thus, in the combined event an increase in arousal may be sufficient to counteract any decrements in performance resulting from exercise-induced fatigue. Factors that may have produced anxiety, and potentially reduced performance in series one, may therefore prove less influential to performance in series two and three. Analysis of the heart rate trace indicates that this effect may be present. In Study 2 (Chapter 6, Figure 6.1), heart rate increased during the beginning of series one, which can indicate the presence of anxiety (Oudejans & Pijpers, 2010). This pattern was not apparent in series two and three, where heart rate gradually reduced between the beginning and end of each series. As such, it appears that the negative effects of pre-competition anxiety may be similar, or greater, than the negative effects of exercise. In series one, modern pentathletes should consider the psychological aspects of performance, such as methods to reduce anxiety, in addition to the biomechanical and physiological aspects of the event. For instance, Oudejans and Pijpers (2010) reported that training with mild anxiety can help maintain high performance levels when under high levels of anxiety, such as during competition. Techniques to enhance shooting performance in series one should therefore be a consideration for future research.

A second implication of the similarities between series is that, when developing shooting technique, shooting training in isolation could be effective in addition to combined run and shoot training. Training without the need to replicate the entire event is not only more simple, but would also enable modern pentathletes to focus solely on the demands of shooting, without additional considerations such as pacing strategies that are associated with each running phase. Determining effective methods of developing shooting technique is essential, as greater shooting accuracy, not running performance, has been suggested to determine the most successful athletes (Le Meur et al., 2010). Many shots taken by participants in the current study missed the target, meaning that athletes who can shoot accurately will have a considerable advantage over many of their competitors. Combined run and shoot training will also remain important to allow athletes to become accustomed to other aspects of the event such as the transition between each phase.

A particularly important outcome from this study is the contrast between the current findings and those which have investigated biathlon performance (Hoffman et al., 1992). Biathlon appears to be the shooting event most similar to the combined event, and yet, analysis of the combined event revealed a considerably different effect of exercise on shooting performance. Hoffman et al. reported that following exercise, shot score and rifle stability significantly decreased, whilst shot dispersion and centre of pressure movements significantly increased ($p<.05$). These findings were used to inform the first hypothesis. However, this effect was not present when analysing the performances of participants in the current research, demonstrating the unique performance requirements of the combined event.

The contrasting findings with previous research indicate that reducing exercise intensity immediately prior to shooting, as used by biathletes, may not be an effective strategy in the combined event. This may be unsurprising, given the different methods of hold for a pistol and a rifle, with the rifle more susceptible to other physiological changes such as heart rate. The reduced effects of exercise on pistol shooting were highlighted by Brown et al. (2013) who reported that, in pistol shooting, heart rate was not significantly correlated with either shooting accuracy or precision. Thus, it seems likely that reducing running speed prior to shooting, similar to biathlon, would not enhance shooting performance. This statement is supported by the finding that shooting performance was not better in series one, prior to the 1 km running phases. Consequently, modern pentathletes must now develop their own strategies when attempting to enhance shooting performance, rather than relying on the strategies of other, seemingly similar, events.

Each running phase had a limited effect on both shooting performance and on movement of the centre of pressure. The non-significant changes in centre of pressure movement were particularly surprising and in contrast to both the first hypothesis and the findings of previous research (Bove et al., 2007; Hoffman et al., 1992; Nardone et al., 1997; Niinimaa & McAvoy, 1983). Research has reported significant increases in path length following both cycling (Niinimaa & McAvoy, 1983) and treadmill (Bove et al., 2007; Nardone et al., 1997) exercise. It should be acknowledged that neither Bove et al. or Nardone et al.'s research was based on shooting performance, instead recording movement during quiet stance. The demands of combined event shooting are likely to be sufficient to destabilise the centre of pressure, even after minimal exercise, beyond that which is required for these quiet stance tasks. This effect was apparent in Study 1 (Chapter 5), which found a significant increase in centre of pressure movement when changing from precision to combined event shooting ($p<.05$). Thus, as movement is already elevated in comparison to more simple stance tasks, any additional increases following exercise may be less pronounced.

An additional explanation for the differences between the findings of the current research and previous studies is the methods used to quantify fatigue. Nardone et al. (1997) compared non-fatigued exercise trials, where heart rate was below 60% age-adjusted maximum, with fatigued trials at 93% of the maximum. Whilst the maximum heart rate reported by Nardone was similar to that recorded for modern pentathletes in series three, the minimum heart rate was lower than that recorded in any of the three series in the current research. Even in series one, prior to which participants had only completed 20 m of running, minimum heart rate was 69% of age-adjusted maximum. Thus, the smaller changes in heart rate between each shooting series in comparison to the non-fatigued and fatigued trials used by Nardone et al. may explain why exercise had less of an effect on centre of pressure movement for modern pentathletes.

A key consideration throughout this research series has been whether group analysis is an appropriate method of analysing shooting performance. This was investigated by comparing the group results with the performance of four participants selected as case studies. Only one participant produced the expected decline in score with each series, whilst two demonstrated the predicted increase in pistol movements and anterior-posterior path length. The same increase was not evident for the other centre of pressure variables. Thus, neither group nor individual analysis provided clear support for the anticipated changes in shooting performance following each 1 km run phase.

The individual data, whilst not providing any clear support for the hypotheses, did support the need for intra-individual analysis of shooting performance (Ball et al., 2003; Mason et al., 1990). The performance of some participants varied little between series, consistent with the findings of group analysis. None of the selected participants displayed the same change between series as the group median for all dependent variables. This was particularly evident for shot score. For instance, participant 5 maintained relatively consistent scores across each series, ranging between 7.5 and 8.2 points. Participant 1 demonstrated less consistency, with a decline of 1.1 and 1.4 points with each successive series. With the exception of vertical pistol movements and mediolateral centre of pressure range, at least one of the four participants produced the same pattern between series as the group median for each variable. However, the highly individual nature of combined event pistol shooting means that the group median will rarely reflect each individual's response to the shooting task. Consequently, coaches should be cautious when applying the findings from purely group-based analyses.

This study has revealed, for the first time, the limited effect of each running phase on combined event shooting performance. There are limitations which could be built on to further enhance the understanding of performance in the event. Participants all provided blood lactate samples at specific stages during the event, but none completed VO_2 max tests prior to testing. This additional information would have provided an insight into the intensity at which each participant was performing, allowing more detailed comparisons with previous research. Quantifying the intensity at which each participant was completing each running phase would also provide a greater understanding of the non-significant changes in shooting performance between series. Statistical limitations also made comparisons of correlations between series difficult. Correlations were restricted to six shots within each series, meaning that the critical value required to achieve significance was high (0.881 for $p<.007$). Future research which allowed participants a greater number of shots would decrease the critical value, thereby increasing the likelihood of uncovering correlations in each series. As mentioned in Study 2 (Chapter 6), this would require consideration of an appropriate method to maintain validity. Also described in Study 2 was the inability to recreate the effects of competitor's performances owing to the use of force platforms as part of the testing procedure. Thus, the influence of competitors on performance would be an interesting topic for future research.

7.5 Conclusion

This study has clearly highlighted that the sequence of running phases that form part of the combined event do not significantly influence shooting performance. These similarities in shooting performance throughout the event have potential implications for training, with the possibility that shooting training in isolation may be effective in addition to the complete event format. The findings also highlight the need for modern pentathletes to consider other factors, such as the effects of anxiety on performance in series one. The combined event clearly has unique performance requirements in comparison to other shooting disciplines, such as biathlon. Consequently, modern pentathletes must establish unique methods to enhance shooting success. This is important if athletes wish to enhance not only their combined event, but also overall competition performance. Few correlations were identified for each series, suggesting that there must be other variables which further influence combined event shooting performance. Future research should consider the effects of other aspects of technique on success in each shooting series. Finally, whilst both group and individual analysis failed to support the hypotheses it was clear that group analysis alone is not sufficient to reflect the performances of all individuals.

Chapter Eight

Change in Research Focus: Combined Event to Precision Shooting

The first three studies have considered pistol shooting performance as it exists in the combined event of modern pentathlon. This research has provided four main conclusions:

(i) combined event performance differs significantly from precision shooting. As such, modern pentathletes who were previously successful in precision shooting are not guaranteed a similar degree of success in the combined event without additional training;

(ii) the time constraints associated with each 70 s shooting series did not significantly affect shooting performance. Thus, athletes maintain consistent shooting performances from the beginning of a shooting series to the end where there is progressively less time to achieve five hits on target;

(iii) the 1 km running phases that separate each shooting series did not significantly affect shooting performance. This suggests that anxiety prior to the beginning of the event has a negative effect on shooting performance in series one. An additional implication of the similarities in shooting performance between each series is that shooting training in isolation may be beneficial in addition to recreating the entire combined event; and

(iv) pistol shooting performance varied considerably between individual participants. Thus, reliance on group average data when investigating elite shooting performance is not recommended. Instead, intra-individual methods of analysis must be used.

These studies have provided a more detailed understanding of shooting performance in the combined event. They have also identified that there must be other variables in addition to pistol and centre of pressure movement that influence performance, as demonstrated by the small number of significant correlations between kinematic variables and score. Consequently, more detailed analysis of technique is required, such as that which can be offered by motion analysis systems. The first three studies utilised analysis methods that have been used in previous investigations of pistol shooting performance, such as force platforms and optoelectronic shooting systems. These methods provide information on the outcomes of performance but do not consider how these movements, such as centre of pressure and pistol movement, are generated. There are many potential sources of movement between the centre of pressure below the feet and the pistol in the hand. More detailed investigations of these movements will make it possible to develop a more in-depth understanding of the difference between a more or less successful shooting performance. By increasing the understanding of the mechanisms behind a successful performance, research can become more applied, and useful to athletes and coaches who wish to achieve the high levels of stability that have been associated with elite level shooting performances.

When designing the final two studies for this thesis, issues arose with the availability of elite modern pentathletes for testing. Furthermore, additional modifications to the format of the combined event, with a change to four 50 s shooting series and four 800 m run phases, meant that athletes were still adapting to the new demands placed on them (Figure 8.1). To address these issues the focus of the final two studies was modified to analyse the performances of elite precision, rather than combined event shooters.

With the change in participants, there was a clear change in the focus of this research, from the quick movements associated with combined event shooting to the highly accurate and controlled sport of precision shooting. Study 1 has identified the significant differences which exist between these two shooting formats, but key themes are maintained between the first three and the final two studies that form this thesis. The final two studies investigated the movements that are responsible for pistol movement, thus building on the centre of pressure and pistol movements that were recorded in the first three studies. Studies 1 - 3 have each stated that there are many potential sources of movement between the centre of pressure under the feet and the hand holding the pistol. It is therefore important to examine movement when shooting in more detail to understand how a shooting performance is created. Whilst this will be determined for precision shooting in the final two studies, the measurement techniques and methods of analysis have the potential for future use in the combined event.

Another of the conclusions from the first three studies was that individual analysis is essential for the analysis of elite shooting performance. This is particularly important for precision shooting where the smallest movements can affect success. As such, individual analysis will be a key theme throughout Studies 4 and 5.

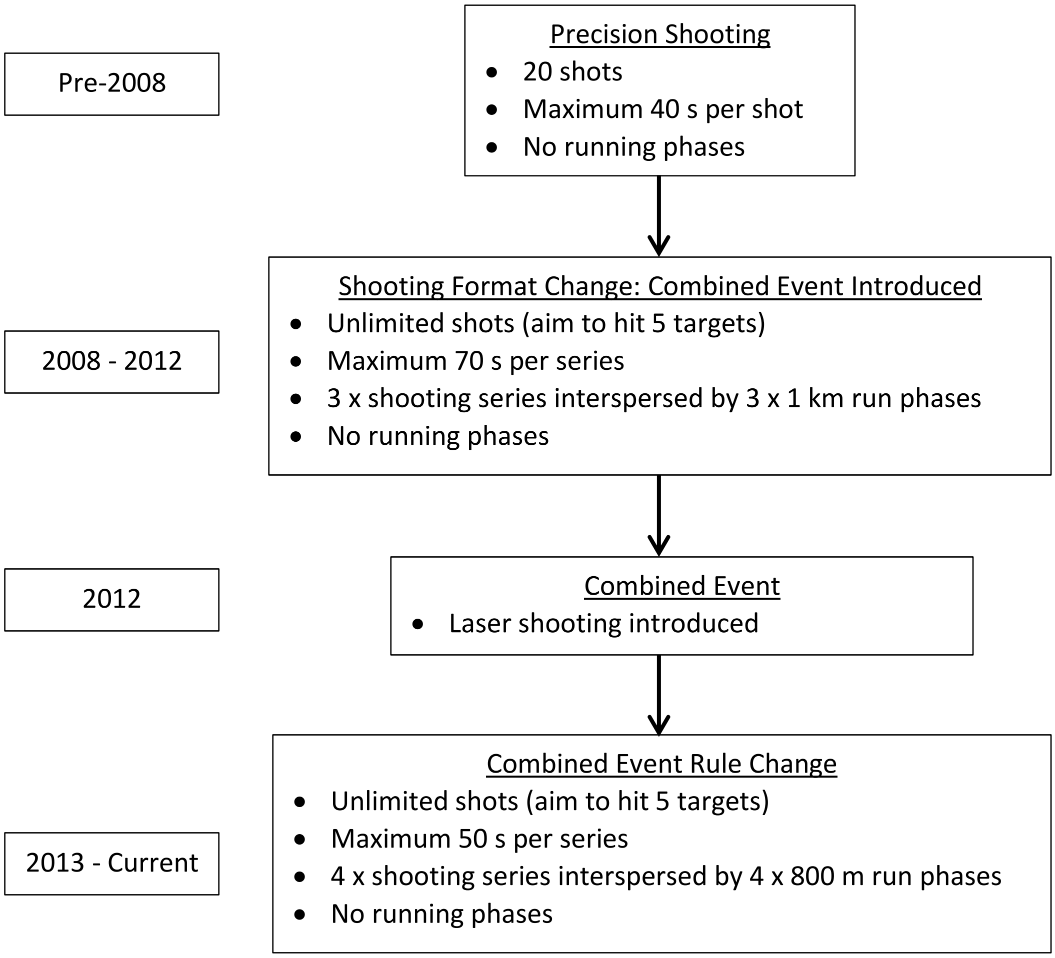


Figure 8.1. Timeline of modifications to the pistol shooting event in modern pentathlon, from the original precision event to the combined event in its current format.

Chapter Nine

Review of the Literature – Movement Variability, Coordination and Stance Position

In the comparisons of combined event shooting in the first three studies, discrete methods of analysis were used as a method of quantifying performance. Discrete measures, such as range and standard deviation, use single values taken from a kinematic series of data to represent an entire movement. These measures have commonly been used in previous research (Fleisig, Chu, Weber, & Andrews, 2009; Kao, Ringenbach, & Martin, 2003; Owings & Grabiner, 2004) as they provide a simple method of representing movement variability at key points within a task (Bartlett, Wheat, & Robins, 2007). Within shooting, variables such as trace length of the pistol can provide information regarding the outcome of the shooting task, and how it varies either between participants, or different shots. Whilst there are benefits of using discrete analysis, the use of one value to represent an entire trial can often oversimplify the data. The shape of a kinematic curve can indicate how a particular movement is accomplished (Preatoni et al., 2013) and so discrete analysis can discard potentially important information related to the temporal and spatial aspects of a performance. This is an important aspect of sports biomechanics if research is to become more applicable to athletes and coaches. For instance, rather than stating that elite pistol shooters produce smaller pistol and centre of pressure movements than lower ability shooters, it would be more useful to explain how these movements are achieved.

Recent motor control research has identified two continuous aspects of performance, movement variability and movement coordination, which are considered to greatly influence the success of a performance (Bartlett et al., 2007; Preatoni et al., 2013). This review will describe the theories associated with movement variability and coordination, including examples of their use in previous research.

9.1 Movement Variability

When an individual performs a movement, their level of success often varies from one repetition to the next. Despite repeated practice, even elite athletes cannot perfectly replicate a movement between trials (Davids et al., 2003; Preatoni et al., 2013). These inconsistencies when replicating an action are termed movement variability, and are an inherent aspect of human movement (Lakie, 2010; Latash, Scholz, & Schöner, 2002). By understanding movement variability it is possible to understand, and potentially influence, the success of a particular task. For this reason the study of movement variability has become a popular topic within biomechanics and motor control research.

Investigations into movement variability and its effect on task performance began with the work of Bernstein (1967). Bernstein's research was the first analysis of movement variability, reporting that every attempt made by an individual to replicate a movement resulted in a marginally different motor output. These inconsistencies were termed "repetition without repetition" (Bernstein, 1967 as cited in Stergiou & Decker, 2011, p. 1), and signalled the beginning of the development of motor variability theories. This section of the literature review explains how the perception of movement variability and the methods used to measure it have changed over recent years. It also outlines the findings of previous research, and explain how they have proved useful both to athletes attempting to improve sports performance and to individuals in the wider population. Finally, it highlights the current gap in the literature regarding the effects of movement variability on pistol shooting performance.

9.1.1 Developments in the Theory of Movement Variability

Movement variability analysis considers two aspects of a task; outcome and performance variability (Horan, Evans, & Kavanagh, 2011; Preatoni et al., 2013). Outcome variability examines how the outcome of a task, such as reaching for and grasping an object, varies between attempts. Performance variability reflects how the performance of a task, such as the movements of the body that influence the task outcome, vary between trials (Preatoni et al., 2013). In pistol shooting, outcome variability reflects aim point movement, or the location of shots on the target, whilst performance variability concerns the movements of the body and upper limb which can influence the movement of the pistol, and hence the aim point on the target.

Research has traditionally considered the variability associated with reaching and balance tasks in elderly and disabled populations (Black, Smith, Wu, & Ulrich, 2007; Cirstea & Levin, 2000; Darling, Cooke, & Brown, 1989; Levin, 1996). More recently, research has begun to consider the effects of movement variability on elite sports performance, where a greater understanding of the mechanisms behind a successful performance could greatly enhance success (Preatoni et al., 2013; Tucker, Anderson, & Kenny, 2011; Wilson, Simpson, van Emmerik, & Hamill, 2008). This is particularly important in precision sports such as pistol shooting where, at a distance of 10 m, a change in pistol angle of just 0.033^{o} is sufficient to move the aim point of the pistol from the centre of the ten ring to the border of the nine. The consensus within previous literature is that success in a particular task is reflected by a small degree of outcome variability, but there has been greater debate about the contribution of performance variability to the success of a task.

The impact of performance variability on task outcome has been addressed by multiple authors for various activities including pointing tasks (Domkin, Laczko, Djupsjöbacka, Jaric, & Latash, 2005), and sport-specific tasks such as sprinting (Bradshaw, Maulder, & Keogh, 2007), baseball pitching (Fleisig et al., 2009) and the golf swing (Langdown et al., 2012). Initially, variability was considered as noise within a movement system that must be reduced in order to improve performance in accuracy-based tasks (Newell & Corcos, 1993). Under these circumstances, the amount of performance variability should be equal to the variability of the task outcome (Preatoni et al., 2013). More recently, research has considered that whilst a high degree of variability could be detrimental to performance, some variability could be evidence of a functional movement system which is able to adapt to the constraints of a changing environment (Black et al., 2007; Wilson et al., 2008). In this situation, the amount of performance variability should be greater than the variability of the task outcome.

9.1.2 Early movement variability theories: Variability as noise

Bernstein (1967) first considered the effects of movement variability on task outcome, using the movements produced by blacksmiths when striking a chisel with a hammer. By recording the position of light bulbs placed on the hammer and on each joint in the upper limb it was established that there was little variation in the movement of the hammer between strikes, whilst much greater variability was apparent for the movements of the upper limb. It was therefore suggested that more than one movement pattern could result in the same successful task outcome. Based on these findings, Bernstein concluded that the movements produced for each joint of the upper limb were not controlled independently, but instead controlled as part of a wider system which interacts to produce a successful task outcome. Bernstein introduced the theory of motor redundancy in an attempt to explain how such complex movements can be controlled. This theory proposed that there are many more degrees of freedom available to the human movement system than are necessary to complete a task. Thus, when learning a task, an individual must reduce movement variability by initially 'freezing out' some of the degrees of freedom. Each degree of freedom is then gradually released until the individual reaches a state of control where they can consistently accomplish a specific task.

Arutyunyan, Gurfinkel and Mirskii, (1968; 1969) compared the movement variability of novice and elite pistol shooters to provide a clearer indication of how individuals mastered the degrees of freedom in order to succeed at a task. Arutyunyan et al. (1968) reported that novice shooters produced a greater dispersion of pistol movement across the target than experienced shooters, and that this dispersion decreased with practice. The explanation for this change in performance was provided by their subsequent work in 1969, which analysed movements of the wrist and shoulder in addition to the pistol. Experienced shooters produced greater coordination between the movements of the shoulder and the wrist, and between the wrist and the pistol, than the novice shooters. The author used these findings to suggest that elite shooters must have a greater mastery of the degrees of freedom than novice shooters, thus providing further support for Bernstein's principle of redundancy.

9.1.3 Changes in movement variability theories: Functional variability

The principles of mastering the degrees of freedom for a specific task, and the decrease in task outcome variability between novice and elite performers are central to current movement variability theories. However, there is a clear distinction between the original theories and more recent ideas when considering the function of movement variability. Whilst movement variability was originally viewed as noise (Arutyunyan et al., 1969; 1968; Bernstein, 1967), more recently it has been reported as a functional aspect of movement, which could instead facilitate performance. Bartlett, Wheat and Robins (2007) suggest that variability may represent the ability of a movement system to adapt to changes in the environment, or to errors in other components within the system. It should be acknowledged that variability is only considered functional to a degree, beyond which it can still be detrimental to performance (Langdown et al., 2012).

A second difference between original and more recent theories of movement variability is the method by which movements are thought to be controlled. Bernstein's (1967) theory of motor redundancy assumes that an individual freezes any degrees of freedom that are not necessary to achieve a particular task. Recent research instead promotes the concept of motor abundancy, which suggests that the central nervous system takes advantage of the numerous solutions available for movement coordination. This allows the production of multiple movement patterns, each of which result in a successful outcome of the task (Preatoni et al., 2013). The theory of abundancy is based on the principle that any movement is controlled by interactions between the movements of a system of joints or segments. An individual can alter the movement produced for any joint in that system (e.g. in the upper limb when pistol shooting) to respond to any changes in the output from the other the joints within that system. Thus, the variability of each joint could be high, as each compensates for any changes in movement to ensure that the variability of the task outcome can remain low.

Since the change in perspective towards functional variability, there has been an increase in research considering the impact of movement variability on activities in both daily life and sporting activities. In their analysis of novices learning to ski, Vereijken, van Emmerik, Whiting and Newell (1992) measured the three dimensional kinematics of the hip, knee and ankle to identify how the degrees of freedom were progressively released through the stages of learning. The movement recorded at each joint increased with practice, leading the authors to propose that an increase in task success was achieved by increasing movement variability. More recently, Button et al. (2003) examined movement variability between basketball players of different abilities, comparing elbow and wrist angles at the moment of ball release for a free throw. Higher skilled participants demonstrated greater variability at each joint than the lower skilled participants. The greater variability for the more skilled players was used as an example of the compensatory actions of each joint, ultimately used to decrease the variability of ball release, and increase the likelihood of a successful shot.

Whilst research has considered movement variability in sports such as basketball which require a greater amount of movement, none has yet considered movement variability in elite pistol shooting. Some has examined movement variability for pointing tasks, for which the accuracy and stability constraints are more similar to those required for shooting than the previous examples from sports performance (Domkin et al., 2005; Domkin, Laczko, Jaric, Johansson, & Latash, 2002; Kim et al., 2012; Tseng, Scholz, Schöner, & Hotchkiss, 2003). Much of this research has used the uncontrolled manifold hypothesis (UCM) as a more detailed theory to evaluate variability. Introduced by Scholz and Schoner (1999), the UCM proposed that research should not just consider the amount of variability, but also how much of the variability recorded is actually functional to performance. For instance, whilst van Emmerik et al. (1992) and Button et al. (2003) reported that variability increased with increasing skill level, there was no way to determine whether this had a positive effect on performance.

In their development of the UCM hypothesis, Scholz and Schoner (1999) suggested that for any task outcome (e.g. a specific location of the aim point on the target for pistol shooting), joint angles can be separated into two subspaces. One subspace represents the combinations of joint angles that do not affect the task outcome (e.g. the aim point on the target remains in the same location), and the second represents any other combinations of joint angles that alter the task variable (e.g. the aim point moves to a different location on the target). Any combination of angles in the first subspace, often termed goal-equivalent variance, represent functional variability, whilst combinations in the second subspace, termed non-goal equivalent variance, represent variability that is potentially detrimental to performance.

Tseng et al. (2003) and Kim et al. (2012) both used the UCM hypothesis to investigate variability associated with pointing to targets of different sizes. Both groups recorded the movements of a number of body markers to determine how variability changed as target size increased. Tseng et al. reported that, for each target, goal-equivalent variance was significantly greater than non goal-equivalent variance; meaning that most of the movement produced during the pointing tasks represented functional variability of the motor system, rather than noise that negatively affects performance. Kim et al. reported that the more difficult tasks resulted in an increase in goal-equivalent variance. As the increased variability remained within the goal- equivalent subspace, there was no corresponding decline in performance. These findings provide support for the theory that movement variability can represent an attempt to enhance performance, rather than a lack of control, and should be considered as functional, rather than detrimental to performance.

The UCM provides a detailed understanding of variability at discrete points in a movement, but it does not examine how variability changes over time. A continuous analysis of movement variability can be achieved with the use of mean and standard deviation plots, as shown in Figure 9.1. Domkin et al. (2005; 2002) and Kruger et al. (2011) each used these plots to illustrate how the variability of upper limb joint movements changed throughout a movement. Kruger et al. found that variability increased towards the middle of the task, then decreased near the end of the movement. Thus, they concluded that control of reaching movements is more effective for the second half of a reaching action. In contrast, Domkin et al. found variability to decrease throughout a pointing task, and from pre-test to post-test conditions. Domkin et al. also used the UCM to quantify variability, but there were no clear effects of practice on goal-equivalent and non-goal equivalent variance. Thus, the authors suggested that the UCM cannot detect the effects of practice if it occurs quickly, and over a limited number of trials.

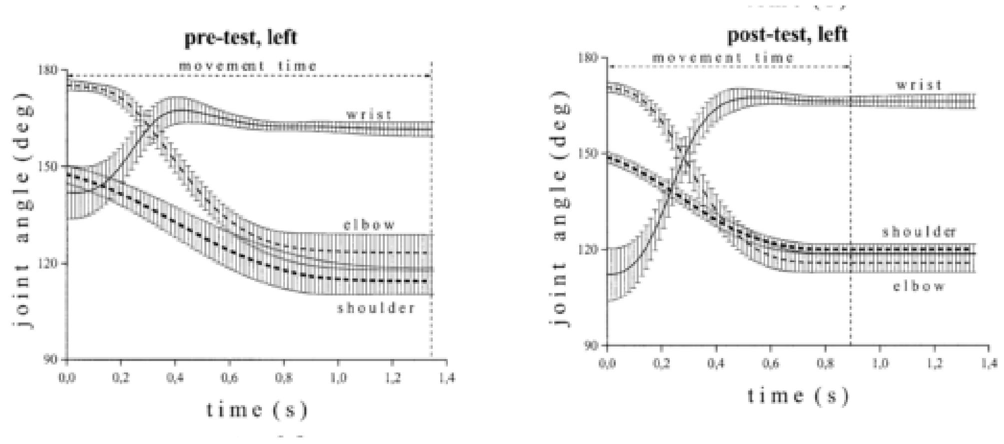


Figure 9.1. Continuous methods of analysing variability, allowing comparisons of pre-trial and post-trial performance for one participant. Dashed lines represent average angle, and vertical bars represent standard deviation (Domkin et al., 2002).

The application of the UCM hypothesis, and the use of mean and standard deviation plots, have both been shown as effective methods of quantifying variability. Each has the potential to be applied when investigating the role of movement variability in pistol shooting performances (Kim et al., 2012; Krüger, Eggert, & Straube, 2011; Scholz & Schöner, 1999; Tseng et al., 2003). The UCM can provide detailed information regarding the degree of functional variability produced by elite shooters, and could also provide a comparison of the degree of functional variability between more and less successful shots (i.e. a shot scoring 10 points compared to one scoring 8). A disadvantage of the UCM is that whilst it could quantify variability at the instance of the shot, it would not examine variability throughout the aiming period. Mean and standard deviation plots provide a more continuous analysis of performance, and can examine how the variability of upper limb movements change throughout the final second to achieve a consistently successful performance. These plots therefore provide an appropriate method of analysis for investigations into the effects of variability on pistol shooting performances.

9.1.4 Movement Coordination

The analysis of movement variability has identified that the performance of a particular task can vary and still result in a successful task outcome. It cannot, however, identify the specific movements, such as shoulder abduction and adduction or wrist flexion and extension, that were used to control the outcome. This aspect of analysis is termed movement coordination, and refers to the movement patterns which can be used to complete a particular skill (Preatoni et al., 2013). Little research has considered how movement is coordinated in pistol shooting, but the coordination of movement in both target pointing tasks and other sports skills have been investigated (Hwang & Wu, 2006; Steven Morrison & Newell, 2000; Vereijken, Emmerik, Whiting, & Newell, 1992).

Much existing coordination research has used cross-correlations to examine the degree of similarity between the movements of different joints or segments of the body, to provide a more detailed understanding of how movement is controlled (Chiu & Chou, 2012; Vereijken et al., 1992; Winter, Patla, & Prince, 1998). Cross-correlations compare how two signals change over a specific time period, and uses a value between -1 and +1 to quantify the degree of similarity of these signals. When analysing human movement, a high positive cross-correlation reflects two movements that are highly similar, such as if a participant produces horizontal shoulder flexion and wrist flexion concurrently during a task. A high negative cross-correlation reflects two opposing movements, such as if a participant produces horizontal shoulder flexion and wrist extension. A cross-correlation near to 0.0 reflects two movements that show few similarities, and thus a change in one movement is not reflected by a change in another. For example, horizontal flexion of the shoulder accompanied by wrist movements that alternated between flexion and extension would result in a low cross- correlation.

Cross correlations are often used to identify the coordination between different joints, often termed a movement synergy. A synergy is based on the principle that, instead of controlling the movement of each independent joint in a system, the central nervous system allows the co-variation of each of the joints in order to achieve a successful task outcome (Scholz et al., 2000; Tseng et al., 2003). An increase in movement about one joint, which could negatively influence the outcome variable, is accompanied by a decrease in movement, or an opposing movement, at another. For instance, in pistol shooting an increase in movement at the shoulder could have a negative effect on the location at which the pistol is pointing at the target. If this is counteracted by a reduced, or opposite, movement at the wrist then the location of the pistol should remain constant. A more effective synergy is generally considered representative of a more adaptable performance (Chiu & Chou, 2012; Hwang & Wu, 2006; Keogh, Morrison, & Barrett, 2004).

As part of their analysis of skill learning using ski apparatus, Vereijken et al. (1992) used cross-correlations to examine movement coordination between the hip, knee and ankle angles. Cross-correlations between all three angles were high when first learning the task, and decreased with practice, which the authors interpreted as the control of each segment becoming increasingly independent. This conclusion was in contrast to more recent research which suggests that lower correlations represent compensatory actions of each joint, and a more adaptable performance rather than independent control (Chiu & Chou, 2012; Hwang & Wu, 2006; Steven Morrison & Newell, 2000). An example of this contrasting viewpoint, promoting an a adaptable performance, can be seen in the research of Chiu and Chou (2012) who examined the effects of age on coordination between the lower limb joints when walking at different speeds. The magnitude of cross-correlations between the hip and knee was significantly higher for elderly than younger participants, regardless of walking speed. These findings were used to suggest that a reduction in gait function was associated with a reduced ability to modify the timings of hip and knee movement, making the elderly less able to adapt gait patterns.

Interactions between each of the upper limb joints when pointing was examined by Keogh et al. (2004) who used cross-correlations to quantify the degree of coupling between the upper limb segments as participants aimed at a target over a period of 30 s. Higher cross-correlations were used to represent a greater coupling between segments. The highest cross-correlations were recorded between the finger and the hand (*r* = 0.71), and the upper arm and forearm (*r* = 0.48). An increase in coupling was also found to be accompanied by an increase in upper limb tremor. Thus, a more flexible performance resulted in reduced tremor, and potentially enhanced the task outcome.

Morrison and Newell (2000) and Hwang and Wu (2006) each investigated how coordination of the upper limb segments was affected by the amount of support provided to the upper limb, and the speed of movement, respectively. Morrison and Newell reported correlations between the finger and the hand of between *r* = 0.61 –0.71 when the limb was not supported, similar to those reported by Keogh et al. (2004). Furthermore, smaller movements of the index finger were produced when the forearm and hand were unsupported than when it was supported. Hwang and Wu found that an increase in movement speed resulted in lower cross-correlations, and therefore a weaker coupling between the forearm, hand and finger. Findings led both groups of authors to conclude that a synergy must exist, in which the wrist plays a crucial role in allowing compensatory movements between the hand and the forearm ultimately resulting in a stable task outcome.

The findings of previous research (Hwang & Wu, 2006; Keogh et al., 2004; Morrison & Keogh, 2001; Steven Morrison & Newell, 2000) can indicate the movements that may be most important to shooting performance, and should be investigated in future shooting research. The degree of accuracy required for these pointing tasks were considerably less than that required for precision shooting, and tasks did not include the additional mass of the pistol that shooters must also control. Thus, research needs to examine movement coordination specifically in pistol shooting to determine how a successful performance is produced.

Currently only Pellegrini et al. (2005) has investigated movement coordination in shooting. The movements of thirteen pistol shooters, with markers placed on the neck, shoulder, elbow, wrist and pistol were recorded throughout the aiming period. Discrete correlations were performed between successive markers (neck – shoulder, shoulder – elbow, elbow – wrist, wrist – pistol) to compare the horizontal and vertical movements over the final second before the shot. High correlations were produced between the movements of the upper limb that were responsible for horizontal pistol motion, leading the authors to conclude that the trunk, arm and pistol all move as one segment. Correlations between the movements responsible for vertical pistol motion were more varied, suggesting that control of vertical pistol movement is more complex than the method of controlling horizontal movement. The use of discrete correlations mean that shooting research has yet to examine the temporal or directional aspects of performance that can be obtained from the use of cross-correlations. Future research should investigate how pistol shooters coordinate body sway and upper limb in the time immediately preceding the shot. This additional information will make it easier for athletes and coaches to understand the variables which are most crucial to success in a sport which requires such extreme levels of accuracy and precision.

9.2 Stance Position

The analysis of movement variability and coordination can provide a detailed understanding of how an elite shooting performance is produced. These movements are likely to be beyond the degree that a shooter could consciously control if they wish to enhance performance, and so other changes in performance that could influence the amount of variability and coordination must be examined. One potential method is to adapt the stance position used when shooting, which seems important, given that in precision shooting there are few external influences on performance. Stance position has currently received little attention in previous literature, but more studies have examined its effects on stability in quiet stance tasks. This section of the review will outline what is currently known about stance position and stability both in quiet stance tasks and in pistol shooting.

The most common theme in stance position research has been the effect of stance width on centre of pressure and centre of mass movement during quiet stance tasks (Day, Steiger, Thompson, & Marsden, 1993; Goodworth & Peterka, 2010; Henry, Fung, & Horak, 2001; Hwang, Huang, Cherng, & Huang, 2006; Kirby, Price, & MacLeod, 1987; Winter et al., 1998). Kirby et al. (1987) investigated the effects of changing mediolateral stance width (0 – 45 cm) on centre of pressure displacement, and Goodworth and Peterka (2010) compared centre of mass displacement for different stance positions (5 – 31 cm). Both studies reported that wider stance widths resulted in greater mediolateral stability, but did not report the effects on anterior-posterior movement.

The effects of stance position were considered in more detail by Winter et al. (1990) and Day et al. (1993) who investigated how mediolateral stance width affected both mediolateral and anterior-posterior stability. Winter et al. used three stance widths (approximately 14, 28 and 42 cm), and quantified stability by the range of movement of centre of pressure and centre of mass movements. Day et al. compared five stance widths (0 cm, 4 cm, 8 cm, 16 cm and 32 cm), and measured the standard deviation of the movements of the centre of pressure, and of various body markers (shoulders, hips, knees and ankles). Both studies reported that greater mediolateral stability was observed for wider stance widths, supporting the findings previously reported (Goodworth & Peterka, 2010; Kirby et al., 1987; Winter et al., 1998). More conflict exists regarding the effects of mediolateral stance width on anterior-posterior stability. Winter et al. reported that anterior-posterior movements did not differ significantly with changes in stance width, whilst Day et al. found that anterior- posterior stability was significantly greater for wider stance widths.

Less research has investigated how anterior-posterior stance width can affect stability. Kirby et al. (1987) incorporated the effects of anterior-posterior stance widths on centre of pressure displacement into their analysis. Five stance positions were compared with the right foot either in line with (0 cm), or placed in front or behind the left foot (10 cm and 30 cm). In contrast to the effects of mediolateral stance position, greater stability was observed for the narrower (0 - 10 cm) stance widths. This effect was observed for both mediolateral and anterior-posterior stability, highlighting the potential importance of anterior-posterior stance position to shooting performance. The effects of mediolateral and anterior-posterior stance widths were considered separately, and so any interactions between the two positions were not considered.

Previous stance position research has demonstrated clear effects of stance position on stability, but the effects of stance width on movement variability and coordination have yet to be considered. The findings of Hwang et al. (2006), who investigated the effects of stance stability on movement coordination during a pointing action, indicate why these comparisons are important. Hwang et al. used cross- correlations to compare the coupling of upper limb segments between unilateral (single leg) and bilateral (both legs) stance positions. Higher correlations, and thus greater coupling between the movements of the upper limb, were observed for the less stable stance position. Consequently, less stable stance positions may lead to a less adaptable performance which may result in a less consistent task outcome. Thus, the effects of stance position on variability and coordination is an important topic within pistol shooting. Comparisons between unilateral and bilateral stance positions are very different to those between different stance widths. As such, it remains to be seen whether changing mediolateral or anterior-posterior foot position can affect movement coordination.

Whilst previous research has examined the effects of stance width on stability during quiet stance tasks, there is currently only one investigation into these effects specifically for pistol shooting (Hawkins & Sefton, 2011). Hawkins and Sefton examined the effects of changing stance position on the stability of the pistol and centre of pressure for 12 nationally ranked pistol shooters who each completed ten shots using five different mediolateral stance widths (30 cm, 45 cm, 60 cm, 75 cm and 90 cm). Centre of pressure stability was greatest in the narrowest stance position (30 cm), as demonstrated by significantly decreased centre of pressure speed and path length (*p*<.05). Stability of the pistol was significantly lower for the 75 cm and 90 cm widths (*p*<.05). The greater stability recorded for narrower stance positions was in contrast to the findings previously reported for the quiet stance tasks (Day et al., 1993; Goodworth & Peterka, 2010; Kirby et al., 1987; Winter et al., 1998). These contrasting findings may be a result of the stance widths selected for analysis, which were greater for Hawkins and Sefton than for most of the previous research. The widest stance positions used by Goodworth and Peterka and Day et al. were 31 cm and 32 cm respectively, which are similar to the narrowest stance position (30 cm) used by Hawkins and Sefton. Such comparisons suggest that stability increases until stance width is approximately 30 cm, and then decreases for wider stances.

Given the differences between quiet stance tasks and precision shooting, research should now investigate the effects of stance position specifically on shooting performance. Comparisons have yet to be made for the effects of anterior-posterior stance width on performance. Research should examine how a range of stance widths similar to those used when pistol shooting affect stability, and whether any changes in stability are sufficient to influence shooting success. Finally, research needs to examine the effects of stance position on movement variability and coordination to determine the mechanisms behind a more or less successful stance position.

9.3 Research Aims and Hypotheses

Previous research has examined movement coordination and variability in quiet stance tasks, but has yet to examine how movement is controlled in pistol shooting. Understanding the mechanisms behind a successful shooting performance is important if athletes wish to further enhance success. With the exception of Hawkins & Sefton (2011), there is currently little evidence about the effects of stance position on shooting performance, and so research should consider whether adapting stance width is a potential method of influencing movement coordination and variability, and ultimately improving performance. The overall aims of the final two studies were to:

(i) identify the patterns of movement coordination and variability that are associated with a successful precision pistol shooting performance; and

(ii) examine how changing stance position can affect shot score and patterns of movement coordination and variability.

The first aim is addressed in Study 4, and was achieved by analysing the performances of elite precision pistol shooters as they completed shots as they would in training and competition. The second aim is examined in Study 5, and was achieved by modifying participants' stance positions and comparing the performances between each of these new stance positions. More specific objectives will be presented in the introduction to each study. The hypotheses that accompany the overall aims were:

(i) movement patterns of the upper limb will vary between shots, as a numberof different movement strategies could result in a similar location of the aim-point on the target;

(ii) movement variability would be greater for the movements of the torso and the upper limb than for the pistol;

(iii) wider mediolateral and anterior-posterior stance widths would improve shooting performance in comparison to narrower stance widths;

(iv) movement patterns would be more consistent for the least successful stance positions; and

(v) the most successful stance positions would be characterised by greater variability of upper limb movements and smaller variability for the pistol.

Chapter Ten

Pilot Testing – The Use of Motion Analysis Systems in Pistol Shooting

10.1 Suitability of the Motion Analysis System

The final two studies require an in-depth analysis of precision pistol shooting performance. Precision shooting requires extremely high levels of accuracy (Pellegrini & Schena, 1990) and any attempts to record movement during the event, and identify its subsequent effect on performance, must therefore be achieved using high resolution motion analysis techniques. A common method of motion analysis used in both sport and exercise research is a three dimensional motion analysis system which tracks the movement of reflective markers positioned at various anatomical sites on the body. Such analysis has been shown to be effective for a number of activities, such as walking (Chiu & Chou, 2012), the golf swing (Tucker et al., 2011), and aiming tasks (Tseng, Scholz, & Schöner, 2002). With the exception of Pellegrini et al. (2005), research has yet to provide a more in-depth analysis of pistol shooting performance using similar methods.

10.1.1 Testing Criteria

The tasks that have commonly been analysed in previous research are associated with movements of greater magnitude than those necessary for precision shooting. Thus, it was necessary to ensure that the procedure used in the final two studies would provide accurate and highly repeatable measurements of the exceptionally small movements produced by pistol shooters. The accuracy of a system refers to how closely the measurements it produces reflect that which is produced in reality (Windolf, Götzen, & Morlock, 2008), and the repeatability of measurements reflects how much the systems' measurements vary between trials (Feng & Max, 2014). To ensure that the system was appropriate for testing the following three criteria had to be met before testing could begin:

1. a system that could consistently record every marker within the capture

area;

2. a system with sufficient resolution to distinguish between a stationary marker and a marker placed on a participant completing a shooting task. There should also be minimal variation between the movements recorded for a number of stationary marker trials to ensure that measurements are highly repeatable; and
3. a system which could be synchronised with an optoelectronic shooting system without the two systems producing interference.

10.1.2 Pilot Testing 1 – Vicon 360

Initially, a Vicon 360 infra-red motion analysis system (Vicon, UK), which consisted of eight infra-red cameras with a sampling rate of 120 Hz was used for data collection. The opto-electronic shooting system used in studies 1 - 3 (SCATT, Russia) was again used to record the position of the aim-point of the pistol on the target. A number of pilot testing sessions were completed using this initial set-up in order to develop a procedure which would meet each of the three testing criteria.

Two conditions, one participant and one control, were used to examine the accuracy of the motion analysis system. In each condition, the position of three markers placed on the pistol (on the butt of the grip, the side of the cylinder and the end of the cylinder) was recorded. In the participant condition an experienced pistol shooter completed 15 shots to the best of their ability, and in the control condition the pistol was fixed to a tripod. This procedure was used to ensure that the system could differentiate between the movements of a pistol shooter and the movements recorded for a stationary marker, which would represent noise.

Following refinement over a number of preliminary pilot testing sessions, the procedure was able to meet the first two testing criteria. All three markers placed on the pistol were recorded consistently, matching criteria one. The range of movement produced for markers in the stationary trial was smaller than the range produced in the participant trial, thus also meeting criteria two. Issues were encountered when attempting to meet the final criteria, as the motion analysis and optoelectronic shooting systems would not record simultaneously without the infra-red emissions from each system producing interference. Consequently, the shooting system was replaced with an alternative system that did not experience interference when used with Vicon (Noptel Sport II; Noptel, Finland). By changing the optoelectronic shooting system, all three criteria were satisfied. Once all three criteria were met, the performances of five elite pistol shooters were recorded and analysed.

10.1.3 Pilot Testing 2 – Vicon MX

Following testing of five elite pistol shooters, an updated version of the motion analysis system became available to use as part of the testing procedure. The updated, Vicon MX motion analysis system (Vicon, UK) comprised fourteen T-Series, 16 megapixel, infra-red cameras (Vicon, UK) and two Bonita 720c video cameras (Figure 10.1). Each camera was linked to a Dell Precision T1650 computer, operating Vicon Nexus software (Vicon, UK), and sampling at 120 Hz for data acquisition.

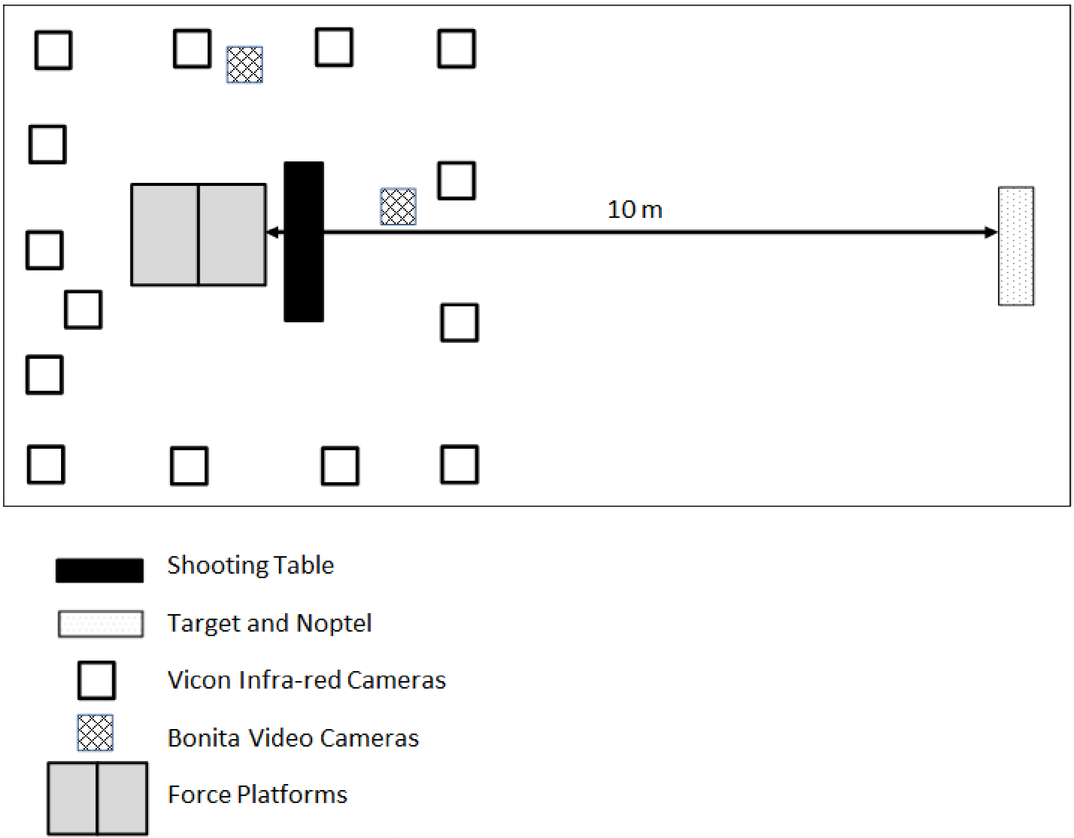


Figure 10.1. Laboratory set-up for the Vicon MX system including the motion analysis, force platform and opto-electronic shooting systems.

With the modified hardware, it was important to ensure that the testing procedure still satisfied the three criteria required for testing, and so pilot testing procedures similar to those detailed for the Vicon 360 system were completed. The movements of the same participant who took part in previous pilot testing sessions were compared to those recorded for markers placed on a skeleton and the pistol. A greater number of markers were used, to more closely recreate the number that would be recorded during testing, positioned on the spine (C7), upper limb (shoulder, elbow, wrist and hand) and pistol.

For each condition, two angles (shoulder and wrist) that would be used as part of the analysis for studies 4 and 5 were calculated. Each angle, measured in milliradians (mRad) (1 milliradian = 1/1000th radian), was calculated from the coordinates of three markers (Shoulder: C7, shoulder and elbow markers; Wrist: elbow, wrist and hand markers). All markers were consistently recorded, thus matching the first criteria. To ensure that the system met the second criteria, range of movement produced over 1 s was compared between the participant and stationary marker trials, to ensure that the system was accurate. Standard deviation over ten trials was also analysed to ensure measurements were highly repeatable. In reality, no movement occurred in the stationary, skeleton trials and so both range and standard deviation should be close to zero. The maximum range of movement recorded for the skeleton trials (0.015 mRad) (Table 10.1) indicated a high degree of accuracy. The accuracy of the system was further reflected by the comparisons between skeleton and participant trials, where range of motion and standard deviation were consistently greater for the participant trials (Table 10.1). This was most evident for vertical wrist movement which was 3.04 - 3.21 mRad in the participant trials, compared to just 0.002 – 0.010 mRad for the skeleton. Standard deviation for the skeleton trials was 0.005 and 0.003 mRad for vertical shoulder and wrist movement respectively, indicating a high degree of repeatability of measurements. Thus, the updated motion analysis system satisfied the second criteria by consistently distinguishing between markers used in participant and stationary trials. Interference between the motion analysis system and the SCATT opto-electronic system remained, and so the Vicon MX motion analysis system was used in conjunction with the Noptel shooting system to ensure that the third criteria was also met.

Table 10.1. Range of the movement for shoulder and wrist angles recorded for participant and skeleton (stationary marker) trials. Range of movement over 1 s is displayed for two trials in each condition. Red highlighted text denotes the greatest movement over the four trials, and grey represents the smallest movement. For the system to meet the second criteria, only skeleton trials should be highlighted grey.

	Vertical range of movement (mRad)		**Horizontal range of movement (mRad)**	
	Shoulder	**Wrist**	**Shoulder**	**Wrist**
Participant Trial 1	2.35	3.04	3.58	2.06
Participant Trial 2	0.51	3.21	1.73	2.75
Skeleton Trial 1	0.015	0.010	0.012	0.004
Skeleton Trial 2	0.002	0.002	0.001	0.009

NB: mRad = 1/1000th radian

10.1.4 Pilot Testing 3 – Vicon 360 and MX Comparisons

With the change in motion analysis system, it was important to investigate whether the original system used to record the performances of the first five participants produced a comparable level of accuracy and repeatability. Thus, an additional pilot testing session was designed in which both Vicon systems recorded simultaneously as a single pistol shooter completed ten shots. Reflective markers were placed in the locations detailed for pilot testing in section 10.1.3, and once the participant was ready to shoot, an additional marker was placed within the capture area. The appearance of this single marker on the recordings from both Vicon systems meant that the timings of each system could be synchronised, allowing for comparisons between the movements recorded during the final second before the shot.

To determine whether the two systems had a comparable degree of accuracy and repeatability, the range of movement of the shoulder and wrist was compared between the same two shooting trials and standard deviation was compared across ten trials. The range of movement measured by the original 360 system was consistently greater than that recorded by the new MX system (Table 10.2). This was most evident for vertical range of movement of the wrist, as measurements produced by the original system were over eight times that measured by the new system in trial two. The standard deviation over the ten shots was lower for the new MX system, indicating greater repeatability of measurements. For instance, the standard deviation of vertical shoulder and wrist movements were 1.05 and 0.94 mRad for the MX system in comparison to 1.73 and 2.92 mRad for the 360 system. Thus, whilst both systems could meet criteria two, and differentiate between a stationary trial and a participant shooting, the lower resolution of the original 360 system meant that it could not measure the movements produced when shooting to the same level of accuracy or repeatability as the new system.

To determine the extent to which the reduced accuracy recorded by the original 360 system affected the interpretation of results, cross-correlations were performed between the movements recorded for consecutive markers (shoulder – wrist and wrist – pistol) over a 1 s period (Table 10.3). In trial one, cross-correlations between the movements recorded for the horizontal wrist and pistol markers were negative from both systems. In trial two, cross-correlations between the movements recorded by the 360 system indicated that there was little similarity between the vertical movements of the wrist and the pistol (r = -.364). In contrast, the cross- correlations of movements recorded by the new MX system suggest that movements of the wrist and pistol are very similar (r = .916). These differences would lead to drastically different conclusions about the role of wrist movement when controlling motion of the pistol.

Whilst the original 360 system would provide sufficiently accurate and repeatable data for activities that involve a greater degree of movement, or a smaller capture volume, the exceptionally fine movements produced for pistol shooting were beyond that which it could accurately measure. This means there is the potential for the wrong interpretation of results when using the 360 analysis system. Given these findings, a decision was made that the data recorded for the five participants using the original 360 system could not be analysed in studies 4 and 5.

Table 10.2. Range of movement recorded for shoulder and wrist angles during the same trials by Vicon 360 and Vicon MX systems. Range of movement over 1 s is displayed for the same two trials for each system. Red highlighted text denotes the greatest movement over the four trials, and grey represents the smallest movement.

	Vertical (mRad)		**Horizontal (mRad)**	
	Shoulder	**Wrist**	**Shoulder**	**Wrist**
Trial 1: Vicon 360	3.25	8.92	3.88	15.99
Trial 1: Vicon MX	1.08	2.13	1.08	2.86
Trial 2: Vicon 360	6.60	11.29	7.59	10.34

NB: mRad = 1/1000th radian

Table 10.3. Cross-correlations between each angle recorded during the same trials by Vicon 360 and Vicon MX systems.

	Vertical		**Horizontal**	
	Shoulder - Wrist	**Wrist – Pistol**	**Shoulder - Wrist**	**Wrist – Pistol**
Trial 1: Vicon 360	-.326	-.493	.415	-.545
Trial 1: Vicon MX	-.912	-.364	-.191	-.662
Trial 2: Vicon 360	-.140	-.296	-.365	-.547
Trial 2: Vicon MX	.986	.916	-.288	-.158

10.2 Methodological Issues: Noptel Shooting System

To determine the accuracy of the optoelectronic shooting system, cross-correlations were used to compare the movement of the markers placed on the pistol, as measured by the Vicon MX system, with the movement of the aim point on the target, as measured by Noptel. Cross-correlations between the movement of the pistol marker and the movement of the aim-point over 20 shots ranged between -.835 to .746 and -.539 to .857 for horizontal and vertical movements respectively. Thus, issues with the Noptel system meant that the horizontal and vertical components of movement were not accurately recorded. Previous research which has examined movements of a hand-held laser pointer on a target, have reported cross-correlations of between .68 to .77 between the movement of the hand and the laser movement on the target (Keogh et al., 2004). Consequently, the Noptel optoelectronic shooting system was not considered sufficiently accurate to represent the movements of the pistol on the target when shooting. As a result, studies 4 and 5 examined the movement of the pistol, but were not able to examine the subsequent movement of the aim-point on the target.

Chapter Eleven

Research Study 4 - Movement Coordination and Variability of Elite Precision Pistol Shooting

11.1 Introduction

To date, the majority of pistol shooting research has considered the outcomes of a shooting performance, such as movements of the pistol and centre of pressure (Ball et al., 2003; Mason et al., 1990). Limited research has examined the sources of each movement, such as motion of the torso or the upper limb. By incorporating these additional aspects of analysis it will be possible to determine the mechanisms behind a successful precision shooting performance, and consequently enhance performance in an event where precision and accuracy are vital to success.

Only two studies have examined body movements when shooting in detail, beginning with Arutyunyan (1969) who found a high degree of coordination between movements of the shoulder and wrist, and the wrist and pistol. Pellegrini et al. (2005) built on these findings, reporting high correlations between the upper limb movements that affected horizontal position of the pistol, and lower correlations between the movements that affected vertical pistol movement. This led Pellegrini et al. to conclude that the upper limb moves as one segment when controlling horizontal pistol movements, but that the method of controlling vertical pistol movements is more complex.

Pellegrini et al. (2005) generated a more detailed understanding of pistol shooting performance than was previously achieved from the analysis of centre of pressure and pistol movement. Their analysis was based on discrete correlations which demonstrated a strong linear association between the movements of each segment, but did not assess the temporal aspects of performance, such as the change in movement during the final second before the shot. This is a common limitation of discrete analysis methods (Bartlett et al., 2007; Preatoni et al., 2013), and has led to an increase in the popularity of continuous methods of analysis to evaluate performance. Such methods of analysis may have an important role in the study of exceptionally small movements such as those associated with pistol shooting. Research should now build on Pellegrini et al.'s findings by using continuous methods to analyse movement of the torso and upper limb, and identify the movements that are most closely associated with the movements of the pistol.

As yet, few studies have attempted to describe the variables that influence movement of the pistol. Researchers have considered the movements associated with other precision-based tasks, such as pointing to a target (Kim et al., 2012; Latash, Aruin, & Zatsiorsky, 1999; Tseng et al., 2002). Two popular concepts within the literature are the existence of synergies within a movement system, and the principle of motor abundancy. Research into movement synergies has demonstrated that, rather than producing one consistent output, the segments that make up a movement system work concurrently to ensure that a task is completed accurately (Gorniak, Duarte, & Latash, 2008; Latash et al., 1999; Preatoni et al., 2013). This means that there are many movement strategies that can be used to achieve the same task outcome (Tseng et al., 2002). Thus, whilst pistol shooters are attempting to achieve a highly consistent performance, it is likely that more than one movement pattern can be used to ensure that the aim point of the pistol remains in the same location. Research should now investigate the movement patterns that are produced in pistol shooting, and the extent to which any patterns vary both within and between shooters. Any group tendency towards a particular movement pattern would indicate a successful strategy to control movements of the pistol.

The principle of motor abundancy is related to the concept of movement synergies, and suggests that variability of the components within a movement system are often high to ensure that the variability of the task outcome remains low (Gorniak et al., 2008; Scholz & Schöner, 1999; van Beers, Haggard, & Wolpert, 2004). This pattern has been observed for a wide range of skills, from gross movements such as sprinting (Bradshaw et al., 2007), to highly repetitive tasks such as the golf swing (Langdown et al., 2012) and pointing tasks (Tseng et al., 2002). In pistol shooting this pattern should be represented by high variability of upper limb movements, and low variability in pistol position. Research should examine whether this pattern is displayed by elite pistol shooters, or whether there are other strategies which result in a successful shooting performance.

There is currently a limited understanding of the movements and processes behind a successful precision shooting performance. Thus, the current research will produce a detailed kinematic analysis of the movements produced in the final second before a shot. The objectives of this research, designed to meet the overall aims detailed in Chapter 9 (Section 9.4) are to:

(i) examine the movement patterns of the torso and upper limb to identify the movements which are most closely associated with motion of the pistol;

(ii) quantify the movement variability of the torso, upper limb and pistol to identify how performance variability influences the variability in pistol position; and

(iii) identify any movement patterns or variability that are common to all participants.

Analysis of movement coordination and variability will help to develop a more detailed understanding of the way in which pistol movement is created and controlled. This will help to identify whether there are any performance characteristics common to all participants, thus determining key traits of an elite shooting performance. The hypotheses to accompany these three objectives are:

(i) movement patterns of the upper limb will vary between shots, as a number of different movement strategies could result in a similar location of the aim-point on the target;

(ii) movement variability will be greater for the movements of the torso and the upper limb than for the pistol;

11.2 Methods

11.2.1 Participants

Ten elite female pistol shooters (mean age 28.4 ± 10.2 years, mass 67.3 ±7.7 kg) with an average pistol shooting experience of 9.5 (± 3.3) years completed the shooting task. Throughout all testing sessions participants used the equipment with which they would normally compete (shooting shoes, training/competition pistol; 4.5 mm calibre compressed air CO_2 single shot air pistol, weighing less than 1500 g). Written informed consent was obtained from all participants prior to testing, which was approved by the Manchester Metropolitan University research ethics committee.

11.2.2 Tasks

Testing took place in a specially designed shooting range within the University's Biomechanics Laboratory which met all ISSF shooting regulations. Participants stood behind a firing line 10 m from the target (Figure 11.1), with a table placed in front of the line on which participants rested the pistol, pellets, and any other equipment they were using. Each participant had an unlimited time period in which to complete twenty live fire shots, aiming at a standard air pistol target (17 cm × 17 cm), and attempting to achieve the highest possible score.

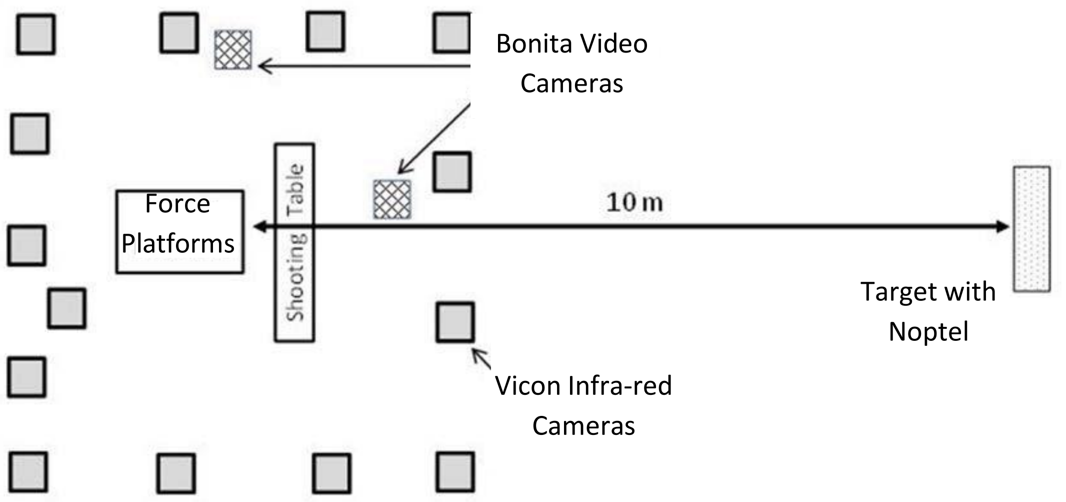


Figure 11.1. Laboratory set-up including motion analysis (Vicon), force platform (AMTI) and opto-electronic shooting (Noptel) systems.

11.2.3 Data Collection

11.2.3.1 Body Movement and Centre of Pressure Measurements

A Vicon MX motion analysis system (Vicon, UK) recorded the three-dimensional coordinates of 14 reflective spherical markers (14 mm diameter) positioned at various landmarks on the body and pistol. Each body marker was positioned according to common locations recommended for use with the Vicon system (Davis III, Ounpuu, Tyburski, & Gage, 1991; Kadaba et al., 1989) (Figure 11.2) (Table 11.1). Two additional markers were included to capture the movement of the pistol (Figure 11.3). These were:

Pistol 1 (right side of the cylinder, in front of the trigger);

Pistol 2 (end of the cylinder of the pistol).

Each marker was positioned to aid analysis of pistol movement without obscuring the participants' vision or shooting technique. To record each of the nineteen markers, 14 T-Series infra-red cameras (Vicon, UK) and two Bonita 720c video cameras were positioned around the perimeter of the laboratory. Cameras were linked to a Dell Precision T1650 computer, operating Vicon Nexus software (Vicon, UK), sampling at 120 Hz for data acquisition.

Two AMTI OR6-7-2000 force platforms (Advanced Mechanical Technology, Inc. Massachusetts), each measuring 46.7 × 51.0 cm were used to record ground reaction force throughout the aiming period of each shot. A Data Translation 3002 12-bit A-D converter linked the platforms to the same computer which recorded the body marker position data. Vicon Nexus software recorded kinetic data and body marker co- ordinate data simultaneously, both sampled at 120 Hz. Nexus software also calculated centre of pressure location from the ground reaction force data for each force platform. To enable synchronisation of the data with the shot, a microphone was positioned close to the pistol. The output from the microphone was represented as a voltage pulse on an additional channel. Participants positioned themselves with one foot fully on each force plate whilst shooting; this required no change to their normal shooting stance.

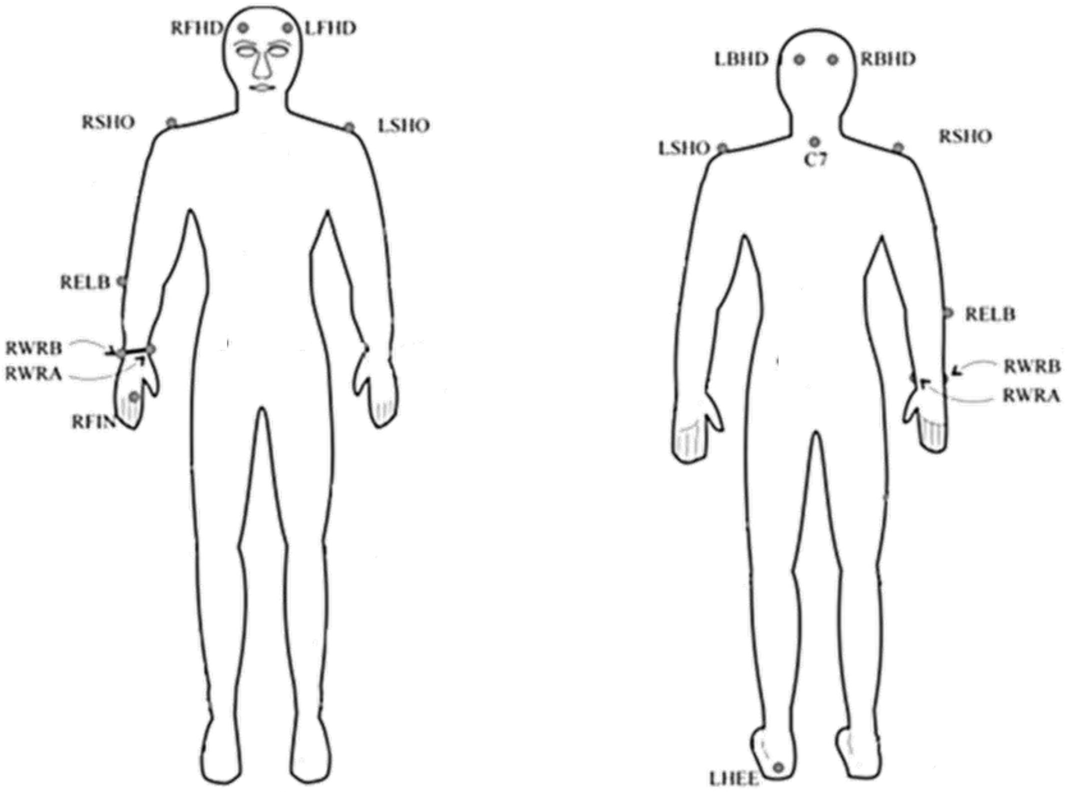


Figure 11.2. Placement of the full body marker set for a right handed shooter, adapted from the 37 locations specified by the Vicon Plug-in Gait model (Davis III et al., 1991; Kadaba et al., 1989).

Figure 11.3. Placement of the additional markers on the pistol, and a participant shooting with the body and pistol marker set.

Table 11.1. Definition of marker placement abbreviations presented in Figure 11.2.

Abbreviation	Full Name	Location
RFHD; LFHD	Right forehead; Left forehead	Either side of the forehead, above the temples.
RBHD; LBHD	Right backhead; Left backhead	Either side of the back of the head, in line with the forehead markers.
C7	C7 of the vertebral column	Spinous process of the seventh cervical vertebrae.
RSHO; LSHO	Right shoulder; Left shoulder	Right and left shoulders, placed on the acromio-clavicular joint.
RELB*	Right elbow	Lateral epicondyle of the humerus.
RWRA*;	Right wrist A;	Lateral aspect of the wrist joint when in the anatomical position.
RWRB*	Right wrist B	Medial aspect of the wrist joint, placed on the lateral epicondyle of the ulna.
RFIN*	Right finger	Dorsum of the hand, below the second metacarpal.
LHEE*	Left heel	On the heel of the left shoe, over the calcaneus.

N.B. Marker positions as used for right handed participants. All markers highlighted with'*' were the opposite for left handed participants (e.g. right elbow marker replaced with left elbow marker).

Following data acquisition, three-dimensional marker co-ordinate data, vertical ground reaction force data and centre of pressure co-ordinate data were exported from Vicon Nexus software to Microsoft Excel (Microsoft Excel 2010, Microsoft ,USA). The centre of pressure for the whole body was calculated by combining the ground reaction force and centre of pressure data from each force platform. This procedure was identical to that previously reported for studies 1-3 (Chapter 4, section 4.3.2). Centre of pressure and marker co-ordinate data were both reduced to only include information for the final second preceding the shot.

11.2.3.2 Pistol Movements and Shot Location

Pistol movements were recorded using a Noptel-ST 2000 Sport II shooting system (Noptel, Finland), operated using NOS4 software (Noptel, Finland) recording at 67 Hz, a frequency pre-determined by the software. The Noptel system comprised an infra-red transmitter and receiver unit attached to the pistol which recorded the position of the unit in relation to reflectors fixed to the target (Figure 11.4). By recording the position of the transmitter in relation to the target it was possible to determine the location of the aim-point of the pistol on the target. Shot scores were recorded based on the position of the pellet on the target, in accordance with ISSF regulations.

11.2.4 Data Analysis

Shot score, used to measure shooting accuracy, was recorded directly from the target, to a maximum of 10.9. Shot dispersion, measured as the horizontal and vertical spread of the shot group, was recorded from the target and used to assess shooting precision. A greater shot dispersion reflected a wider distribution of shots on the target, and thus low repeatability in the location of the shots. Trace length, used to represent pistol movement, was recorded over the final second before the shot, and calculated as the distance (mm) moved by the aim point of the pistol on the target along the X (horizontal) and Y (vertical) axes.

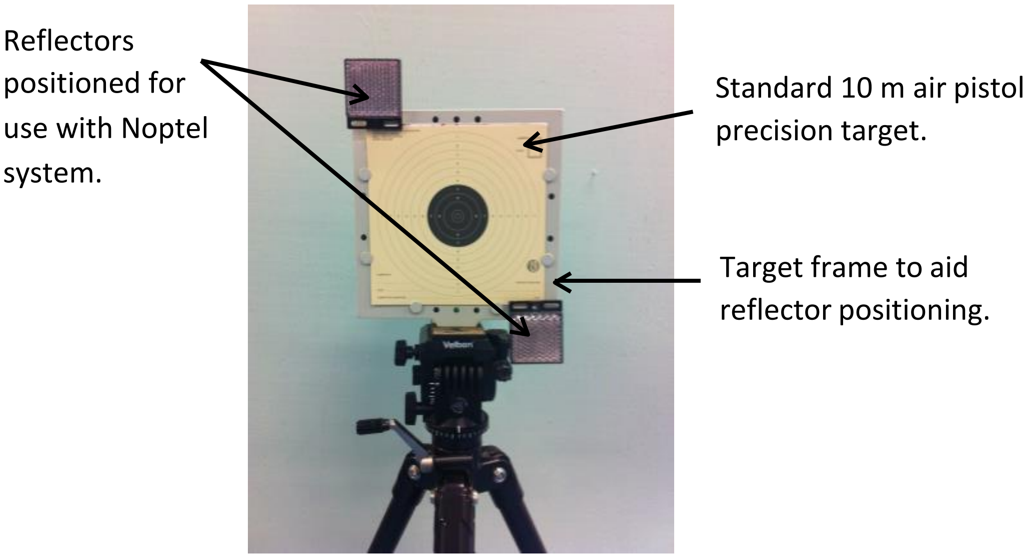


Figure 11.4. Set up of Noptel-ST 2000 Sport II required to record pistol movement.

Two variables, centre of pressure range (mm) and path length (mm), were selected to represent centre of pressure movement over the final second before the shot, in accordance with previous shooting research (Ball et al., 2003; Mason et al., 1990). Both variables were calculated using the same method as previously reported in studies 1-3 (Chapter 4, section 4.4). To aid comparisons between centre of pressure movement and pistol movement, each direction of centre of pressure movement was analysed in relation to the equivalent direction of pistol movement across the target (Figure 11.5). Mediolateral movement reflected motion along a plane perpendicular to the target. This movement takes place in the same plane as vertical pistol movement, and thus has the potential to influence vertical motion of the pistol. Anterior-posterior movement represented motion across a plane parallel to the target. This movement takes place in the same plane as horizontal pistol movement, with the potential to influence the horizontal motion of the pistol across the target.

A number of angles, chosen to reflect the movements important to pistol shooting, were selected for the analysis of body movement. Each angle was calculated based on the arrangement of a combination of either two or three reflective body markers (Table 11.2), and was either a relative joint angle (Shoulder, Wrist, Pistol), or an absolute angle representing body sway (Mediolateral and Anterior-Posterior Torso Sway).

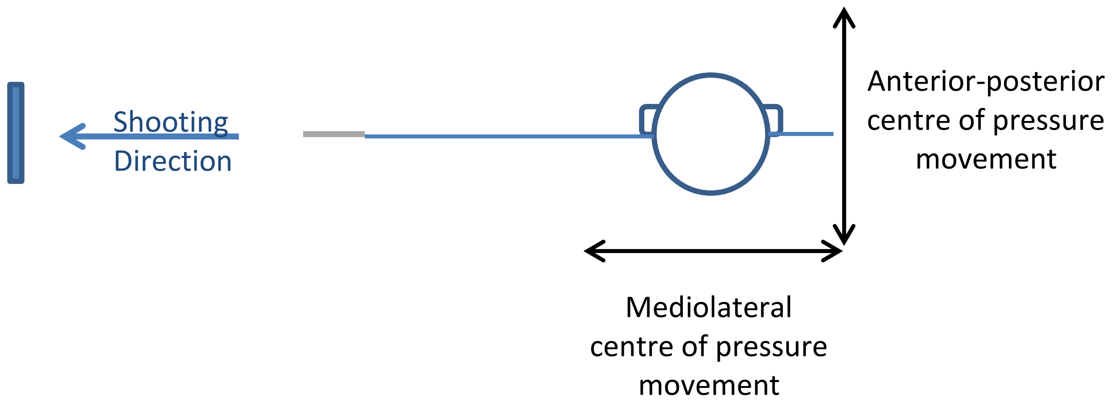


Figure 11.5. Centre of pressure movement in relation to the target.

Movements were grouped into two categories based on the plane in which they took place. One category included the movements that took place along a vertical plane running between the target and the pistol, and thus had the potential to influence vertical motion of the pistol (Figure 11.6). The second category included the movements that took place along a horizontal plane, with the potential to influence horizontal motion of the pistol (Figure 11.6). The movements that were included in each category, and the terms which will be used to describe each movement, are presented in Table 11.2. All angles were converted from degrees to milliradians (mRad), a popular convention to measure angles within shooting. One mRad is equivalent to 1/1000th radian. The equations used to calculate each angle are presented in Appendix 3.

Table 11.2. The combination of markers required to calculate each angle, and descriptions of the movements produced when each angle either increases or decreases.

					Movement Description	
Plane of Movement	**Angle**	**Marker 1**	**Marker 2**	**Marker 3**	**Increase in Angle**	**Decrease in Angle**
Vertical (perpendicular to target)	Mediolateral Torso+	C7	Left Heel	Horizontal^{+}	Sway away from target	Sway towards target
	Shoulder	C7	Shoulder	Elbow	Adduction	Abduction
	Wrist	Elbow	Mid-Wrist	Hand	Ulnar deviation	Radial deviation
	Pistol	Floor	Pistol 1	Pistol 2	Downwards tilt	Upwards tilt
Horizontal (parallel to target)	Anterior-posterior Torso*	C7	Left Heel	Horizontal^{+}	Posterior sway	Anterior sway
	Shoulder	C7	Shoulder	Elbow	Horizontal extension	Horizontal flexion
	Wrist	Elbow	Mid-Wrist	Hand	Extension	Flexion
	Pistol	Floor	Pistol 1	Pistol 2	Pans right	Pans left

* Angles used to represent body sway.
\+ Angle in relation to line drawn in a vertical plane, perpendicular to the target, from the left heel marker.
♦ Angle in relation to line drawn in a horizontal plane, parallel to the target, from the left heel marker.

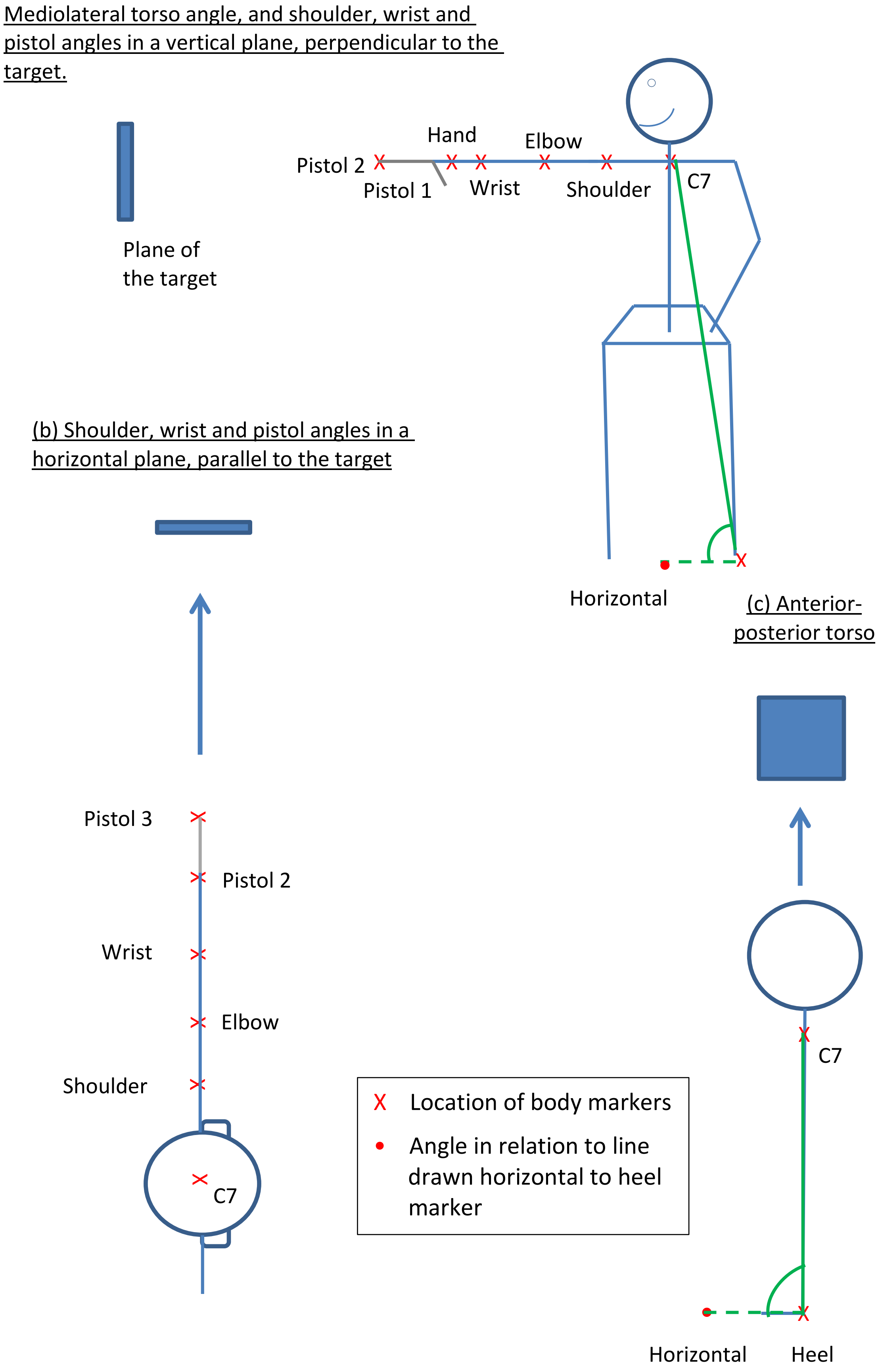


Figure 11.6. Angles and torso sway (a) in a vertical plane, perpendicular to the target, and (b, c) in a horizontal plane, parallel to the target.

11.2.5 Statistical Analysis

Data did not meet parametric assumptions, and transformations were performed. Comparisons were made between the natural log transformation and Log10 transformation to determine which was the most effective to allow the data to meet parametric assumptions, but still closely reflect performance. The Log10 transformation is a more powerful test to reduce positively skewed data, but the exceptionally small changes in each variable meant that the results did not closely reflect performance (Figure 11.7a). As such, the natural log was selected as the most effective way to transform the data (Figure 11.7b). Even following transformation, some data sets did not meet parametric assumptions, and so with the exception of cross-correlations, non-parametric tests were selected. In the absence of a non-parametric equivalent for cross-correlations, each test was performed using the transformed data sets, in an attempt to use data that met the parametric assumptions as closely as possible.

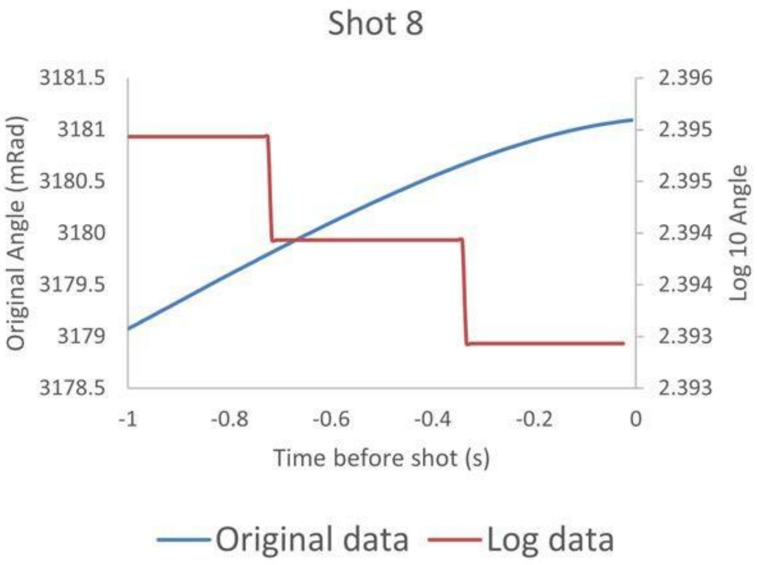


Figure 11.7a. Comparisons between original data recorded for the wrist, and the effects of the Log10 transformation.

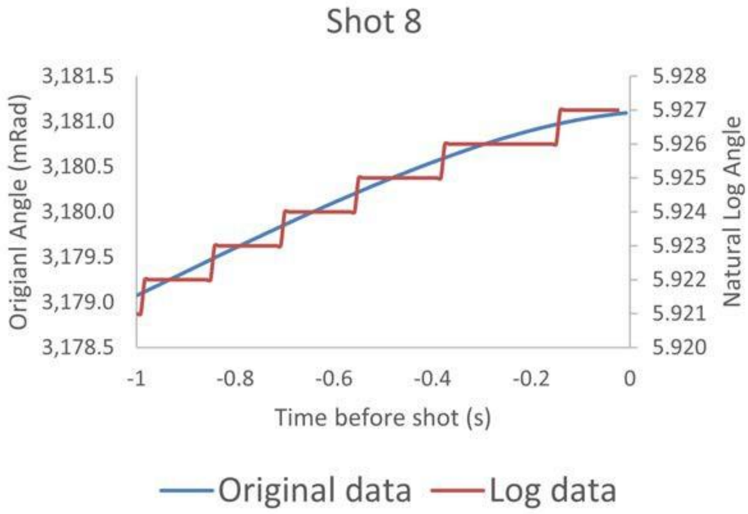


Figure 11.7b. Comparisons between original data recorded for the wrist, and the effects of the Natural Log transformation.

Cross-correlation analysis was used to compare the changes in different joint angles over the final second before the shot. Cross-correlations assess the degree of similarity between two curves (Stergiou, 2004), and can be used to assess the coordination between different joints or body segments (Davids, Bennett, & Newell, 2006). The use of this technique made it possible to understand how movement is transferred through the torso and upper limb to the pistol, and ultimately determine the movements that are likely to have the greatest influence on shooting outcome. Cross-correlations were performed between each of the movements that could affect horizontal pistol motion, and between each of the movements that could affect vertical pistol motion. This method can provide coaches and athletes with more practical information concerning the way in which a successful shooting performance is generated.

An additional aspect of cross-correlation analysis was the comparison between movement patterns of the centre of pressure and torso sway. Anterior-posterior movement path of the centre of pressure was correlated with anterior-posterior torso sway, and mediolateral centre of pressure path was correlated with mediolateral torso sway. These comparisons made it possible to identify how accurately the changes in centre of pressure movement actually reflect movements of the body when shooting.

Maximum, minimum and median range of movement (±IQR) over the twenty shots provided a discrete analysis of the degree to which each movement changed over the final second. Range of movement was quantified for every angle for each of the twenty shots, and the median value was calculated. Maximum and minimum range of movement were used to represent the shot with the greatest and smallest range of movement respectively. This provided a clear comparison of the degree of movement produced for the torso, upper limb and pistol, and how this differed for horizontal and vertical movements.

Performance variability was assessed by breaking the final second into 0.008 s time periods. The median angle and the IQR across the twenty shots was calculated for each time period, with the IQR used to quantify variability across the twenty shots. Two aspects of performance variability were considered; positional variability and movement variability, examples of which are provided in more detail below (Figures 11.8 and 11.9).

Positional variability represented how closely each angle was reproduced over the twenty shots, indicating how well participants could recreate their shooting position. As an example, the shoulder angles produced by one participant over the twenty shots are demonstrated in Figure 11.8(a). The median angle for each 0.008 s time period over the final second before the shot was calculated, and plotted in Figure 11.8(b). To examine how much shoulder movement varied from the median over the twenty shots, IQR was also plotted as error bars for each 0.008 s period (Figure 11.8b). This was used to represent positional variability, and how it varied throughout the final second. Whilst positional variability provided a clear indication of the changes in a participants' body orientation between shots, the degree of variability far exceeded the range of movement of each angle over the final second. As such, it was not possible to identify the changes in movement pattern, such as an increase or decrease in angle, prior to the shot (Figure 11.8).

To incorporate movement variability into the analysis it was essential to reduce the positional variability between trials. To achieve this, the median angle was calculated for the first 0.008 s time period, and the data from each shot was adjusted to begin at the median start angle. The median adjusted angle and IQR were plotted, which made it possible to identify how closely participants recreated a movement pattern between shots (Figure 11.9).

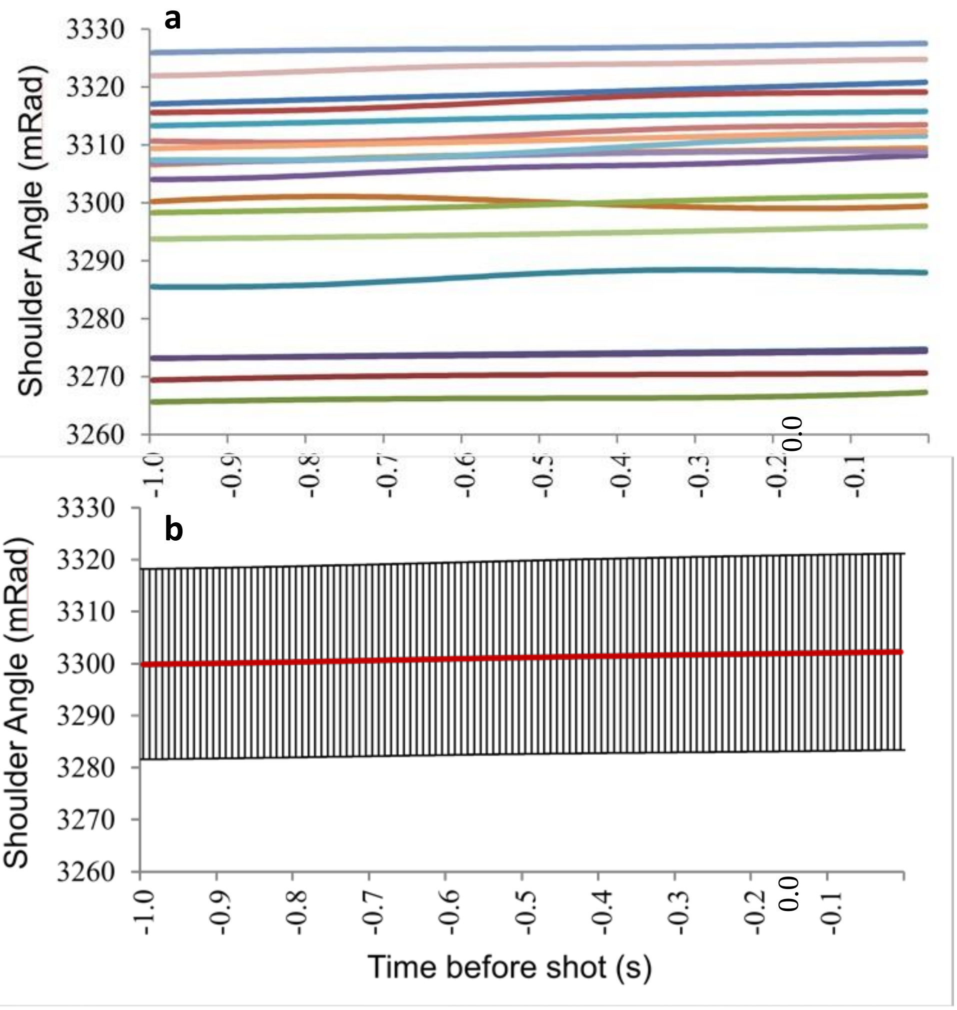


Figure 11.8. a) Vertical shoulder angle recorded over 20 shots for one participant, and b) median angle (shown in red) (± IQR) included as a measure of positional variability. mRad = 1/1000th radian.

To aid comparisons between the degree of variability produced for the torso, upper limb and pistol, the median variability over the final second was also calculated. This represented the median of the IQR values across each of the 0.008 s values within the final second. For instance, median variability of the shoulder in Figure 11.9 is 0.99 mRad

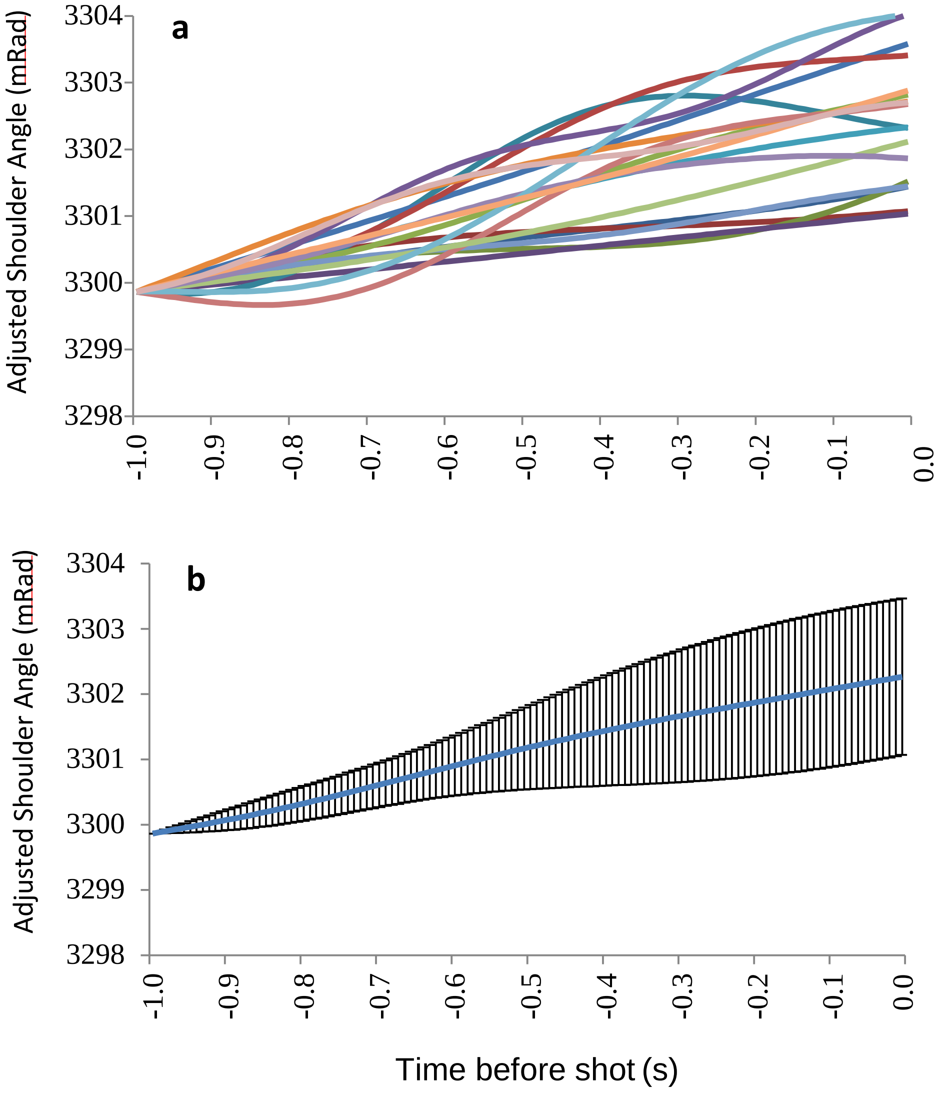


Figure 11.9. a) Adjusted vertical shoulder angle over 20 shots for one participant, and (b) median adjusted angle (shown in blue) (± IQR) included as a measure of movement variability. mRad = 1/1000th radian.

11.3 Results

11.3.1 Shot score and Shot Dispersion

The success of each participant varied considerably, with a range of 12 points between the highest and lowest scores achieved (Table 11.3). In addition to the variation in scores, both horizontal and vertical dispersion of the shot groups increased between the highest and lowest scoring participants. Participant 4, who achieved the highest score, had the smallest horizontal and vertical shot dispersion of all participants. This was particularly apparent for horizontal shot dispersion, which was 8 mm smaller than for any other participant. Horizontal shot dispersion was between 8 mm – 12 mm greater than vertical dispersion for three participants (Table 11.3). Only participant 5, who had the lowest score, produced a greater degree of vertical than horizontal shot dispersion.

Table 11.3 Total score and horizontal and vertical shot dispersion achieved by each participant over 20 shots.

Participant Number	Score (maximum 200)	Shot Dispersion (mm)	
		Horizontal	Vertical
4	189	26	26
1	187	**34**	26
3	184	**35**	26
2	179	**45**	33
5	177	34	**39**

11.3.2 Movement Coordination

Cross-correlations were used to compare torso sway and movements of the shoulder, wrist and pistol over the final second before the shot. Correlations were performed for each of the twenty shots to identify how the changes in torso sway and upper limb movement over the final second compared to the changes in movement of the pistol. Cross-correlations compare how two signals change over time, from which a value between -1 and +1 is produced to quantify the degree of similarity between the signals. A positive correlation reflects two movements that are highly similar (e.g. if the shoulder and elbow both flex synchronously the final second before the shot), and a negative correlation reflects two movements that are highly similar, but take place in opposing directions (e.g. if the shoulder flexion mirrors the elbow extension) (Figure 11.10). A correlation close to 0.0 reflects two movements that show few similarities as they change over time (e.g. the shoulder flexes, whilst the wrist flexes then extends). This analysis was used to determine the movement patterns responsible for control of horizontal and vertical pistol movements.

11.3.2.1 Centre of Pressure Movement and Torso Sway

To examine the effectiveness of using centre of pressure movement to represent body sway in pistol shooting, Pearson’s correlations were performed between centre of pressure variables and torso sway. Neither centre of pressure range nor path length were significantly correlated with torso sway ($p>.05$). Cross-correlations between the path of the centre of pressure and torso sway during the final second of every shot were low, with an average across participants of .16 (±.51) and .04 (±.38) for anterior-posterior sway and mediolateral sway movements respectively.

11.3.2.2 Torso Sway and Pistol Movement

Comparisons were made between anterior-posterior torso sway and horizontal movements of the pistol. As shown in Figure 11.10, high positive correlations would indicate that torso sway contributed to pistol movement, whilst high negative correlations would indicate that torso sway counteracted, and produced opposing movements, to the pistol.

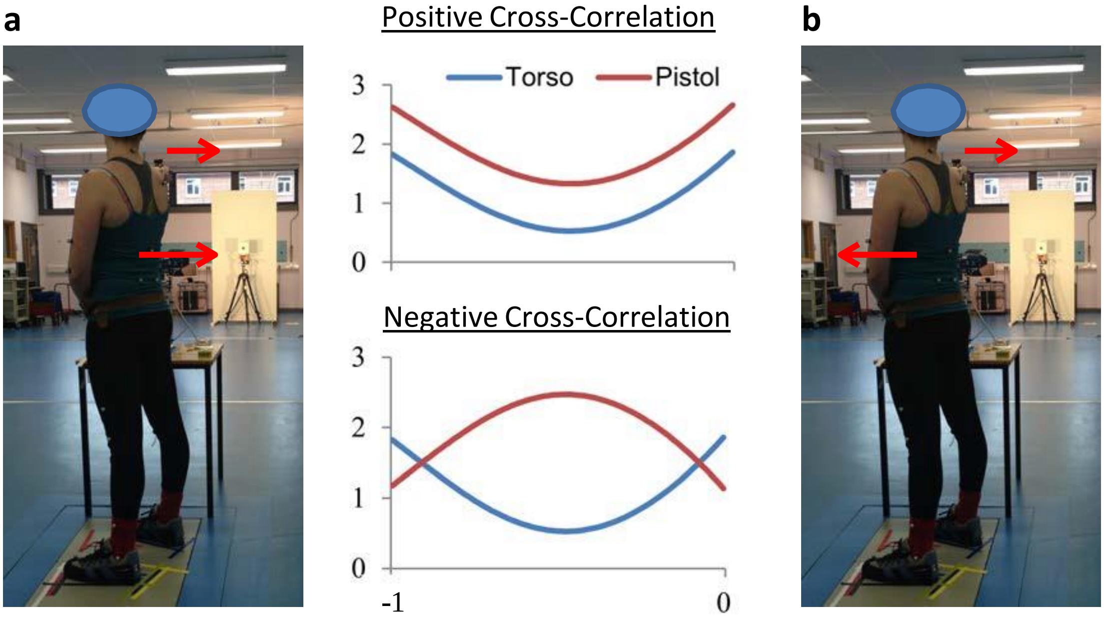


Figure 11.10. Example movements that would produce (a) positive and (b) negative correlations between anterior-posterior torso sway and horizontal pistol movement.

All participants produced negative cross-correlations between anterior-posterior torso sway and horizontal movements of the pistol (Table 2). These opposing movements, as demonstrated in Figure 11.10(b), suggest that the upper limb counteracted torso sway in an attempt to maintain a consistent position of the pistol on the target. Each participant produced anterior sway accompanied by the pistol panning right across the target for some shots, and posterior sway accompanied by the pistol panning left for others. For instance, participant 1 produced anterior sway in 5 shots and posterior sway in the other 15, whilst participant 4 produced anterior sway for 12 shots and posterior sway for 8.

Table 11.4. Mean cross-correlations (± SD) between movements of the torso and the pistol over the 20 shots.

	Participant				
	1	**2**	**3**	**4**	**5**
Anterior-posterior	-.89 (.16)	-.89 (.15)	-.30 (.65)	-.72 (.35)	-.87 (.22)
Mediolateral	-.00 (.80)	.16 (.71)	.72 (.32)	-.18 (.36)	.21 (.74)

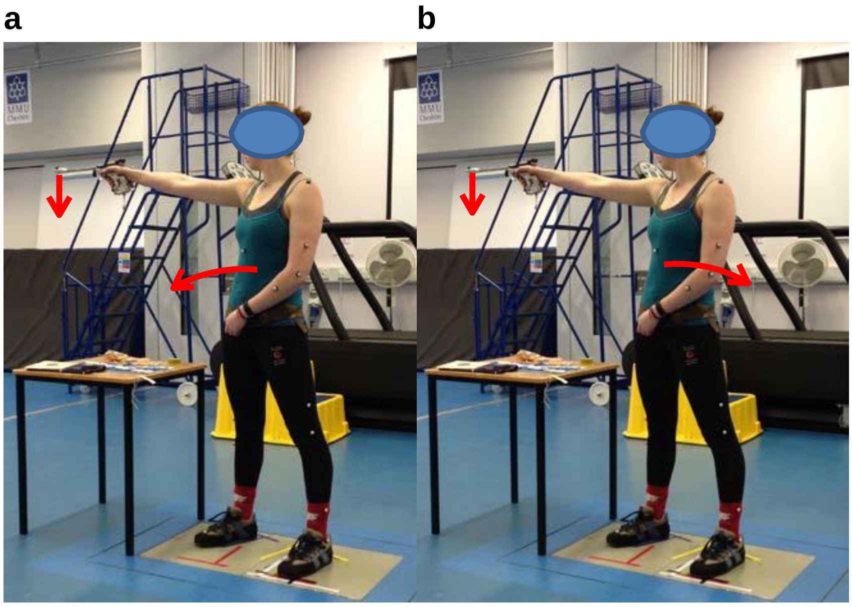


Figure 11.11. Example movements that would produce (a) positive and (b) negative correlations between mediolateral torso sway and vertical pistol movement.

Mediolateral torso sway was compared to vertical movements of the pistol. Examples of a positive correlation, produced if torso sway contributes to pistol movement, and a negative correlation, produced if torso sway counteracts pistol movement, are presented in Figure 11.11.

Cross-correlations between mediolateral sway and vertical pistol movement varied more over the twenty shots than those for anterior-posterior sway and horizontal pistol movements. Average cross-correlations over the twenty shots were low for participant 1 and participant 4 (Table 11.4). For participant 4 this was a result of consistently low cross-correlations between mediolateral sway and vertical pistol movement, suggesting that torso sway had little effect on vertical pistol motion. The low mean value recorded for participant 1 was a result of a wide variation in correlations, ranging between .96 and -.92. Only participant 3 produced a strong relationship between the two movements, with positive correlations produced for all shots. Thus, for 17 shots the torso swayed away from the target, and the pistol tilted upwards, and for 3 shots the torso swayed towards the target and the pistol tilted down (Figure 11.11a).

If movements of the pistol were caused by torso sway alone, high positive cross-correlations would be expected between torso sway and pistol movement. These results were not apparent for control of horizontal pistol movements, and only one participant displayed this pattern for control of vertical pistol movements. Thus, other movements must be involved, justifying comparisons between upper limb movements to determine additional methods of controlling pistol movement.

11.3.2.3 Control of Horizontal Pistol Movement

A potential cause of the opposing movements between anterior-posterior torso sway and horizontal pistol movement is the motion of the shoulder, specifically horizontal flexion and extension. If negative cross-correlations are produced between the torso and the shoulder, then the arm will move in the opposite direction to torso sway, as shown in Figure 3a. Assuming that the wrist does not produce further corrective movements, then the pistol will also move in the opposite direction to torso sway, resulting in the negative cross-correlations that were observed between the torso and the pistol.

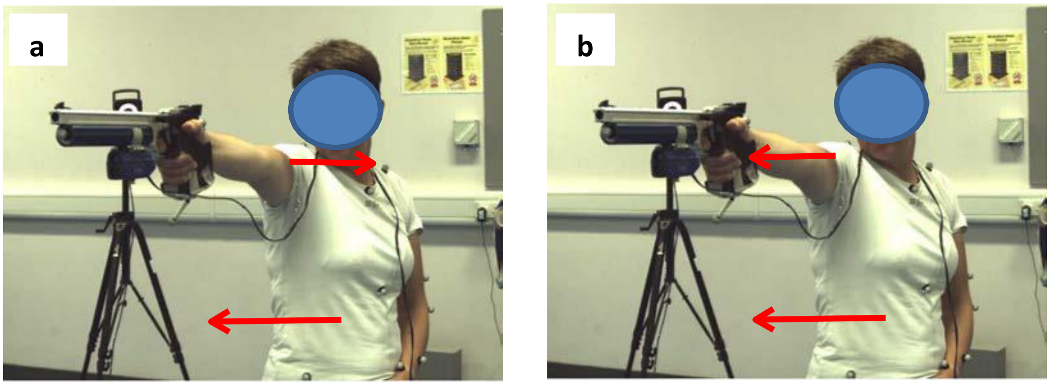


Figure 11.12. Example movements that would produce (a) negative and (b) positive correlations between anterior-posterior torso sway and shoulder horizontal flexion-extension.

Only participant 1 produced a consistent pattern between anterior-posterior torso sway and shoulder movement. Positive cross-correlations indicated that movements of the shoulder complimented torso sway, as anterior torso sway was accompanied by horizontal flexion of the shoulder in 8 shots, and posterior torso sway was accompanied by horizontal extension in the other 12 shots. No clear movement patterns were produced for the other participants, as cross-correlations varied between every shot (Table 11.5). Furthermore, many cross-correlations were low, indicating that horizontal flexion and extension was independent of the direction of torso sway.

None of the comparisons between anterior-posterior torso sway and shoulder movements fully explained the opposing movements of the torso and pistol. Thus, the most likely source of the opposing movements between the torso and pistol is the wrist. This was clear for participant 1, for whom movements of the wrist counteracted shoulder movement and complimented movements of the pistol in all twenty shots (Table 11.5). For instance, in the 8 shots where anterior torso sway was accompanied by horizontal shoulder flexion, wrist extension was produced so that the pistol panned right across the target.

Table 11.5. Mean cross-correlations (± SD) between anterior-posterior torso sway, shoulder and wrist movement and horizontal pistol movements.

	Participant				
	1	**2**	**3**	**4**	**5**
Torso – Shoulder	.81 (.27)	-.01 (.85)	.14 (.77)	.28 (.73)	-.27 (.82)
Shoulder - Pistol	-.70 (.27)	.26 (.81)	-.17 (.73)	.06 (.90)	.33 (.77)
Shoulder - Wrist	-.62 (.40)	-.05 (.64)	-.28 (.62)	-.40 (.60)	.07 (.83)
Wrist - Pistol	.67 (.26)	.18 (.64)	.09 (.76)	.05 (.62)	.20 (.69)

No other participant produced a single, consistent movement pattern for all shots. Participant 4 experienced an interaction between the shoulder and the wrist, resulting in two movement patterns, reflected by the low average correlations in Table 11.5. In 14 shots the shoulder complimented torso sway (.81 ±.19), and was counteracted by movements of the wrist, and in the other 6 shots the shoulder counteracted torso sway (-.69 ±.30) and the wrist complimented shoulder movement. Thus, adapting the movement patterns of the upper limb meant that horizontal pistol movement remained opposite to anterior-posterior torso sway (Table 11.4).

For participant 2, the opposing movements between anterior-posterior torso sway and horizontal pistol movements could be explained for 10 shots where shoulder movement counteracted torso sway (Torso and Shoulder: -.76 ±.27; Torso and Pistol:.84 ±.22). The cause of the opposing sway and pistol movements were less clear for the other 10 shots where shoulder movement complimented torso sway. Correlations between the shoulder and wrist, and the wrist and the pistol, varied between every shot.

Cross-correlations between the torso, upper limb and pistol varied between every shot for participants 3 and 5 (Table 11.5). Thus, there were few clear patterns to explain how horizontal movements of the pistol were controlled. Whilst opposing movements were produced between anterior-posterior torso sway and horizontal pistol movement for participant 5 (Table 11.4), the correlations between the torso and upper limb varied between every shot. Cross-correlations between torso sway, upper limb movement and horizontal pistol movement varied between every shot for participant 3. Consequently, there was no clear evidence for the way in which either participant controlled horizontal movements of the pistol.

11.3.2.4 Control of Vertical Pistol Movement

Cross-correlations between mediolateral torso sway and vertical pistol movement varied between shots for most participants. Thus, movements of the upper limb must play an important role in controlling vertical pistol movements. First, shoulder abduction and adduction were compared to mediolateral torso sway. If positive cross-correlations are produced then the arm will move in the same direction to torso sway, such as sway away from the target and shoulder abduction (Figure 11.13). Negative cross-correlations represent opposing movements of the torso and shoulder, such as sway away from the target and shoulder adduction.

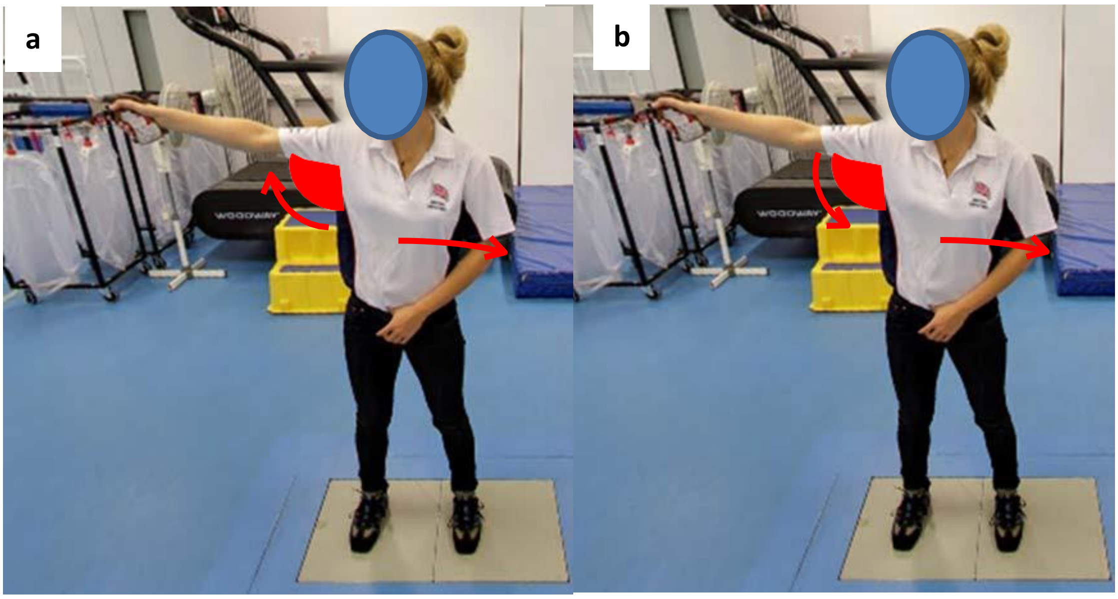


Figure 11.13. Example movements that would produce (a) positive and (b) negative correlations between mediolateral torso sway and shoulder abduction-adduction.

Most participants produced negative cross-correlations between mediolateral torso sway and shoulder abduction-adduction (Table 11.6) indicating that the shoulder generally counteracted mediolateral torso sway. Thus, opposing movements of the torso and shoulder maintained a consistent position of the upper arm. For each participant, the opposing movements were mostly reflected by sway away from the target accompanied by shoulder adduction, particularly for participant 1 for whom all 20 shots followed this pattern. Participant 3 was one of the only participants to experience sway towards the target accompanied by shoulder abduction, although in only 3 of the 20 shots.

Table 11.6. Mean cross-correlations (± SD) between mediolateral torso sway, shoulder and wrist movement and vertical pistol movements.

Participant	**1**	**2**	**3**	**4**	**5**
Torso – Shoulder	-.86 (.25)	-.93 (.07)	-.73 (.35)	-.04 (.78)	-.96 (.05)
Shoulder - Pistol	-.06 (.64)	.33 (.66)	-.69 (.24)	-.51 (.36)	-.11 (.73)
Shoulder - Wrist	-.03 (.77)	-.22 (.82)	-.71 (.34)	.02 (.65)	.09 (.78)
Wrist - Pistol	.13 (.64)	.15 (.62)	.68 (.28)	.07 (.64)	-.22 (.62)

Adduction and abduction of the shoulder explained neither the positive cross- correlations between torso sway and vertical pistol movement for participant 3, nor how vertical pistol movement was controlled for the other participants (Table 11.6). Thus, the most likely additional source of vertical pistol movement was through radial and ulnar deviation of the wrist. Negative cross-correlations between shoulder and wrist movements produced for participant 3 indicated that wrist deviation counteracted shoulder movement (Table 11.6). In the 17 shots where shoulder adduction was produced the wrist produced radial deviation. This, alongside positive correlations between the wrist and pistol for all 20 shots, demonstrated the important role of wrist movements in maintaining the positive correlations between mediolateral torso sway and vertical pistol movements.

Shoulder abduction and adduction played a more important role in controlling the pistol than mediolateral torso sway for participant 4. The shoulder counteracted vertical pistol movements (Table 11.6), resulting in shoulder adduction and upwards tilt of the pistol for 16 shots, and shoulder abduction and downwards tilt of the pistol for 4 shots. These opposing movements were primarily attributed to deviation of the wrist. The low average correlations between the wrist and the shoulder, and the wrist and the pistol reported in Table 4 were a result of two movement patterns produced by the wrist. In 11 shots the wrist counteracted shoulder movements (-.57 ±.34) and complimented movements of the pistol (.58 ±.40). In the other 9 shots, the wrist complimented shoulder movement (.56 ±.36), and counteracted movement of the pistol (-.40 ±.33). Each of the 9 shots involved shoulder adduction, ulnar deviation and upwards tilt of the pistol.

Cross-correlations between the movements of the upper limb varied between every shot for the three other participants (1, 2 and 5). Thus, no consistent effects of upper limb movement on vertical movements of the pistol were identified.

11.3.3 Range of Movement

Comparisons of the movements affecting horizontal pistol motion demonstrated that, with the exception of participant 4, range of movement was greater for the pistol than for anterior-posterior torso sway or the upper limb

(Figure 11.4). Range of movement of the pistol was between two and seven times greater than that recorded for the torso. For example, horizontal pistol range of movement for participant 1 was 3.50 mRad, compared to 1.15 mRad for torso sway. Participant 3 produced a greater relative increase between the torso (0.37 mRad) and pistol (2.61 mRad) than any other participant. Participant 4, who achieved the highest score, produced a smaller range of horizontal pistol movement than any other participant (1.69 mRad). Two participants (1 and 5) produced the smallest range of movement at the shoulder, and another (participant 2) produced the smallest range of movement for the wrist.

Comparisons of the movements affecting vertical pistol motion demonstrated that all participants produced the smallest range of movement for mediolateral torso sway (Figure 11.14). Range of movement of torso sway was between two to five times smaller than range of vertical pistol movement. For example, participant 1’s vertical pistol movement and torso sway ranges were 0.31 and 1.49 mRad respectively. In contrast to horizontal pistol movements, participant 4 who achieved the highest score, produced a greater range of vertical pistol movement than any other participant (2.15 mRad).

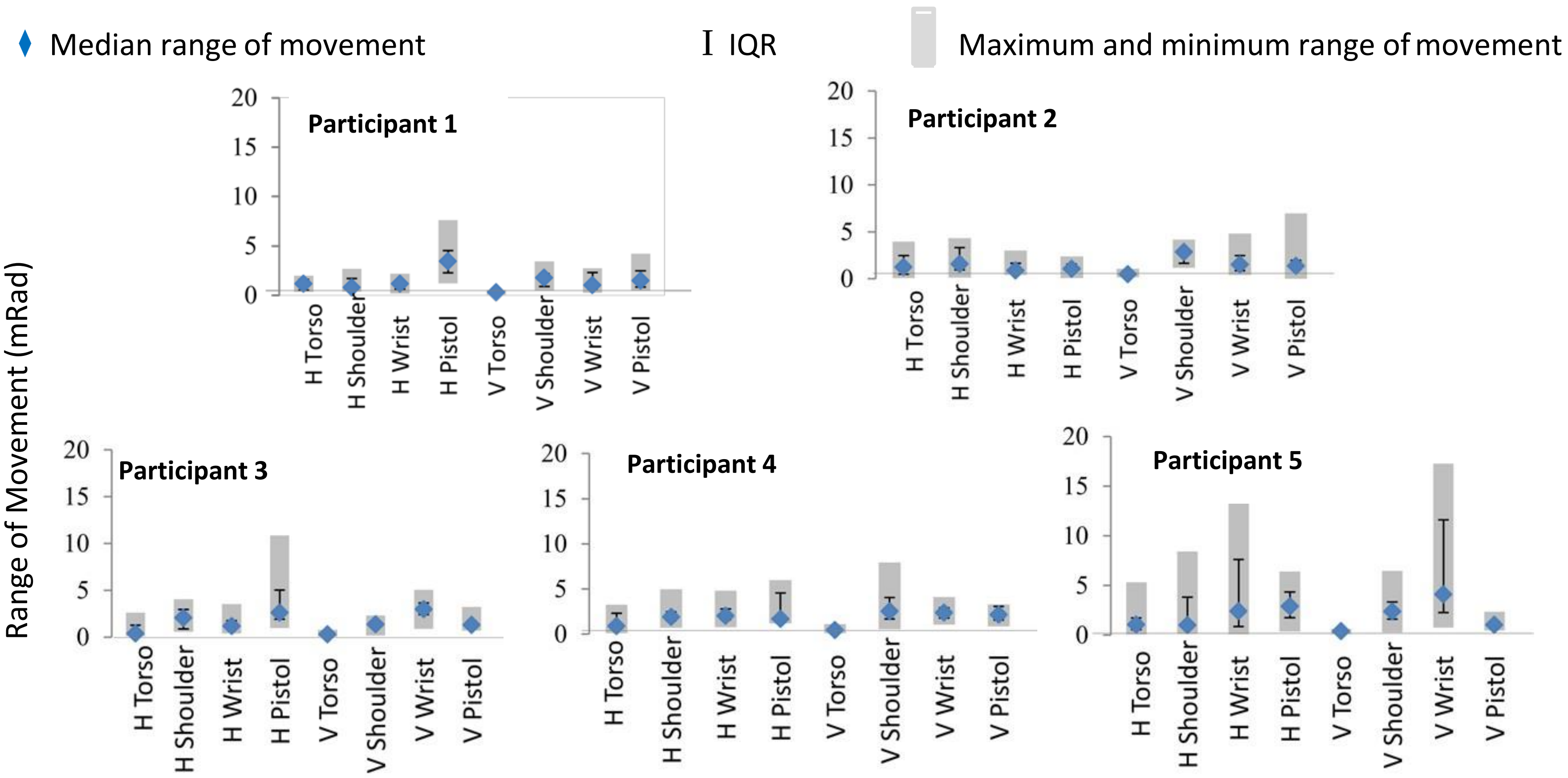


Figure 11.14. Range of movement produced by each participant over 20 shots (mRad = 1/1000th radian).
H represents movements compared to horizontal pistol movement (anterior-posterior torso sway, shoulder horizontal flexion/extension, wrist flexion/extension).
V represents movements compared to vertical pistol movement (mediolateral torso sway, shoulder abduction/adduction, wrist radial/ulnar deviation).

11.3.4 Performance Variability

Performance variability relates to how closely a performance is reproduced over the twenty shots and was examined using two variables, *positional variability* and *movement variability.*

- Positional variability, measured over the final second, examines how closely an angle is reproduced over the twenty shots. For example:
    - zero positional variability = the wrist angle is the same for every shot (e.g. a participant produces the same wrist angle throughout the final second of every shot);
    - moderate positional variability = the wrist angle is similar, but not identical, for every shot (e.g. a participant produces wrist angles between 2000 – 2050 mRad throughout the final second of every shot);
    - high positional variability = the wrist angle is different throughout the final second before the shot (e.g. a participant produces a variety of wrist angles, ranging between 2000 - 3000 mRad).
- Movement variability compares how the movement produced at a particular joint changes over the final second before a shot, and how similar the change in movement is between the 20 shots. For example:
    - low movement variability = in each of the 20 shots, a pistol shooter progressively flexes the wrist throughout the final second;
    - moderate movement variability = a participant produces a different degree of wrist flexion over the final second in each of the 20 shots;
    - high movement variability = a participant produces wrist flexion for some shots, and wrist extension for others.

Examples of how each variable was calculated were provided in the methods section (Chapter 11, section 11.2.5).

11.3.4.1 Control of Horizontal Pistol Movement

Positional variability was smaller for anterior-posterior torso sway than for any movements of the upper limb or pistol, indicating that the angle of the torso was closely recreated between shots (Appendix 3.2a – 3.6a). The amount of variability exhibited by the upper limb and pistol varied more between participants. For two participants (1 and 5), positional variability decreased from proximal to distal (Appendix 3.2a and 3.6a), ensuring that it was smallest for the pistol (Table 11.7). Participants 4 and 3 also produced the greatest degree of positional variability for movements of the shoulder (Appendix 3.4a and 3.5a), but the smallest variability for the wrist. Participant 2 produced one of the most unique patterns of positional variability (Appendix 3.3a), which was high for both the wrist and the pistol (Table 11.7). Variability of the shoulder was smaller than for any other participant, representing the most predictable positioning of the upper arm across the twenty shots.

Table 11.7. Average positional variability over the final second before the shot (mRad) for movements used to control horizontal movements of the pistol.

	Participant				
	1	**2**	**3**	**4**	**5**
Anterior-posterior torso sway	5.2	8.3	6.4	7.8	5.0
Shoulder abduction-adduction	41.5	13.0	30.8	51.1	14.8
Wrist flexion-extension	14.1	24.9	6.4	6.9	10.1
Horizontal pistol movement	9.5	21.6	19.9	15.6	7.8

Movement variability was smaller for anterior-posterior torso sway than horizontal pistol movements for all participants, and increased closer to the instance of the shot (Appendix 3.2c – 3.6c). This represented different sway patterns used across the twenty shots, such as anterior sway for some shots and posterior sway for others. Movement variability of the upper limb for participants 1 and 5 increased from proximal to distal (Table 11.8). Participants 3 and 2 also produced the greatest variability for the pistol, but smallest variability for the wrist (Appendix 3.3c and 3.4c). Participant 4 achieved the highest score of all participants, and produced the smallest degree of horizontal pistol movement variability (Table 11.8). Pistol variability decreased in the final 0.2 s before the shot (Appendix 3.5c), a pattern that was not observed for any other participant.

Table 11.8. Average movement variability over the final second before the shot (mRad) for movements used to control horizontal movements of the pistol.

	Participant				
	1	**2**	**3**	**4**	**5**
Anterior-posterior torso sway	0.7	1.3	0.5	1.1	0.8
Shoulder abduction-adduction	0.7	1.2	1.2	1.0	1.2
Wrist flexion-extension	1.0	0.8	1.1	1.8	2.2
Horizontal pistol movement	3.3	3.0	1.9	1.4	2.3

11.3.4.2 Control of Vertical Pistol Movement

Positional variability of mediolateral torso sway was smaller than variability of the shoulder and wrist, but greater than that of the pistol for most participants (Appendix 3.2b – 3.6b). Torso sway variability was smaller than all other movements for participant 2. The movements of the upper limb and the pistol that produced either the greatest, or the smallest, degree of variability differed between participants. For instance, participants 3, 4 and 5 each experienced a decrease in variability from proximal to distal (Table 11.9). This was particularly apparent for participant 4, for whom average positional variability decreased by 34 mRad between the shoulder and the wrist. Participants 1 and 2 both produced the greatest variability for the wrist, and smallest variability for the pistol. Despite both showing the same pattern of variability, pistol variability for participant 2 was over four times greater than that recorded for participant 1 (Table 11.9).

All participants produced a smaller degree of movement variability for mediolateral torso sway than for any movement of the upper limb and pistol (Table 11.10). Torso variability remained consistently low throughout the final second, indicating that a similar pattern of sway was produced for each of the twenty shots. Variability of the upper limb increased, albeit marginally from proximal to distal for participants 1 and 2, resulting in the greatest movement variability produced for the pistol (Appendix 3.2d and 3.3d). In contrast, the pistol was the least variable for participants 4 and 5, and the greatest degree of movement variability was produced for the wrist (Appendix 3.5d and 3.6d). Participant 3 produced a smaller degree of variability than any other participant for all upper limb movements, with greatest variability recorded for the shoulder (Appendix 3.4d).

Table 11.9. Average positional variability over the final second before the shot (mRad) for movements used to control vertical movements of the pistol.

	Participant				
	1	**2**	**3**	**4**	**5**
Mediolateral torso sway	4.2	14.9	3.1	7.3	5.0
Shoulder flexion-extension	9.5	22.3	18.8	50.3	16.1
Wrist radial-ulnar deviation	11.4	35.2	12.3	15.6	15.8
Horizontal pistol movement	3.5	15.2	2.5	2.9	4.2

Table 11.10. Average movement variability over the final second before the shot (mRad) for movements used to control vertical movements of the pistol.

	Participant				
	1	**2**	**3**	**4**	**5**
Mediolateral torso sway	0.1	0.2	0.2	0.5	0.2
Shoulder flexion-extension	0.7	1.0	0.7	1.4	0.9
Wrist radial-ulnar deviation	0.7	1.0	0.6	1.9	5.1
Horizontal pistol movement	0.8	1.3	0.6	1.1	0.8

11.4 Discussion

The objectives of this study were to examine the movement patterns associated with elite shooting performances and to quantify the degree of variability produced for the torso, upper limb and pistol. This was achieved by analysing the performances of elite precision pistol shooters as they completed shots as they would in training or competition.

11.4.1 Shot Score

Each participant was selected based on their status as an elite or high level pistol shooter. No participant had any previous experience of shooting in the university laboratory, or shooting when using the Vicon motion analysis system. Scores, however, were similar to those achieved in official shooting competitions near to the time of testing (Appendix 3.7), and so the testing format was not considered to have a detrimental effect on performance. Performances in testing sessions were therefore considered a fair representation of performance in training and competition.

11.4.2 Centre of Pressure Movement in Relation to Torso Sway

No significant correlations were identified between range of movement of the centre of pressure and either anterior-posterior or mediolateral torso sway. This finding was unexpected given the popularity of using centre of pressure movement to represent body sway within both shooting literature (Ball et al., 2003; Era et al., 1996; Hawkins & Sefton, 2011; Hawkins, 2013; Mason et al., 1990) and other, stability-based, research (Bove et al., 2007; Hwang et al., 2006; Nardone et al., 2009; Noda & Demura, 2007).

A potential explanation for the differences between centre of pressure movement and torso sway may be the small degree of movement which exists during the final second before a shot. Previous research has examined the accuracy of force platforms, and their suitability for stability analysis (Chockalingam, Giakas, & Iossifidou,2002; Gill & O'Connor, 1997; Middleton, Sinclair, & Patton, 1999). Chockalingam et al. (2002) assessed the AMTI force platform used in the current research, and reported that the accuracy of the estimates increased as the vertical force applied to the platform was increased. To achieve centre of pressure estimates within 3 mm standard deviation of the actual centre of pressure location, vertical force had to exceed 90 N. The forces associated with shooting stance are greater than the 90 N threshold, but the centre of pressure movements are considerably smaller than the 3 mm accuracy accepted by Chockalingam. In the current study, anterior-posterior standard deviation of the centre of pressure varied between just 0.14 – 0. 94 mm, and mediolateral movement ranged between 0.15 – 0.54 mm. Thus, analysis of centre of pressure movement may not be sufficient to represent movements in elite shooting, where movement is significantly smaller than that recorded for the general population (Aalto et al., 1990; Era et al., 1996; Herpin et al., 2010). Furthermore, both Chockalingam and Middleton et al. (1999) stated that the accuracy of the centre of pressure estimation is reduced at the edge of a force platform compared to when the feet are positioned on the centre. The current research required participants to shoot using their current stance position, and so it was not possible to move a participants' foot further from the edge of the force platform without potentially affecting their shooting performance. This may have further attributed to the low correlations between centre of pressure movement and torso sway.

The few similarities identified between centre of pressure movement and torso sway further highlight the importance of using more detailed analysis methods when examining elite shooting performances. This finding supports the conclusions of studies 1 – 3 that other movements must influence a shooting performance, and helps to explain the low correlations reported between centre of pressure and pistol movement in the first three studies. These low correlations justify the analysis of torso and upper limb movements that were the focus of this research.

Two aspects of torso and upper limb movement were analysed, movement coordination and performance variability. Movement coordination, analysed using cross-correlations, investigated the movement patterns used to control motion of the pistol. Multiple movement patterns are suggested to be an example of a successful movement synergy, which enable individuals to adapt a performance and achieve a successful task outcome (Domkin et al., 2005; Tseng et al., 2002). Performance variability, composed of positional and movement variability, was used to investigate how the movements of the torso, upper limb and pistol differed between shots. Variability has commonly been used to reflect the principle of abundancy (Tseng et al., 2002). Motor abundancy proposes that the motor system takes advantage of the numerous possible movement solutions in order to produce a successful task outcome (Domkin et al., 2005; Tseng et al., 2002), and suggests that this provides further evidence of a successful synergy between the movements used to complete a task. Practically, this means that variability of the system can be high to ensure that task outcome variability remains low (Davids et al., 2003; Domkin et al., 2005; Scholz et al., 2000; Scholz & Schöner, 1999; Tseng et al., 2002). In pistol shooting, motor abundancy should be reflected by a high degree of positional variability of torso sway and upper limb movements, and a small degree of variability for the pistol. Throughout this section, coordination and variability will be considered in relation to the concepts of movement synergies and motor abundancy.

11.4.3 Movement Coordination

Anterior-posterior torso sway was important to horizontal movements of the pistol for most participants, as the pistol consistently moved in the opposite direction to which the body was swaying. These opposing movements aid pistol shooters in maintaining a consistent position of the pistol on the target, and were produced through a coordination of the movements of the shoulder, wrist and pistol. The specific coordination patterns differed between every participant. For instance, participant 1 produced a consistent performance, as the wrist moved in the opposite direction to both torso sway and movements of the shoulder during every shot. Other participants, particularly participants 3 and 5, produced more flexible movement patterns for which cross-correlations varied between every shot.

The existence of multiple movement patterns when shooting supports the conclusions of previous motor control research that a flexible performance can be used to produce a consistent task outcome (Gorniak et al., 2008; Tseng et al., 2002). It does not fully support the pistol shooting research of Pellegrini and Schena (2005) who suggested that the trunk, arm and body move as one rigid segment. The contrasting results may arise from different methods of statistical analysis used in each study. The current research used cross-correlations to compare the movement patterns of the torso, upper limb and pistol throughout the final second of every shot, whilst Pellegrini et al. used discrete correlations between the neck, shoulder, wrist and pistol to compare how the magnitude of movement changed between shots. Discrete methods, such as those used by Pellegrini et al. are useful to examine whether a change in one movement is likely to lead to changes in another, but cannot examine more detailed information such as the temporal and spatial aspects of performance (Chiu & Chou, 2012; Hamill, Haddad, & McDermott, 2000; Preatoni et al., 2013). For instance, the markers recorded by Pellegrini et al. produced a similar change in the magnitude of movement between shots, but each marker could have been moving in different directions. Consequently, discrete analysis, with no supplementary continuous methods, cannot fully determine how a shooting performance is produced. The findings of the current research support Pellegrini et al.'s conclusions concerning the close associations between torso and pistol movement, but also offer additional information regarding the direction of movement and the strategies used to maintain pistol position on the target.

The association between mediolateral torso sway and vertical pistol movement was less consistent than that reported between anterior-posterior sway and horizontal pistol movement. Thus, it appears that upper limb movements play a more important role than torso sway in controlling vertical movements of the pistol. The use of different strategies to control vertical pistol movement provides support for Pellegrini et al. (2005) that the movements used to control the vertical position of the pistol are more complex than those used to control horizontal position. Consequently, whilst most pistol shooters could benefit from adapting patterns of anterior-posterior sway if they are attempting to influence horizontal pistol movement, controlling the amount of mediolateral sway may be less critical to performance.The less important role of mediolateral sway to pistol movement is unsurprising, given the exceptionally small ranges of movement that were produced. Median range of movement was between 0.23 mRad and 1.22 mRad smaller than anterior-posterior torso sway. Such differences, which would be almost unnoticeable in most activities that require a greater magnitude of movement, can have a considerable impact on 10 m pistol shooting performance. In pistol shooting, a movement of just 0.033 mRad is sufficient to move the aim point of the pistol from the centre of the target to the edge of the 10 ring. Thus, the effects of mediolateral torso sway on pistol movement will be considerably smaller than the effects of anterior- posterior torso sway.

The variability in upper limb coordination, both between different participants and within each participants' performance, mean that it was not possible to identify a single movement which was most influential to either horizontal or vertical pistol movement. Instead, pistol movement appears to be determined by interactions between a multi-joint system composed of the torso and movements of the upper limb. Thus, the first hypothesis that movement patterns would vary between shots, was accepted. This is consistent with the reports of existing motor control research concerning the concept of flexibility within the movement system (Domkin et al., 2005; Preatoni et al., 2013; Tseng et al., 2002). Tseng et al. (2002) highlighted how flexibility must exist even in repetitive skills such as shooting, stating that whilst a repetitive movement should, theoretically, only require one movement solution, there will always be factors that affect performance. Each factor has the potential to cause a change in the output of individual components of the system, and in response other components must alter their output to ensure that a stable task outcome is achieved. Factors affecting shooting performance could include small changes in stance position between shots, muscle fatigue throughout the course of a shooting competition, and the noise that is an inherent characteristic of a biological system. Thus, it is unsurprising that most participants required more than one movement pattern to achieve a consistently high level of performance.

A common finding throughout this research was the unique strategies used by each participant to control pistol movement. This was particularly evident for participant 3 for whom mediolateral torso sway was consistently accompanied by upwards motion of the pistol, whilst the association between anterior-posterior torso sway and horizontal pistol movements varied between every shot. Thus, unlike the other participants, mediolateral sway was more important to performance. This finding, alongside the different patterns of upper limb coordination experienced by each participant highlights that there are multiple methods in which to achieve a world-class shooting performance. This further promotes the importance of intra- individual analysis when investigating elite shooting performances (Ball et al., 2003; Bartlett et al., 2007; Mason et al., 1990). Scholes et al. (2012) who stated that taking the average performance of a number of participants results in a mythical average participant that does not fully reflect any individual's responses to the task. This conclusion is particularly relevant to pistol shooting. Given that each participant displayed different patterns of movement coordination to control pistol movement, it would be impossible for the group average to accurately reflect each participants' performance.

Further evidence of the individual nature of elite shooting performances was provided by the analysis of the upper limb coordination of participants 1 and 3. Whilst most participants produced flexible movement patterns, participants 1 and 3 each produced one consistent pattern for the movements affecting horizontal and vertical pistol motion respectively. Despite not demonstrating the patterns that are typically thought to reflect an effective synergy, (Tseng et al. 2002), participants achieved the second and third highest scores respectively. This finding has two potential implications; either it provides further evidence that there is more than one way to achieve a world-class performance, or it indicates that these participants could further enhance performance if they are able to increase the number of movement patterns during the final second before the shot. Whilst the flexibility of a movement pattern is not necessarily something that can be consciously controlled, it could be modified by other methods, such as changing stance position.

Hwang et al. (2006) reported that, in less stable stances, coupling of the upper limb joints increases, resulting in a less flexible movement system. Thus, by changing stance position and potentially increasing stability, the synergy between the upper limb movements may be enhanced, resulting in a more stable position of the aim point on the target.

11.4.4 Performance Variability

Positional variability of anterior-posterior torso sway was small, as each participant closely recreated the position of the torso between shots. Greater variability was evident for the upper limb and pistol, indicating that the position of the shoulder, wrist and pistol were adapted for each of the 20 shots. Variability was not always smaller for the pistol than for the upper limb. This led to a rejection of the second hypothesis, and does not fully represent the pattern anticipated by the principle of abundancy. This reflects the different coordination patterns used by each participant to control the horizontal movement of the pistol. Individual movement strategies were again apparent, particularly when comparing the performances of participants 1 and 3 who achieved similar scores, (187 and 184 respectively), and similar horizontal shot distributions (34 mm and 35 mm). Despite these apparent similarities, participant 1 experienced the greatest changes to the position of the shoulder and wrist, whilst participant 3 made the majority of adjustments with changes to the position of the shoulder and the pistol, with a minimal contribution from the wrist. The similar success of these participants, despite the differences in performance, provide support for Chow et al. (2011), Langdown et al. (2012) and Davids et al. (2003), who suggested that athletes should not attempt to replicate another individual’s technique, and should instead devise their own movement strategies that will result in a successful task outcome. This again supports the need for individual analysis of elite sports performance (Ball et al., 2003; Mason et al., 1990; Preatoni et al., 2013; Scholes et al., 2012).

Movement variability of anterior-posterior torso sway increased over the final second before the shot, indicating that sway patterns were altered nearer to the instance of trigger pull. Given the strong association between torso sway and pistol movement, adapting torso sway may be essential to determine the location of the aim point on the target. Movement variability was greater for the pistol than the upper limb for four participants, allowing for fine adjustments in position to ensure accurate placement of the shot. Previous research has commonly reported that movements are made of two components; a gross, primary submovement used to move the limb towards the target, and secondary, fine, submovements which are used to correct any errors in position and enhance accuracy (Dounskaia, Wisleder, & Johnson, 2005; Khan & Franks, 2003). The greater movement variability recorded for the pistol is therefore likely to reflect a variety of submovements used to correct any errors in the location at which the pistol is aiming.

Participants demonstrated some common traits for the variability of movements affecting vertical motion of the pistol. Positional variability was smaller for the pistol than the torso and upper limb, demonstrating the pattern typically associated with the principle of abundancy (Davids et al., 2003; Domkin et al., 2005; Latash, 2000; Scholz & Schöner, 1999; Tseng et al., 2002). This pattern reflected that anticipated by the third hypothesis. The relatively small variation in pistol position indicates that the flexible movement patterns that were previously identified by the analysis of movement coordination produced an effective synergy to control pistol movement.

Movement variability was smaller for mediolateral torso sway than the upper limb or pistol, reflecting the findings from the analysis of movement coordination that each participant consistently swayed away from the target in the final second before the shot. The greatest degree of movement variability was recorded for the pistol for some participants and for the wrist for others. This indicates that the submovements used to control the vertical position of the aim point on the target varied between participants. These findings again highlight that there are a number of methods to achieve a successful performance.

Analysis of performance and movement variability provided further evidence of the different strategies used to control horizontal and vertical movements of the pistol. All participants demonstrated the characteristics of abundancy for movements affecting vertical pistol motion, but only two (participants 1 and 5) produced the same characteristics for control of horizontal pistol movement. As such, the principle of abundancy, and the ability to successfully create a synergy between the angles of the upper arm, plays a critical role in the vertical placement of shots on the target. The submovements used to make fine changes to pistol position were more important for controlling horizontal pistol movement, as movement variability was greater for most movements affecting horizontal than vertical movements of the pistol.

This research has provided an insight into the multiple methods that are used to produce a successful shooting performance. There are limitations to the study that should be acknowledged. Participants were required to step off the force platform between each shot to allow for zeroing. This potentially allowed participants to change stance position between shots; something that could potentially affect the degree of positional variability. To minimise this effect, foot position was marked onto each force plate prior to the first shot. Participants were also shooting in a laboratory environment to which they were not accustomed and did not provide the pressures associated with competition. Scores achieved during testing were, however, similar to those achieved in previous shooting competitions, and so the testing environment was not considered detrimental to performance. Future research should now consider the ways in which movement strategies can be modified. As previously discussed, the exceptionally small degree of movement associated with elite precision shooting may be beyond the magnitude that can be consciously controlled. There is still potential to modify other aspects of performance, such as stance position, which may have a resultant impact on coordination and variability. A further consideration for future research is the importance of other variables, such as velocity of centre of pressure motion, to elite shooting performances. Positional and movement variability were analysed in the current research, in accordance with the majority of previous shooting research which has focused on variables such as range and path length. Future research should examine how other variables also contribute to a successful shooting performance.

11.5 Conclusion

This research has provided a descriptive analysis of the movements associated with elite precision pistol shooting. Horizontal pistol movements occurred in the opposite direction to anterior-posterior torso sway for most participants, whilst mediolateral torso sway was less influential to performance. Movement patterns of the upper limb were more varied, indicating a high degree of flexibility within the movement system. Thus, it appears that elite pistol shooters have developed effective synergies to produce a highly consistent task outcome. When controlling vertical pistol motion, positional variability was greater for upper limb movements than the pistol, demonstrating the characteristics of motor abundancy. The same pattern was not evident for horizontal pistol movements. Instead, a higher degree of movement variability indicted that secondary submovements were used to make fine adjustments to the position of the pistol. Analysis of movement coordination and variability both revealed a high level of individual variation, highlighting that there are multiple ways in which to achieve an elite level shooting performance. It is recommended that future research now considers how other aspects of shooting, such as stance position, can influence movement coordination and variability, and potentially further enhance precision shooting performance.

Chapter Twelve

Research Study 5 - The Effects of Stance Position on Elite Precision Pistol Shooting Performance

12.1 Introduction

Previous shooting research has established some of the mechanisms behind a successful shooting performance, but has yet to consider the methods that shooters could use to modify technique and potentially enhance performance. In a sport where movement of just 0.016° is enough to reduce a point score (Zatsiorsky & Aktov, 1990), and athletes are regularly separated by less than a point in competition, an understanding of methods that can enhance performance is clearly important.

Currently, only Hawkins and Sefton (2011) have considered how modifying technique could influence pistol shooting performance. When shooting in a range of stance positions, between 30 cm - 90 cm, stability of the pistol was significantly reduced when stance widths exceeded 75 cm, and centre of pressure movement was smallest for the narrowest, 30 cm, stance position. Thus, existing research suggests that pistol shooters should adopt a narrower stance width to increase postural stability and shooting performance. These findings are in contrast to existing pistol shooting manuals, which recommend that shooters should adopt a stance of shoulder width or greater (Leatherdale & Leatherdale, 1995; National Rifle Association of America, 2008; Yur'yev, 1985). For most people, this stance width would exceed the 30 cm recommended by Hawkins and Sefton.

The research of Hawkins and Sefton (2011) provides a basis from which future research can further develop an understanding of the effects of shooting stance on performance. Whilst this provides an indication of the effects of mediolateral stance width on shooting performance, it does not consider the effect of changing anterior- posterior foot position. Furthermore, the stance positions selected by Hawkins and Sefton were all greater than 30 cm. Thus, there is no current evidence for the effects of narrower mediolateral stance widths on performance.

Currently, research has considered the effects of stance position on pistol and centre of pressure stability, but not how changing stance width affects either shot score or the movements of the torso and upper limb. Examining these effects of stance position is an extension to the analysis performed in Study 4, and can determine which stance positions produce the highest scores alongside the mechanisms, such as changes in movement patterns and variability, which are behind any changes in performance. Recent research suggests that more variable movement patterns tend to result in a more successful task outcome (Preatoni et al., 2013; Scholz & Schoner., 1999). This is in conflict to the original theory which proposed that movement patterns should be highly repeatable in order to achieve success (Arutyunyan et al., 1969; 1968; Bernstein, 1967). This research will therefore identify whether the most successful shooting performances are associated with more variable movement patterns of the upper limb, as suggested by recent research. This information will provide coaches and athletes with a more detailed understanding of why manipulating the stance position may improve performance.

Finally, research has yet to examine the effects of stance position on shooting performance for individual participants, with current group-based findings suggesting that a mediolateral stance width of 30 cm is optimal for performance (Hawkins & Sefton, 2011). Given that the first three studies of this thesis consistently highlighted the individual nature of pistol shooting performance, the optimal stance position is also likely to vary between individuals. Thus, the effects of stance position on individual performances must also be examined.

Given the limited existing knowledge on the effects of stance position on shooting performance, the final study will now consider this topic in greater detail. There are two objectives for this research, which are to:

(i) identify the most effective mediolateral and anterior-posterior stance widths, based on analysis of shot scores; and
(ii) identify the effect of changes in stance position on movement

patterns and movement variability.

There are three hypotheses to accompany these objectives:

(i) wider mediolateral and anterior-posterior stance widths will improve shooting performance in comparison to narrower stance widths;
(ii) the movement patterns of the most successful stance positions will be more variable; and
(iii) the most successful stance positions will be characterised by greater variability of upper limb movements and smaller variability for the pistol.

12.2 Methods

12.2.1 Participants

The same participants completed each shooting task as those who took part in Study 4; ten elite female pistol shooters (mean age 28.4 ± 10.2 years, mass 67.3 ±7.7 kg), with an average pistol shooting experience of 9.5 (± 3.3) years. Throughout all testing sessions participants used the equipment with which they would normally compete (shooting shoes, training/competition pistol; 4.5 mm calibre compressed or CO_2 single shot air pistol, weighing less than 1500 g). Written informed consent was obtained from all participants prior to testing, which was approved by the Manchester Metropolitan University research ethics committee.

12.2.2 Tasks

Testing took place in the shooting range within the University's Biomechanics Laboratory as previously detailed for Study 4 (Chapter 11, section 11.2.3). Each participant completed nine stance position conditions, each of which consisted of ten live fire shots. Each condition used a combination of one mediolateral (Current, Wide or Narrow), and one anterior-posterior (Current, Foot in Front and Inline) stance width (Table 12.1), which was manipulated by altering the position of a participants’ rear foot, whilst the front foot remained in the current stance position (Figure 12.1). Each stance was a variation on the participants’ existing stance position recorded for Study 4 (Chapter 11, section 11.2.2), and so the exact width of each position varied between participants. This was particularly evident for mediolateral stance width, for which there was a range of 18 cm between participants.

Table 12.1. The combination of stance positions used to create the nine stance conditions completed by each participant.

	Mediolateral Stance Width	**Anterior-Posterior Stance Width**
1	Current	Current*
2	Current	Foot in Front
3	Current	Inline
4	Narrow	Current
5	Narrow	Foot in Front
6	Narrow	Inline
7	Wide	Current
8	Wide	Foot in Front
9	Wide	Inline

* Current Current stance positions are taken from shots 11 – 20 recorded for Study 4.

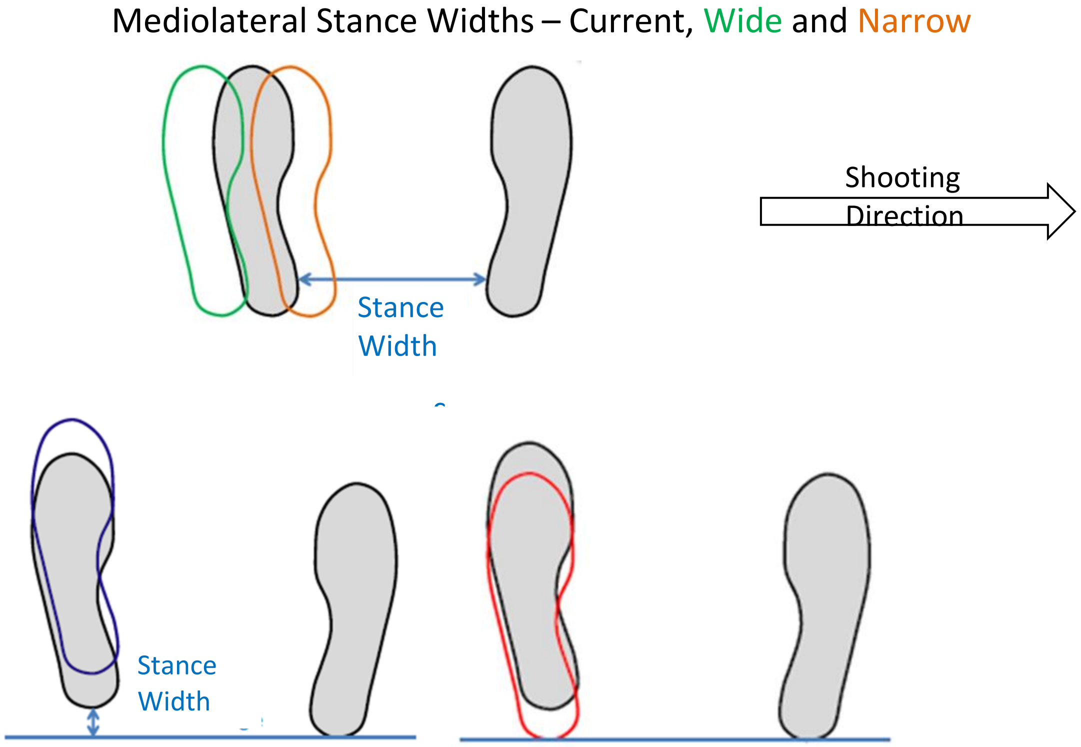


Figure 12.1. Mediolateral and anterior-posterior stance widths used to create the nine stance positions

Mediolateral: Current = participant’s existing stance width; Wide = 25% wider than the current stance; Narrow = 25% narrower than the current stance.
Anterior-posterior: Current = participant’s existing stance width; Foot in Front = rear foot 100% further forwards than the distance recorded in the current stance; Inline = rear foot 100% further back than the distance recorded in current stance.

The order in which trials were completed was randomised for each participant to reduce any potential learning or fatigue effects. Prior to beginning each trial, participants were asked to complete a minimum of ten practice shots in order to become familiar with each modified position. Once familiarisation was completed, participants had an unlimited time period in which to complete the ten live fire shots. Participants aimed at a standard air pistol target (17 cm × 17 cm), and attempted to achieve the highest possible score. Testing procedures were identical to those used during Study 4 (Chapter 11, section 11.2.2).

Table 12.2. Current and modified stance widths used for each participant.

	Stance Width (cm)					
	Mediolateral stance width			**Anterior posterior stance width**		
Participant	**Current**	**Narrow**	**Wide**	**Current**	**Foot in Front**	**Inline**
1	24.0	18.0	30.0	2.0	4.0	0.0
2	20.0	15.0	25.0	2.0	4.0	0.0
3	22.5	16.9	28.1	5.0	10.0	0.0
4	28.0	21.0	35.0	-3.5	0.0	-7.0
5	38.0	28.5	47.5	2.0	4.0	0.0

12.2.3 Data Collection

The experimental set-up was identical to that previously detailed for Study 4 (Chapter 11, section 11.2.3), using the Vicon MX motion analysis system (Vicon, UK) to accurately record the position of nineteen reflective spherical markers whilst participants were completing each shot. Pistol movement was recorded by the Noptel shooting system (Noptel-ST 2000 Sport II; Noptel, Finland), and shot score was recorded directly from the target to a maximum of 10.9. The position of participants' feet was marked with tape at the beginning of each stance condition to ensure that participants remained in the same position for all ten shots.

12.2.4 Data Analysis

Shot score, used to measure shooting accuracy, was recorded from the target, to a maximum of 10.9. To reduce the effect of any sighting errors, shot score was calculated from the centre of the shot group, and not the centre of the target. Shot dispersion, measured as the horizontal and vertical spread of the shot group (mm), was measured directly from the target and used to assess shooting precision.

Movements of the torso, shoulder, wrist and pistol were analysed over the final second before the shot using the same methods as those reported in Study 4 (Chapter 4, section 11.2.4). Discrete analysis of performance was provided from the range of movement, and continuous analysis analysed movement patterns, examined using cross-correlations, and movement variability, quantified by the median angle and IQR throughout the final second.

12.2.5 Statistical Analysis

Data did not meet parametric assumptions, as previously reported for Study 4 (Chapter 11, section 11.2.5), and so with the exception of cross-correlations, non-parametric tests were selected. Spearman's Rank correlations were used to compare the order in which participants completed each trial and the scores achieved. These comparisons were used as an indication of whether a learning effect had taken place throughout the duration of the testing session.

Performance in each stance position was analysed for the group as a whole and for individual participants. A Friedman's ANOVA compared the scores achieved in each stance position, and the range of movement produced for the torso, upper limb and pistol. Any results of $p<.05$ were considered statistically significant. Significant results were accompanied by post hoc Wilcoxon tests with Bonferroni corrections, and any results less than $p<.01$ were considered significant.

Two participants (1 and 3) were selected as examples for analysis of the movement patterns and performance variability produced in the highest and lowest scoring stance positions. The three lowest scoring stance positions achieved significantly lower scores than the top two stance positions for participant 1, and the two most successful stance positions produced significantly higher scores than all other stance positions for participant 3.

Cross-correlations were used to compare the movement patterns produced in the highest and lowest scoring stance positions. This identified the degree of similarity between the movements produced for the torso, upper limb and pistol over the final second before the shot. Each correlation followed the procedure detailed in Study 4 (Chapter 11, section 11.2.4), with correlations for the movements affecting horizontal and vertical pistol movement analysed separately.

Performance variability was again quantified using positional variability and movement variability, as detailed in Study 4 (Chapter 11, section 11.2.4). Any differences in the degree of variability produced for the torso, upper limb or pistol were used to indicate changes in performance between a more, or less, effective stance position.

12.3 Results

12.3.1 Shot Score – Group Analysis

Changing stance position had a significant effect on the scores achieved by the group (χ^2 (8) = 34.93, $p<.05$), and surprisingly, the lowest score was achieved when participants used their Current stance position (Table 12.3). The combination of Current and Foot in Front stance positions was the most successful, producing significantly higher scores than those achieved in five of the other eight stance positions (ranging from Current Inline: T = 196, p = .000, r = -0.63 to Narrow Current: T = 485.5, p = .001, r = 0.28). Two other stance positions, Narrow Foot in Front and Narrow Inline, also produced significantly higher scores than other stances (Table 12.3).

Table 12.3 Total group scores achieved when using each stance position. Participant numbers in brackets denote the position in which each participant achieved their highest score.

Rank		**Mediolateral stance width**	**Anterior-posterior stance width**	**Score**
1	(Participant 4)	Current	Foot in Front	496.5
2	(Participant 1)	Narrow	Foot in Front	492.2
3	(Participant 5)	Narrow	Inline	489.6
4	(Participant 3)	Wide	Current	489.2
5		Narrow	Current	486.2*
6	(Participant 2)	Wide	Foot in Front	484.6*♦
7		Wide	Inline	480.8*†
8		Current	Inline	479.4*♦†
9		Current	Current	477.0*

* significantly different to Current Foot in Front stance position (*p*<.007)
♦ significantly different to Narrow Foot in Front stance position (*p*<.007)
† significantly different to Narrow Inline stance position (*p*<.007)

12.3.2 Shot Score – Individual Analysis

Individual analysis revealed a significant effect of stance position on shot score for all participants (Table 12.4). The highest score could not be attributed to a particular stance position (Current, Narrow or Wide), but with the exception of participant 1, all participants produced their highest score using a mediolateral stance width of between 25.0 and 28.5 cm. Optimal anterior-posterior stance width varied more between participants, and some achieved both their highest and lowest scores using the same position. The effects of stance position will now be reported for each participant.

Scores achieved by participant 1 varied by 8.8 points between the highest (102.7 points) and lowest (93.4 points) scoring stance positions (Appendix 4.1). The difference in score between stances was considerably greater than the variation within each stance position, which ranged between 0.8 – 2.9 points. Both the highest and lowest scores were achieved when using the Foot in Front anterior-posterior width, and score was significantly increased simply by changing mediolateral stance width (6 cm decrease) from Current to Narrow. The lowest scoring position produced greater horizontal and vertical shot distribution than the highest scoring stance, by 11 mm and 14 mm respectively.

Table 12.4. Statistical comparisons between the scores achieved in each of the nine stance positions. Any values below *p*<.05 indicated a significant difference between the scores achieved in the highest and lowest scoring stances.

Participant	χ^2	*p* value
1	37.95	<.001
2	35.44	<.001
3	48.44	<.001
4	36.66	<.001
5	51.12	<.001

Scores for participant 2 varied by 13.5 points between the highest (102.2 points) and lowest (88.7 points) scoring stance positions (Appendix 4.2). Scores achieved within each stance position ranged between 1.8 – 2.3 points, again smaller than the difference between stance positions. The lowest score was achieved using the Current stance position, in agreement with the findings of group analysis. The highest score was achieved with a Wide Foot in Front stance, which reduced horizontal and vertical shot distribution in comparison to the lowest scoring stance by 29 mm and 8 mm, respectively.

Manipulating stance position produced a difference of 7.8 points for participant 3, whilst the variation within each stance was between 1.1 – 2.0 points. The highest score of 102.8 points was achieved using a Wide Current stance (Appendix 4.3), and the lowest score of 95.0 points was produced in the Current Inline position, for which horizontal and vertical shot distribution increased by 14 mm and 11 mm, respectively. Whilst the Wide Current stance produced the highest score, the Foot in Front position also enhanced performance, producing consistently high scores regardless of mediolateral stance width.

Participant 4 demonstrated fewer effects of the changes in stance position than any other participant, with a small, albeit significant, difference of 6.3 points between stances (Appendix 4.4). Variation within stances was lower than that recorded between each stance position, ranging from 1.4 to 2.4 points. The Foot in Front anterior-posterior stance width was the most effective, producing the three highest scores. The highest score was achieved when this was paired with the Current mediolateral stance width, matching the results of group analysis. The lowest score was produced in the Wide Current position, for which horizontal and vertical shot distribution increased by 11 mm and 10 mm respectively in comparison to the highest scoring position.

Score varied by 10.8 points between stance positions for participant 5 (Appendix 4.5), whilst variation within each stance position ranged between 1.2 and 2.2 points. The highest score of 99.4 points was produced using the Narrow Inline stance position, and the lowest score of 88.6 points was achieved in the Wide Foot in Front stance. Changing stance position had a considerably greater effect on horizontal shot distribution than vertical distribution, which increased by 29 mm and 1 mm respectively between the highest and lowest scoring positions. Some effects of anterior-posterior stance angle were evident, with the Inline position consistently producing higher scores than the Foot in Front position.

Two participants (1 and 3) were selected as case studies for analysis of movement patterns and performance variability based on the individual statistical analysis of shot score (Appendix 4.1 and 4.3). Whilst most participants in Study 4 produced flexible movement patterns, participant 1 experienced one consistent pattern for control of horizontal pistol motion, and participant 3 produced one consistent pattern for vertical motion. Thus, it was suggested that changing stance position could potentially enhance performance for these participants by producing more flexible movement patterns. Consequently, both participants were selected for this study to examine the specific effects of changing stance position on performance. The lower scores achieved by both participants was reflected by an increase in either vertical or horizontal shot distribution in comparison to the higher scoring stances. Consequently, both vertical and horizontal movements were compared between stance positions.

Range of movement produced for the torso, upper limb and pistol did not differ significantly between stance positions, and so comparisons between the highest and lowest scoring stances were based on two aspects of performance, movement coordination and performance variability. Movement coordination refers to how torso sway and upper limb movements affect the motion of the pistol, and is analysed using cross-correlations, as described in Study 4 (Chapter 11, section 11.3.2). Performance variability relates to how closely a performance is reproduced across the 10 shots in a particular stance position. Positional variability and movement variability were considered, also detailed in Study 4 (Chapter 4, section 11.3.4). Positional variability examines how closely an angle is reproduced over the twenty shots, and movement variability compares how the movement changes over the final second, and how similar the change in movement is between the 20 shots.

12.3.3 Case Study: Participant 1 – Movement Coordination

Five stance positions were selected for analysis, including two of the higher scoring stances (Narrow Foot in Front and Narrow Current), and three of the lowest scoring stances (Wide Inline, Current Inline and Wide Current).

Cross-correlations between anterior-posterior torso sway and horizontal movements of the pistol were consistently negative for the higher scoring positions. Anterior torso sway was accompanied by the pistol panning right across the target (for six shots in Narrow Foot in Front and five shots in Narrow Current), with the remaining shots experiencing posterior torso sway and the pistol panning left. In contrast, cross- correlations varied between every shot for the lower scoring positions (Table 12.5). Correlations between mediolateral torso sway and vertical movements of the pistol did not demonstrate the same distinction between higher and lower scoring stances, and varied considerably within each stance position (Table 12.5). Only one stance position (Wide Current) produced a predictable pattern as sway contributed to pistol movement.

Table 12.5. Mean cross-correlations (±SD) for participant 1 between anterior-posterior torso sway and horizontal movement of the pistol, and mediolateral torso sway and vertical movements of the pistol for the highest and lowest scoring stance positions.

		Average cross-correlation with pistol movement (± SD)	
	Stance Position	**Anterior-posterior torso sway**	**Mediolateral torso sway**
Highest	Narrow Foot in Front	-.87 (.22)	-.20 (.78)
	Narrow Current	-.48 (.30)	.34 (.75)
Lowest	Wide Inline	.26 (.67)	.25 (.78)
	Current Inline	-.23 (.60)	.39 (.62)
	Wide Current	-.36 (.58)	.78 (.17)

In the highest scoring stances, cross-correlations revealed that shoulder movement counteracted anterior-posterior torso sway for some shots (five shots for Narrow Foot in Front: -.84 ±.23, and four shots for Narrow Current: -.74 ±.18). Thus, the shoulder was responsible for producing the opposing movements of anterior-posterior torso sway and horizontal pistol movement. In the remaining shots, shoulder movement contributed to torso sway (five shots for Narrow Foot in Front: .38 ±.16 and six shots for Narrow Current: .81 ±.26). This indictes that other movements must be responsible for the opposite motion of the torso and the pistol. Cross-correlations between the shoulder, wrist and pistol differed between each of these shots, making it difficult to identify a specific movement pattern responsible for controlling horizontal pistol movement.

For the lowest scoring stance positions, shoulder movement appeared less important to performance. In two of the least successful stances, horizontal movements of the pistol were primarily determined by the wrist, which consistently contributed to pistol movement (Wide Inline: .92 ±.08; Current Inline: .67 ±.27). Each stance postion produced five shots with wrist flexion accompanied by the pistol panning left across the target, and five where wrist extension was accompanied by the pistol panning right. Control of horizontal pistol movement for the other low scoring stance position (Wide Current) was highly variable, and no clear patterns between the torso, upper limb and pistol could be identified.

No clear distinction could be made between the higher and lower scoring stances based on the movement patterns produced between mediolateral torso sway and either vertical pistol movements (Table 12.5) or movements of the shoulder (Table 12.6). Differences were more apparent when comparing movements of the upper limb, which were highly predictable for the lower scoring stances. Each of the least successful stances exhibited two methods of controlling vertical pistol movement. In one pattern the shoulder counteracted mediolateral torso sway and the wrist complimented movements of the shoulder. In the other position, the shoulder still counteracted torso sway, but the wrist counteracted shoulder movement. The second pattern was most apparent for the Wide Current stance position, and resulted in consistently positive correlations between torso sway and vertical pistol movements. In contrast, different movement patterns were produced for every shot in the higher scoring stance positions, meaning that no clear methods of controlling vertical pistol motion could be identified.

Table 12.6. Mean cross-correlations between mediolateral torso sway and shoulder adduction/abduction for the highest and lowest scoring stance positions.

	Stance Position	**Mean cross-correlation (±SD)**
Highest	Narrow Foot in Front	-.11 (.72)
	Narrow Current	-.90 (.12)
Lowest	Wide Inline	-.92 (.07)
	Current Inline	-.72 (.32)
	Wide Current	-.83 (.28)

12.3.4 Case Study: Participant 1 – Performance Variability

Differences between stance positions were most evident in the positional variability of the pistol, which was greater for the lower than for the higher scoring stances (Table 12.7). No clear differences were evident between stances when comparing the positional variability of anterior-posterior torso sway or upper limb movements (Appendix 4.6).

Greater movement variability of anterior-posterior torso sway was evident for the higher scoring stances (Table 12.8). Although average movement variability of the pistol did not distinguish between stance positions, the degree of variability increased over the final 0.3 s for the higher scoring positions (Appendix 4.7). No clear differences were evident between stance positions for the movement variability of the upper limb.

Positional variability of the wrist distinguished between stances (Appendix 4.8), with the highest scoring positions producing a smaller degree of variability than the lowest scoring stances (Table 12.7). No other differences were evident when comparing positional variability of the torso, upper limb or pistol.

Movement variability provided a greater distinction between stance positions, as mediolateral torso sway was more variable for the higher than the lower scoring positions (Table 12.8). The higher scoring stances also produced a smaller degree of wrist movement variability, with only a slight increase in variability seen over the final second before the shot (Appendix 4.9).

Table 12.7. Median positional variability over the final second before the shot for participant 1.

		Movements affecting horizontal pistol motion (mRad)				Movements affecting vertical pistol motion (mRad)			
		A-P Torso Sway	**Shoulder Flexion/ Extension**	**Wrist Flexion/ Extension**	**Pistol**	**M-L Torso Sway**	**Shoulder Abduction/ Adduction**	**Wrist Ulnar/ Radial Deviation**	**Pistol**
Highest	Narrow Foot in Front	5.04	28.02	1.75	13.23	4.54	2.42	5.15	7.23
	Narrow Current	7.48	22.04	11.76	12.48	6.13	17.83	17.35	5.02
	Wide Inline	9.45	17.96	4.61	17.20	6.91	35.67	5.71	7.91
Lowest	Current Inline	5.37	19.19	3.78	38.00	7.46	13.03	11.18	7.89
	Wide Current	6.34	28.98	11.35	15.34	6.41	18.54	6.41	5.06

Table 12.8. Median movement variability over the final second before the shot for participant 1.

		Movements affecting horizontal pistol motion (mRad)				Movements affecting vertical pistol motion (mRad)			
		A-P Torso Sway	**Shoulder Flexion/ Extension**	**Wrist Flexion/ Extension**	**Pistol**	**M-L Torso Sway**	**Shoulder Abduction/ Adduction**	**Wrist Ulnar/ Radial Deviation**	**Pistol**
Highest	Narrow Foot in Front	0.50	1.03	0.94	2.21	0.18	0.38	0.62	0.66
	Narrow Current	0.59	1.49	0.83	0.90	0.13	0.45	0.63	0.92
	Wide Inline	0.69	1.76	0.88	1.31	0.11	0.84	0.92	1.56
Lowest	Current Inline	0.66	1.13	1.06	1.61	0.08	0.52	1.09	0.63
	Wide Current	0.68	0.64	0.39	1.88	0.07	0.34	1.12	0.69

12.3.5 Case Study: Participant 3 – Movement Coordination

Four stance positions were selected for comparisons of movement coordination and performance variability. Wide Current and Narrow Foot in Front stances both produced significantly higher scores than all seven other stance positions. The Current Current and Current Inline positions were selected as the two lowest scoring stances, both producing significantly lower scores than the top two positions.

Cross-correlations between anterior-posterior torso sway and horizontal movements of the pistol varied between each stance position, and therefore did not distinguish between higher or lower scoring stances (Table 12.9). Mediolateral torso sway appeared more important to performance, as sway contributed to vertical pistol movement in the lowest scoring positions, but varied for the higher scoring stances (Table 12.9).

Table 12.9. Mean cross-correlations (±SD) for participant 3 between anterior-posterior torso sway and horizontal movement of the pistol, and mediolateral torso sway and vertical movements of the pistol for the highest and lowest scoring stance positions.

		Average cross-correlation with pistol movement (± SD)	
	Stance Position	**Anterior-posterior torso sway**	**Mediolateral torso sway**
Highest	Wide Current	-.52 (.72)	.06 (.66)
	Narrow Foot in Front	.08 (.85)	.33 (.59)
Lowest	Current Current	-.29 (.61)	.52 (.40)
	Current Inline	-.83 (.28)	.81 (.21)

The movement patterns produced for the upper limb did not distinguish between stance positions for this participant. In the lower scoring stances wrist flexion and extension counteracted movements of the shoulder for every shot (-.55 ±.28). However, correlations between the wrist and pistol differed for every shot and so there was no consistent pattern to explain how horizontal pistol movement was controlled. In one of the higher scoring stances (Narrow Foot in Front) the wrist contributed to pistol movement for all shots (0.9 ±.09), but this consistent pattern was not evident for the other high scoring position (Wide Current). Movement patterns of the upper limb were highly consistent for the lower scoring stance positions, as shoulder movement counteracted mediolateral torso sway (Current Current: .97 ±.04; Current Inline: .97 ±.04), which was in turn counteracted by movements of the wrist (Current Current: -.69 ±.38; Current Inline: -.77 ±.35). As such, every shot produced sway away from the target, shoulder abduction and radial deviation. This consisent performance was not evident for the higher scoring stances, for which there were no clear movement patterns to indicate how vertical pistol movements were controlled.

12.3.6 Case Study: Participant 3 – Performance Variability

Positional variability of the torso and pistol was smaller for the highest than the lowest scoring stance positions (Table 12.10). No differences were observed between stance positions for the positional variability of the upper limb (Appendix 4.10). Movement variability did not distinguish greatly between the highest and lowest scoring stances for any movement of the torso, upper limb or pistol (Appendix 4.11).

Stance position had clear effects on vertical positional and movement variability (Appendix 4.12 and 4.13). Positional variability of the torso, shoulder and pistol were each smaller for the lowest scoring positions (Table 12.10). No clear difference between stances was evident for positional variability of the wrist.

The highest scoring stances produced a greater degree of movement variability for the shoulder, wrist and pistol than for the lowest scoring stance positions (Table 12.11). Furthermore, whilst the degree of movement variability for the wrist and pistol was relatively consistent throughout the final second in the lower scoring positions, variability increased prior to the shot for the higher scoring stances (Appendix 4.13).

Table 12.10 Median positional variability over the final second before the shot for participant 3.

		Movements affecting horizontal pistol motion (mRad)				Movements affecting vertical pistol motion (mRad)			
		A-P Torso Sway	Shoulder Flexion/ Extension	Wrist Flexion/ Extension	Pistol	M-L Torso Sway	Shoulder Abduction/ Adduction	Wrist Ulnar/ Radial Deviation	Pistol
Highest	Wide Current	1.23	19.21	4.43	16.97	4.25	19.50	12.61	3.44
	Narrow Foot in Front	2.49	72.11	4.69	16.44	8.11	16.25	4.72	6.73
Lowest	Current Current	6.32	18.17	3.86	13.31	3.54	9.76	9.11	1.21
	Current Inline	5.93	23.17	5.35	8.61	2.16	12.80	5.48	1.36

Table 12.11. Median movement variability over the final second before the shot for participant 3.

		Movements affecting horizontal pistol motion (mRad)				Movements affecting vertical pistol motion (mRad)			
		A-P Torso Sway	Shoulder Flexion/ Extension	Wrist Flexion/ Extension	Pistol	M-L Torso Sway	Shoulder Abduction/ Adduction	Wrist Ulnar/ Radial Deviation	Pistol
Highest	Wide Current	0.32	1.97	0.59	1.28	0.18	0.64	1.24	0.82
	Narrow Foot in Front	0.77	1.09	0.80	2.48	0.26	0.51	1.40	0.88
Lowest	Current Current	0.70	2.14	0.63	2.14	0.24	0.30	0.36	0.38
	Current Inline	0.73	0.68	0.59	1.32	0.06	0.47	1.14	0.40

12.4 Discussion

The objectives of this study were to identify whether stance position had a significant effect on shooting success, and to determine the mechanisms behind a successful shooting performance. These were achieved by comparing the scores achieved and range of movement produced in each stance position, and by comparing movement coordination and performance variability between the highest and lowest scoring positions.

Group analysis identified significant differences between the scores achieved in different stance positions, highlighting the need for pistol shooters to manipulate stance position in training to determine the most effective position. The importance of selecting the optimum stance position was particularly apparent given that the lowest score was achieved using participants' Current stance. However, as anticipated from studies 1 – 3, group analysis did not fully reflect the response of any participant to the modifications in stance position. Only one participant produced their lowest score when using their Current stance, and each participant achieved their highest score in a different stance position. For each participant the variation in score between stances was greater than the variation within each stance position. Thus, changes in score appear to be a result of modifications to stance position rather than the natural variation that occurs between shots. This led to the acceptance of the first hypothesis which stated that stance position would significantly affect score, and that the most successful position would vary between participants. Thus, a single optimal stance position cannot be recommended for all shooters. This finding contradicts the current, group-based stance recommendations provided by the majority of coaching aids, which simply suggest a shooting stance where the feet are positioned approximately shoulder width apart (Antal & Skanaker, 1985; Leatherdale & Leatherdale, 1995; National Rifle Association of America, 2008; Yur'yev, 1985). This is clearly a topic which deserves more detailed consideration by athletes and coaches, particularly given the small changes in stance width that brought about the significant changes in score. This was most evident for participant 1 for whom simply decreasing mediolateral stance width by 6 cm produced the difference between the lowest and highest score These small changes in position were enough to influence patterns of movement coordination and variability, and ultimately affect the scores achieved.

Currently, most previous research has examined the effects of mediolateral stance position on stability (Day et al., 1993; Goodworth & Peterka, 2010; Winter et al., 1998) and shooting performance (Hawkins & Sefton, 2011), but little consideration has been given to the effects of anterior-posterior stance position. The current research has therefore provided a novel insight into the effects of anterior-posterior stance width on shooting performance. The importance of anterior-posterior stance position was most apparent for participant 4, who achieved all three top scores using the Foot in Front stance, and for participant 3, for whom three of the top four scores were achieved using the Foot in Front position. These findings clearly highlight the need for shooters to consider both mediolateral and anterior-posterior stance widths when selecting their optimal stance position.

Whilst score was clearly affected by the changes in stance position, no participant produced any significant differences in range of movement of the torso, upper limb or pistol between stances. This non-significant finding may be related to the findings of Hawkins and Sefton (2011) who reported that pistol stability decreased with mediolateral stances wider than 75 cm. All stance positions used in the current research were narrower than 75 cm; the Current mediolateral stance widths of participants did not exceed 38.0 cm, and even the widest of the modified stance positions was only 47.5 cm. Thus, when stance widths are narrower than 75 cm, other performance-related variables that are more sensitive to the changes in stance position must cause the changes in shot score.

The non-significant differences between stance positions in the range of movement recorded for the torso, upper limb and pistol was unexpected given the findings of the majority of previous research (Day et al., 1993; Winter et al., 1998) that has investigated stability of the centre of mass and limb movements in quiet stance. Each study used stance widths more similar to those recorded in the current study (0 – 32 cm and 14 - 42 cm respectively), and reported that stability decreased for narrower stance widths. There are a number of small, but potentially important, differences between quiet stance tasks and shooting that may cause differences in the effects of stance position. For instance, Day et al. required participants to focus on a blank screen whilst completing quiet stance tasks. Postural stability during similar tasks to those used by Day et al. has been reported to be lower than tasks with more complex vision requirements (Stoffregen, Pagulayan, Bardy, & Hettinger, 2000), such as sighting the target in pistol shooting. Research has also reported that postural stability is lower for tasks that require an internal focus, such as quiet stance tasks, than for those with an external focus, such as pistol shooting (Wulf, Mercer, McNevin, & Guadagnoli, 2004). Consequently, the increased stability for more complex tasks may explain the contrasting findings of pistol shooting and quiet stance research. Thus, the effects of stance width on shooting performance should be considered separately to the effects on quiet stance tasks, despite the seeming similarities in stability requirements.

A potential explanation for the differences in score achieved in different stance positions is that, at an elite level, it is not the amount of movement, but the degree of variability and the coordination of the movements of the upper limb and pistol, that most influence shooting success (Bradshaw et al., 2007; Davids et al., 2003; Latash et al., 1999). To investigate whether these variables determined the success of a stance position, two participants were selected for comparisons between the highest and lowest scoring stances. Any changes in movement coordination and variability can be used to indicate the mechanisms behind a more successful stance position.

The effects of stance position on movement coordination and variability differed between the two participants. For participant 1, the most successful stance positions resulted in horizontal pistol movements counteracting anterior-posterior torso sway to maintain a consistent position of the pistol on the target. Mediolateral torso sway was more important for participant 3, as the lowest scores were achieved in the stance positions where sway contributed to vertical movements of the pistol. Such differences in the effects of sway on performance indicate why the optimal stance position varies between participants. The changes in position required to influence torso sway are likely to differ between anterior-posterior and mediolateral sway movements. Currently, conflict exists within the literature regarding the effects of mediolateral stance width on anterior-posterior sway (Day et al., 1993; Winter,1990), and this should be examined in more detail in future research. By examining the effects of a wider range of stance positions on body sway it should be possible to determine whether mediolateral stance position can influence anterior-posterior sway, or whether anterior-posterior stance position must also be manipulated.

Coordination of upper limb movements also determined the success of a stance position. For participant 1, higher scores were achieved when horizontal pistol movements were controlled by interactions between the torso, shoulder and wrist. A variety of movement patterns were produced depending on the relationship between the torso and the shoulder. Movement patterns in the lower scoring stances were less variable, as wrist movement primarily controlled the motion of the pistol. The coordination of vertical upper limb movements were varied for the higher scoring stances, and the presence of the same two movement patterns in each of the lowest scoring positions indicate that patterns that involve the shoulder counteracting mediolateral torso sway are detrimental to performance.

In contrast to participant 1, the coordination of upper limb movements used by participant 3 to control the horizontal position of the pistol did not differ greatly between the highest and lowest scoring stances. Instead, the movements used to control the vertical pistol position had a greater influence on success. One predictable movement pattern produced for the lowest scoring stances was sway away from the target, shoulder adduction and radial deviation of the wrist. Movements varied between shots for the highest scoring stances, making it difficult to identify any common movement patterns.

The finding that more successful stances are often associated with more variable movement patterns concurs with previous research, particularly Schorer et al. (2007), who reported that the ability to adapt a performance can enhance success. Such adaptations in performance can help to maintain a consistent task outcome between trials (Gorniak et al., 2008; Scholz & Schöner, 1999; Tseng et al., 2002). These findings also provide support for Hwang et al. (2006) who stated that more stable stance positions result in a decreased coupling of the upper limb, and therefore an improved ability to adapt a performance. The ability to adapt the movements of the torso and upper limb was most important when controlling horizontal pistol movement for participant 1, and vertical pistol movement for participant 3. In contrast the group-based findings of Pellegrini et al. (2002) suggested that the upper limb moves as one segment when controlling horizontal movements but produces more complex movement patterns when controlling vertical movement. Instead, methods of controlling pistol movement vary between individuals, again explaining why the optimal stance position will likely vary between shooters.

The amount of variability also differed between stance positions, providing further insight into the processes that determine a successful stance position. Positional variability of horizontal pistol movements was smaller for the most successful stances. Thus, both participants reproduced the position of the pistol more closely between shots in the highest scoring stance positions. This corresponds with the greater number of movement patterns produced for the upper limb in the higher scoring stances, and further reflects the increased ability of the movement system to adapt a performance, thereby maintaining a stable task outcome. These findings support existing research that states that when movement coordination is more variable, the outcome will be more consistent for highly skilled performances (Wagner, Pfusterschmied, Klous, von Duvillard, & Müller, 2012; Wilson et al., 2008). These findings support both the second and third hypotheses, that higher scoring stances would have a greater ability to adapt movement patterns of the upper limb, resulting in smaller pistol variability.

Further differences between stance positions were apparent when comparing the variability of movements affecting vertical pistol motion for participant 3. Greater positional variability of the torso and shoulder was recorded for the higher rather than lower scoring stance positions. This reflects previous findings concerning the principle of abundancy, whereby greater variability of movement components result in a more consistent task outcome (Button, Macleod, Sanders, & Coleman, 2013; Tseng et al., 2002). This was accompanied by greater movement variability of the shoulder, wrist and pistol for the most successful stances. Increased movement variability can reflect a greater number of submovements produced during the final second before the shot, which represent fine movement control used to increase accuracy at the target (Dounskaia et al., 2005; Fradet, Lee, & Dounskaia, 2008). The use of submovements should result in a greater degree of control over pistol movement prior to the instance of the shot.

The finding that the changes in movement coordination and variability differ for each participant is unsurprising, given the individual nature of shooting performances discussed throughout this thesis. Whilst intra-individual analysis of coordination and variability had not previously been examined for pistol shooting, the current findings agree with those from a wide range of other activities; from simple tasks such as pointing (Domkin et al., 2002) and walking (Preatoni et al., 2010), to more complex tasks such as triple jump (Wilson et al., 2008). Thus, it is important that when evaluating elite pistol shooting technique, the performance of each shooter is analysed individually. This supports Bradshaw et al. (2007) who stated that whilst many coaches and athletes attempt to follow one, optimal, model of performance, success should instead be achieved using a flexible pattern of movements. Individual analysis is particularly important for a sport such as pistol shooting, where exceptionally small changes in performance can greatly influence success. Thus, reliance on the results of group analysis without consideration of individual performance traits could in fact hinder, rather than enhance, performance. Analyses such as those made here should be made available to coaches and athletes (Langdown et al., 2012) to make it possible for athletes to further develop technique without the traditional focus on recreating one, optimal, performance.

The comparisons made in this research have clearly identified the importance of stance position to elite precision pistol shooting performance. There are limitations to the method that should be acknowledged. Due to the nature of each testing session, only 10 shots were completed in each stance position. This ensured that testing could be completed on a single day, and remain within an acceptable number of shots so that performance did not decline as a result of fatigue. This method appeared successful, as demonstrated by a Spearman's rank correlation which detected no significant correlations between trial order and the scores achieved for either the group or individual participants. Future research should now examine the effect of stance position on the location of the aim point on the target. Whilst the current research has identified how changes in coordination and variability affect movement of the pistol, analysis of the aim point will determine how this affects the exact location at which the pistol is aiming. This analysis was not possible here, owing to interference between the motion analysis and opto-electronic shooting systems, but future research using the new video-based shooting systems should now examine this in more detail. This research should also consider the effects of stance angle on performance. Stance angle, defined as the angle of turnout of the toes in relation to the heel when measured along the long axis of the feet, has previously been reported to have significant effects on shooting performance (Hawkins, 2013), and future research should consider whether the optimal angle varies depending on the stance width selected.

12.5 Conclusion

Stance position had a significant effect on precision pistol shooting success, and is clearly something that requires more consideration than current coaching manuals provide. The optimal stance position varied between participants, indicating that athletes must consider which stance is most effective for their personal performance, taking into account both mediolateral and anterior-posterior foot position. The mechanisms behind any differences in performance varied between individuals, but the more successful stances often demonstrated a greater ability to adapt the movements of the torso and upper limb, resulting in a more consistent position of the pistol. Thus, whilst the specific movement patterns and the degree of variability produced may be beyond that which a shooter can consciously control, manipulating stance position is an effective way of influencing these variables to enhance success. Finally, given the individual variation in the most effective stance position, and its specific effects on movement coordination and variability, simply following a recommended technical model, as often provided in coaching manuals, will not be appropriate for most shooters who fall outside the traditional ‘average’ performance.

Chapter Thirteen

Summary of Findings, Practical Applications and Recommendations for Future Research

This thesis has contributed to existing knowledge of the kinematic variables associated with elite pistol shooting performances. It has enhanced understanding of the modern pentathlon combined event, particularly the non-significant effects of time constraints and running phases on shooting performance. It has also produced a more detailed understanding of the methods used to control movement of the pistol in precision shooting, and the importance of stance position to shooting success. The first three studies examined shooting performance in the modern pentathlon combined event, and investigated:

- the changes in performance with the move from precision shooting to the combined event;
- the effects of the 70 s time limit within each shooting series on shooting performance; and
- the effects of each 1 km running phase on performance in subsequent shooting series.

The focus of the final two studies was modified from combined event to precision shooting. These studies investigated the mechanisms behind successful shooting performances, and potential techniques to further enhance success. This was achieved by examining:

- the movement coordination and variability of the torso and upper limb, and how they affect horizontal and vertical movements of the pistol; and
- the effects of changing stance position on shot score, movement coordination and variability.

13.1 Summary of Findings

No previous research had compared performance between precision and combined event shooting, and so Study 1 (Chapter 5) investigated the changes in performance introduced by the rule change in modern pentathlon. The performances of pistol shooters and modern pentathletes were compared under precision and combined event conditions and, contrary to the hypothesis, the most successful precision shooters were not the most successful in the combined event. This was demonstrated by non-significant differences between pistol shooters and modern pentathletes in the combined event, despite significantly higher scores, and smaller movements of the pistol and centre of pressure ($p<.05$) for pistol shooters when precision shooting. The non-significant differences between the two groups in the combined event were a result of significantly decreased scores and aiming time, and significantly increased pistol and centre of pressure movements ($p<.05$), in comparison to precision shooting. Differences in performance between the two events were further demonstrated by different variables being significantly associated with score in the two events. For example, for one participant shot score was most highly correlated with pistol movements in precision shooting, and with aiming time in the combined event. Different variables being associated with score meant that the second hypothesis was accepted, and highlighted the new performance requirements of the combined event.

The first study examined performance in only the first shooting series, prior to the start of the running phases. No research had investigated the effects of either the 70 s time limit or the running phases on the kinematics of combined event shooting. Thus, studies 2 and 3 provided novel investigations into combined event shooting performance by incorporating the second and third shooting series into the analysis.

Study 2 (Chapter 6) investigated the effects of the 70 s time limit by comparing performance between the first six shots within each shooting series. The hypothesis was rejected, as participants maintained consistent performances throughout each series despite a gradually diminishing time period in which to achieve five hits on target. Consistent performances were produced regardless of whether a participant required less than 30 s, or the full 70 s, to complete a series. Participants maintained consistent aiming times throughout each series, which resulted in non-significant differences in shot score and movements of the pistol and centre of pressure (p>.05). Thus, the 70 s time limit had a limited effect on shooting performance. Correlations revealed that aiming time and pistol and centre of pressure movements accounted for between 57% and 88% of changes in score. This supported the findings of Study 1 that other variables must also affect shooting success.

Study 3 (Chapter 7) examined the effects of each 1 km running phase by comparing shooting performance between each of the three shooting series. The hypothesis was rejected, as each running phase did not appear to have any negative influence on performance in subsequent shooting series. Despite an increasing reliance on anaerobic metabolism following each running phase, there were no significant differences in aiming time, score, or movements of the pistol or centre of pressure between shooting series (p>.05).

A key finding from each of the first three studies was the individual nature of pistol shooting performance. Results from group analysis were used to indicate how performance changed between precision and combined event shooting, and between each shooting series. These results rarely reflected any individual participants' response to the shooting task. For example, group analysis in Study 3 demonstrated that average scores varied by just 0.2 points between each series. This was in contrast to the participants selected as case studies, including one who experienced a decrease in score with every series, and another who experienced a reduction of 1.8 points between series two and three. Individual variation from the group median was also evident for aiming time and movements of the pistol and centre of pressure. These characteristics of an individual's shooting technique are masked by the use of the group median, so intra-individual methods of analysis were selected as the primary method of analysis for the final two studies.

The first three studies identified that variables other than movements of the pistol and centre of pressure must influence success in pistol shooting. Consequently, the final two studies provided a more detailed analysis of the movements produced when shooting than has been achieved in previous literature. Study 4 (Chapter 11)used a three-dimensional motion analysis system to analyse the coordination and variability of movements of the torso, upper limb and pistol. Horizontal movements of the pistol took place in the opposite direction to anterior-posterior sway of the torso for most participants (average cross-correlation: -.84 ±.08), thus enabling the maintenance of a consistent position of the pistol on the target. These opposing movements were produced by an interaction between the shoulder, wrist and pistol, but the exact movement patterns varied between participants. Mediolateral torso sway was less important to performance (average cross-correlation: .18 ±.33), as only one participant demonstrated a predictable relationship between torso sway and vertical pistol movements. Movement patterns varied between shots for the other participants, demonstrating that pistol shooters have developed effective synergies between movements of the torso, pistol and upper limb to produce highly consistent performances. This study provided an in-depth descriptive analysis of precision shooting performance, but further research was required to determine how coordination and variability could be modified to enhance success, and make the findings of practical use to pistol shooters.

The final study (Chapter 12) applied the methods and findings of Study 4 to produce a novel investigation into the effects of mediolateral and anterior-posterior stance position on shooting performance. The hypothesis, that stance position would have a significant effect on shot score, was accepted ($p<.05$). Group analysis indicated that the lowest score was achieved using participants' current stance position. In contrast, intra-individual analysis identified that the position which resulted in the highest or lowest score varied between participants, and only one participant produced their lowest score using their current stance. The processes behind the changes in score, as quantified by changes in movement coordination and variability, also differed between participants. One participant achieved their highest scores for the stances where anterior-posterior sway took place in the opposite direction to horizontal pistol movement, and where coordination of upper limb movement was more variable. Mediolateral torso sway was more important for another participant, who achieved lower scores in the stances where torso sway contributed to vertical pistol movement. Both participants achieved higher scores when the horizontal position of the pistol was less variable. Thus, this study demonstrated how changes to stance position can be used to modify the variables which affect performance, and further enhance the success of elite pistol shooters.

13.2 Key Findings and Practical Applications

Key findings from this research have practical applications for both modern pentathletes and precision pistol shooters. Findings from the combined event research in studies 1-3 can be used by modern pentathletes to aid both training and competition. These findings, and their subsequent implications for performance, include:

- ability in precision shooting does not guarantee success in the combined event (Study 1, Chapter 5). Modern pentathletes therefore need to develop new training methods to adapt to the increased speed of shooting associated with the combined event. Particular consideration should be given to how quickly an athlete can shoot before accuracy is compromised;

- shooting performance does not change significantly within each series despite a gradual decrease in heart rate (Study 2, Chapter 6). This finding corresponds with previous research into the relationship between heart rate and pistol shooting (Brown et al., 2013), but is in contrast to the effects of exercise on biathlon shooting (Hoffman et al., 1992). Thus, using techniques such as reducing running speed prior to each shooting series will not enhance shooting performance; and

- shooting performance does not change significantly following each 1 km running phase (Study 3, Chapter 7). This provides support for existing combined event research (Le Meur et al., 2010), and has two potential implications for performance. One is that, given the similarities in performance, shooting training in isolation could be effective in addition to recreating the entire event. Given that all previous research suggests that performance should decline following exercise, it is surprising that a similar effect was not observed in the combined event. Thus, a second implication is that shooting performance in the first series was already poor, and therefore did not decline further in series two and three. Arguably, this may be due to the negative effects of pre-competition anxiety, which could be greater than those associated with exercise. Exercise can reduce the effects of anxiety (Nibbeling et al., 2014), and thus the impact of anxiety on performance could be reduced in series two and three. Whilst not the focus of this research, evidence from the increase in heart rate at the beginning of the first shooting series, which was not present in series 2 or 3, suggests that these negative anxiety effects may be present. Athletes could consider methods to enhance shooting performance in the first series, such as using pre-event anxiety reduction techniques. This has the potential to improve shooting performance in series one, thus improving overall combined event time.

Findings from the analysis of precision shooting in the final two studies can be used by pistol shooters and coaches to further enhance precision shooting success. These findings, and their corresponding performance implications are:

- even minor changes in stance width can significantly affect the scores achieved by elite pistol shooters. Pistol shooters should therefore consider stance position in much greater detail than is currently provided in coaching manuals. Shooters should consider both the mediolateral and anterior-posterior position of the feet, as Study 5 (Chapter 12) revealed that both have the potential to significantly influence performance. This finding builds on previous pistol shooting stance research (Hawkins & Sefton, 2011); and

- the optimal stance position, and the mechanisms behind any changes in performance, vary between participants (Study 5, Chapter 12). Thus, pistol shooters must examine the effect of stance position on their individual performance, rather than follow guidelines generalised for all shooters. Following group-based recommendations, such as those provided in coaching manuals, is not sufficient if shooters wish to further enhance performance. This expands on existing stance position research in both shooting (Hawkins & Sefton, 2011) and balance tasks (Day et al., 1993; Goodworth & Peterka, 2010), which have recommended optimal stances based on group analysis of performance.

Finally, key findings from this research also have important implications for researchers in the field of motor control. A common theme throughout this thesis has been the importance of intra-individual analysis of performance, rather than the group-based designs that are commonly favoured in the literature. A consequence of group analysis is that extreme data points are masked by calculating the centre point of the data. Elite level performances, however, may often be characterised by these extreme values which lie outside the typical 'average' performance. For instance, group analysis in Study 5 indicated that the highest scores could be achieved when participants used a Current Foot in Front stance position. Intra-individual analysis revealed that only one participant achieved their highest score using this position. Thus, important techniques to enhance performance for all other participants were hidden by the use of group data. Similar effects have previously been reported by Scholes et al. (2012) who questioned the validity of using group-based data when analysing knee mechanics during step landing. Currently, the use of group analysis is compounded by journal policy to accept primarily group-based designs. Until the current preference towards the use of group average data is changed, research will continue to mask important characteristics of both exercise and elite sports performance.

13.3 Recommendations for Future Research

This thesis has expanded current knowledge on both combined event and precision shooting performance. There are now opportunities for future research to build on the current findings and investigate additional ways to enhance performance. One particular consideration is the application of the techniques used in the final two studies (Chapters 11 and 12) to performance in the combined event. Given the significant effects of small changes in stance position on precision shooting performance, research should consider whether similar effects are apparent in the combined event. An additional comparison in the combined event is the specific effect of exercise intensity. In studies 2 and 3 (Chapters 6 and 7), participants were instructed to run at a similar pace to which they would in competition, but specific information concerning whether a constant pacing strategy was used, or whether participants reduced running speed prior to each shooting series, was not recorded. Previous research suggests that pacing strategies should not significantly affect shooting performance (Le Meur et al., 2012), but none has examined the specific effects of exercise intensity on the kinematics of combined event shooting.

Future research should also expand on the effects of stance position on precision shooting performance by incorporating the effects of stance angle on shooting success. Stance angle has previously been reported to significantly affect shooting stability (Hawkins, 2013), but research has yet to consider the effects on score. Study 5 (Chapter 12) revealed that the optimal stance position is produced by an interaction between mediolateral and anterior-posterior stance position, and so stance angle should be examined in relation to various stance widths. Stance position and angle have the potential to influence other variables, such as velocity of centre of pressure movement, that were not examined in the studies within this thesis. Research should therefore incorporate these additional variables into future analyses.

The findings of this research are clearly most applicable to elite shooting-based sport. There is also potential for the transfer of the methods used, particularly in the final two studies, to the wider population. A common consideration of existing research has been how stability changes with ageing (Demura, Kitabayashi, & Aoki, 2008; Freitas & Duarte, 2012), or is affected by illness or disability (Mehdikhani, Khalaj, Chung, & Mazlan, 2014; Termoz et al., 2008). Much of this research has used discrete methods to analyse centre of pressure movement, and little has used more detailed methods, such as the analysis of movement coordination and variability. A particular consideration for future research could be the effects of stance position on stability in clinical groups, something which has currently received limited attention in the literature. More in-depth analyses could enhance the understanding of the processes associated with ageing or balance disorders, and potentially lead to the development of new techniques or technology to aid individuals with balance impairments.

13.4 Conclusion

This thesis has improved the understanding of the kinematic factors associated with shooting performances in the modern pentathlon combined event and for precision pistol shooting. A key theme throughout all five studies was the individual nature of pistol shooting, and the importance of intra-individual analysis of performance. These findings are primarily of benefit to athletes competing in either modern pentathlon or precision shooting events. They will also be of interest to researchers investigating motor control and balance impairments in clinical populations, with the potential for transfer of some of the data collection and analysis methods to research in non- sporting disciplines

Chapter Fourteen

Reference List

Aalto, H., Pyykkö, I., Ilmarinen, R., Kähkönen, E., & Starck, J. (1990). Postural stability in shooters. *Journal for Oto-Rhino-Laryngology and Its Related Specialties*, *52*(4), 232–238.

Abramson, L. Y., Seligman, M. E., & Teasdale, J. D. (1978). Learned helplessness in humans: critique and reformulation. *Journal of Abnormal Psychology*, *87*(1), 49– 74.

Antal, L., & Skanaker, R. (1985). *Pistol Shooting.* Liverpool: Author.

Arutyunyan, G., Gurfinkel, V., & Mirskii, M. (1968). Investigation of aiming at a target.
Biophysics, *13*, 536–538.

Arutyunyan, G., Gurfinkel, V., & Mirskii, M. (1969). Organization of movements on execution by man of an exact postural task. *Biophysics*, *14*, 1103–1107.

Ball, K. A., Best, R. J., & Wrigley, T. V. (2003). Inter- and intra-individual analysis in elite sport: Pistol shooting. *Journal of Applied Biomechanics*, *19*(1), 28–38.

Bartlett, R., Wheat, J., & Robins, M. (2007). Is movement variability important for sports biomechanists? *Sports Biomechanics*, *6*(2), 224–243.

Beilock, S. L., Bertenthal, B. I., McCoy, A. M., & Carr, T. H. (2004). Haste does not always make waste: expertise, direction of attention, and speed versus accuracy in performing sensorimotor skills. *Psychonomic Bulletin & Review*, *11*(2), 373–379.

Bernstein, N. (1967). *The Coordination and Regulation of Movements.* Oxford: Pergamon.

Berrigan, F., Simoneau, M., Martin, O., & Teasdale, N. (2006). Coordination between posture and movement: Interaction between postural and accuracy constraints. *Experimental Brain Research*, *170*(2), 255–264.

Black, D. P., Smith, B. a., Wu, J., & Ulrich, B. D. (2007). Uncontrolled manifold analysis of segmental angle variability during walking: Preadolescents with and without Down syndrome. *Experimental Brain Research*, *183*(4), 511–521.

Bove, M., Faelli, E., Tacchino, A., Lofrano, F., Cogo, C. E., & Ruggeri, P. (2007). Postural control after a strenuous treadmill exercise. *Neuroscience Letters*, *418*(3), 276– 281.

Bradshaw, E. J., Maulder, P. S., & Keogh, J. W. L. (2007). Biological movement variability during the sprint start: performance enhancement or hindrance? *Sports Biomechanics*, *6*(3), 246–260.

Brown, M. J., Tandy, R., Wulf, G., & Young, J. (2013). The Effect of acute exercise-induced fatigue on pistol shooting performance in police officers by. *Motor Control*, 17, 273–282.

Button, C., Macleod, M., Sanders, R., & Coleman, S. (2013). Throw action at different skill levels, *Research Quarterly for Exercise and Sport,* 74(3), 37–41.

Chapman, A. (2008). *Biomechanical Analysis of Fundamental Human Movement*. Champaign, IL: Human Kinetics.

Chiu, S. L., & Chou, L. S. (2012). Effect of walking speed on inter-joint coordination differs between young and elderly adults. *Journal of Biomechanics*, *45*(2), 275–280.

Chockalingam, N., Giakas, G., & Iossifidou, A. (2002). Do strain gauge force platforms need in situ correction? *Gait and Posture*, *16*(3), 233–237.

Chow, J. Y., Davids, K., Hristovski, R., Araújo, D., & Passos, P. (2011). Nonlinear pedagogy: Learning design for self-organizing neurobiological systems. *New Ideas in Psychology*, *29*(2), 189–200.

Cirstea, M. C., & Levin, M. F. (2000). Compensatory strategies for reaching in stroke.*Brain : A Journal of Neurology*, *123(5)*, 940–953.

Coffee, P., & Rees, T. (2011). When the chips are down: effects of attributional feedback on self-efficacy and task performance following initial and repeated failure. *Journal of Sports Sciences*, *29*(3), 235–245.

Coffee, P., Rees, T., & Haslam, S. A. (2009). Bouncing back from failure: the interactive impact of perceived controllability and stability on self-efficacy beliefs and future task performance. *Journal of Sports Sciences*, *27*(11), 1117–1124.

Darling, W. G., Cooke, J. D., & Brown, S. H. (1989). Control of simple arm movements in elderly humans. *Neurobiology of Aging*, *10*(2), 149–157.

Davids, K., Bennett, S., & Newell, K. M. (2006). *Movement System Variability*. Champaign, IL: Human Kinetics.

Davids, K., Glazier, P., Arújo, D., & Bartlett, R. (2003). Movement systems as dynamical systems. *Sports Medicine*, *33*(4), 245–260.

Davis III, R., Ounpuu, S., Tyburski, D., & Gage, J.R. (1991). A gait analysis data collection and reduction technique. *Human Movement Science, 10*(5), 575-587.

Day, B. Y. B. L., Steiger, M. J., Thompson, P. D., & Marsden, C. D. (1993). Effect of vision and stance width on human body motion when standing : Implications for afferent control of lateral sway. *Journal of Physiology*, *469*, 479–499.

Demura, S. I., Kitabayashi, T., & Aoki, H. (2008). Body-sway characteristics during a static upright posture in the elderly. *Geriatrics and Gerontology International*, *8*(3), 188–197.

Demura, S., Kitabayashi, T., & Noda, M. (2006). Selection of useful parameters to evaluate center-of-foot pressure movement. *Perceptual and Motor Skills*, *103*(3), 959–973.

Derave, W., Tombeux, N., Cottyn, J., Pannier, J. L., & De Clercq, D. (2002). Treadmill exercise negatively affects visual contribution to static postural stability. *International Journal of Sports Medicine*, *23*(1), 44–49.

Domkin, D., Laczko, J., Djupsjöbacka, M., Jaric, S., & Latash, M. L. (2005). Joint angle variability in 3D bimanual pointing: Uncontrolled manifold analysis. *Experimental Brain Research*, *163*(1), 44–57.

Domkin, D., Laczko, J., Jaric, S., Johansson, H., & Latash, M. L. (2002). Structure of joint variability in bimanual pointing tasks. *Experimental Brain Research*, *143*(1), 11–23.

Dounskaia, N., Wisleder, D., & Johnson, T. (2005). Influence of biomechanical factors on substructure of pointing movements. *Experimental Brain Research*, *164*(4), 505–516.

Duarte, M., & Freitas, S. M. S. F. (2005). Speed-accuracy trade-off in voluntary postural movements. *Motor Control*, *9*(2), 180–196.

Elliott, D., Hansen, S., & Mendoza, J. (2004). Learning to optimize speed, accuracy, and energy expenditure: A framework for understanding speed-accuracy relations in goal-directed aiming. *Journal of Motor Behavior*, *36*(3), 339–351.

Era, P., Konttinen, N., Mehto, P., Saarela, P., & Lyytinen, H. (1996). Postural stability and skilled performance-a study on top-Level and naive rifle shooters. *Journal of Biomechanics*, *29*(3), 301–306.

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: attentional control theory. *Emotion*, *7*(2), 336–353.

Feng, Y., & Max, L. (2014). Accuracy and precision of a custom camera-based system for 2-d and 3-d motion tracking during speech and nonspeech motor tasks.*Journal of Speech, Language, and Hearing Research*, *57*(2), 426–438.

Fernandez, L., & Bootsma, R. J. (2004). Effects of biomechanical and task constraints on the organization of movement in precision aiming. *Experimental Brain Research*, *159*(4), 458–466.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *The Journal of Experimental Psychology*, *47*, 381– 391.

Fleisig, G., Chu, Y., Weber, A., & Andrews, J. (2009). Variability in baseball pitching biomechanics among various levels of competition. *Sports Biomechanics*, *8*(1), 10– 21.

Fradet, L., Lee, G., & Dounskaia, N. (2008). Origins of submovements during pointing movements. *Acta Psychologica*, *129*(1), 91–100.

Freitas, S. M. S. F., & Duarte, M. (2012). Joint coordination in young and older adults during quiet stance: Effect of visual feedback of the center of pressure. *Gait and Posture*, *35*(1), 83–87.

Gill, H. S., & O'Connor, J. J. (1997). A new testing rig for force platform calibration and accuracy tests. *Gait and Posture*, *5*(3), 228–232.

Goodworth, A. D., & Peterka, R. J. (2010). Influence of stance width on frontal plane postural dynamics and coordination in human balance control. *Journal of Neurophysiology*, *104*(2), 1103–1118.

Goonetilleke, R. S., Hoffmann, E. R., & Lau, W. C. (2009). Pistol shooting accuracy as dependent on experience, eyes being opened and available viewing time. *Applied Ergonomics*, *40*(3), 500–508.

Gorniak, S. L., Duarte, M., & Latash, M. L. (2008). Do synergies improve accuracy? A study of speed-accuracy trade-offs during finger force production. *Motor Control*, *12*(2), 151–172.

Hamill, J., Haddad, J. M., & McDermott, W. J. (2000). Issues in quantifying variability from a dynamical systems perspective. *Journal of Applied Biomechanics*, *16*(4), 407–418.

Hawkins, R. (2013). Effects of stance angle on postural stability and performance with national-standard air pistol competitors. *European Journal of Sport Science*, 13(5),1–7.

Hawkins, R. N., & Sefton, J. M. (2011). Effects of stance width on performance and postural stability in national-standard pistol shooters. *Journal of Sports Sciences*, *29*(13), 1381–1387.

Heimer, S., Medved, V., & Spirelja, A. (1985). Influence of postural stability on sport shooting performance. *Kinezioliogija*, *2*, 119–122.

Helsen, W. F., Elliott, D., Starkes, J. L., & Ricker, K. L. (2000). Coupling of eye, finger, elbow, and shoulder movements during manual aiming. *Journal of Motor Behavior*, *32*(3), 241–248.

Henry, S. M., Fung, J., & Horak, F. B. (2001). Effect of stance width on multidirectional postural responses. *Journal of Neurophysiology*, *85*(2), 559–570.

Herpin, G., Gauchard, G. C., Lion, A., Collet, P., Keller, D., & Perrin, P. P. (2010). Sensorimotor specificities in balance control of expert fencers and pistol shooters. *Journal of Electromyography and Kinesiology*, *20*(1), 162–169.

Hoffman, M. D., Gilson, P., Westenburg, T., & Spencer, W. (1992). Biathlon shooting performance after exercise of different intensities. *International Journal of Sports Medicine*, *13*(3), 270–273.

Horan, S. A., Evans, K., & Kavanagh, J. J. (2011). Movement variability in the golf swing of male and female skilled golfers. *Medicine and Science in Sports and Exercise*, *43*(8), 1474–1483.

Hwang, I. S., Huang, C. T., Cherng, R. J., & Huang, C. C. (2006). Postural fluctuations during pointing from a unilateral or bilateral stance. *Human Movement Science*, *25*(2), 275–291.

Hwang, I. S., & Wu, P. S. (2006). The reorganization of tremulous movements in the upper limb due to finger tracking maneuvers. *European Journal of Applied Physiology*, *98*(2), 191–201.

Kistemaker, D.A. Knock Van Soest, A.J., Wong, J.D., Kurtzer, I. & Gribble, P.L. (2013). Control of position and movement is simplified by combined muscle spindle and Golgi tendon organ feedback. *Journal of Neurophysiology, 109*(4), 1126-1139.

Kadaba, M., Ramakrishnan, E., Wootten, E., Gainey, J., Gorton, G., & Cochran, G.V.B. (1989). Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of Orthopaedic Research,* 7(6), 849-860.

Kao, J. C., Ringenbach, S. D. R., & Martin, P. E. (2003). Gait transitions are not dependent on changes in intralimb coordination variability. *Journal of Motor Behavior*, *35*(3), 211–214.

Keogh, J., Morrison, S., & Barrett, R. (2004). Augmented visual feedback increases finger tremor during postural pointing. *Experimental Brain Research*, *159*(4), 467– 477.

Khan, M. A., & Franks, I. M. (2003). Online versus offline processing of visual feedback in the production of component submovements. *Journal of Motor*

Behavior, *35*(3), 285–295.

Kim, M. J., Karol, S., Park, J., Auyang, A., Kim, Y. H., Kim, S., & Shim, J. K. (2012). Inter- joint synergies increase with motor task uncertainty in a whole-body pointing task. *Neuroscience Letters*, *512*(2), 114–117.

Kirby, R. L., Price, N. A., & MacLeod, D. A. (1987). The influence of foot position on standing balance. *Journal of Biomechanics*, *20*(4), 423–427.

Krüger, M., Eggert, T., & Straube, A. (2011). Joint angle variability in the time course of reaching movements. *Clinical Neurophysiology*, *122*(4), 759–766.

Lakie, M. (2010). The influence of muscle tremor on shooting performance. *Experimental Physiology*, *95*(3), 441–450.

Lambourne, K., & Tomporowski, P. (2010). The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain Research*, *1341*, 12–24.

Langdown, B. L., Bridge, M., & Li, F.-X. (2012). Movement variability in the golf swing.*Sports Biomechanics*, *11*(2), 273–287.

Latash, M. (2000). There is no motor redundancy in human movements. There is motor abundance. *Motor Control*, *4*(3), 259–260.

Latash, M. L., Aruin, A. S., & Zatsiorsky, V. M. (1999). The basis of a simple synergy: Reconstruction of joint equilibrium trajectories during unrestrained arm movements. *Human Movement Science*, *18*(1), 3–30.

Latash, M. L., Scholz, J. P., & Schöner, G. (2002). Motor control strategies revealed in the structure of motor variability. *Exercise and Sport Sciences Reviews*, *30*(1), 26– 31.

Le Clair, K., & Riach, C. (1996). Postural stability measures: what to measure and for how long. *Clinical Biomechanics*, *11*(3), 176–178.

Le Meur, Y., Dorel, S., Baup, Y., Guyomarch, J. P., Roudaut, C., & Hausswirth, C. (2012). Physiological demand and pacing strategy during the new combined event in elite pentathletes. *European Journal of Applied Physiology*, *112*(7), 2583–2593.

Le Meur, Y., Hausswirth, C., Abbiss, C., Baup, Y., & Dorel, S. (2010). Performance factors in the new combined event of modern pentathlon. *Journal of Sports Sciences*, *28*(10), 1111–1116.

Leatherdale, F., & Leatherdale, P. (1995). *Successful Pistol Shooting.* Marlborough: Crowood Press.

Levin, M. F. (1996). Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. *Brain*, *119*(1), 281–293.

Loram, I.D., Maganaris, C.N, & Lakie, M. (2005). Active, non-spring-like muscle movements in human postural sway: how might paradoxical changes in muscle length be produced. *Journal of Physiology, 564*(1), 281-293.

Mason, B., Cowan, L., & Gonczol, T. (1990). Factors affecting accuracy in pistol shooting. *EXCEL*, *6*(4), 2–6.

Mehdikhani, M., Khalaj, N., Chung, T. Y., & Mazlan, M. (2014). The effect of feet position on standing balance in patients with diabetes. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, *228*(8), 819–823.

Mello, R.G.T, Oliveira, L.F., & Nadal, J. (2007). Anticipation mechanism in body sway control and effect of muscle fatigue. *Journal of Electromyography and Kinesiology, (17)*6, 739-746.

Middleton, J., Sinclair, P., & Patton, R. (1999). Accuracy of centre of pressure measurement using a piezoelectric force platform. *Clinical Biomechanics*, *14*(5), 357–360.

Morrison, S., & Keogh, J. (2001). Changes in the dynamics of tremor during goal-directed pointing. *Human Movement Science*, *20*(4-5), 675–693.

Morrison, S., & Newell, K. M. (2000). Postural and resting tremor in the upper limb. *Clinical Neurophysiology*, *111*(4), 651–663.

Nardone, A., Godi, M., Grasso, M., Guglielmetti, S., & Schieppati, M. (2009). Stabilometry is a predictor of gait performance in chronic hemiparetic stroke patients. *Gait and Posture*, *30*(1), 5–10.

Nardone, A., Tarantola, J., Giordano, A., & Schieppati, M. (1997). Fatigue effects on body balance. *Electroencephalography and Clinical Neurophysiology - Electromyography and Motor Control*, *105*(4), 309–320.

National Rifle Association of America. (2008). *Basics of Pistol Shooting*. National Rifle Association.

Newell, K. M., & Corcos, D. M. (1993). *Variability and motor control.* Champaign, IL: Human Kinetics.

Nibbeling, N., Oudejans, R. R. D., Ubink, E. M., & Daanen, H. A. M. (2014). The effects of anxiety and exercise-induced fatigue on shooting accuracy and cognitive performance in infantry soldiers.pdf. *Ergonomics*, *57*(9), 1366–1379.

Nieuwenhuys, A., & Oudejans, R. R. D. (2010). Effects of anxiety on handgun shooting behavior of police officers: a pilot study. *Anxiety, Stress, and Coping*, *23*(2), 225– 233.

Nieuwenhuys, A., & Oudejans, R. R. D. (2011). Training with anxiety: Short-and long- term effects on police officers' shooting behavior under pressure. *Cognitive Processing*, *12*(3), 277–288.

Niinimaa, V., & McAvoy, T. (1983). Influence of exercise on body sway in the standing rifle shooting position. *Canadian Journal of Applied Sport Sciences*, *8*(1), 30–33.

Noda, M., & Demura, S.-I. (2007). Influence of lower leg muscle fatigue on the centre of pressure in a static upright posture. *European Journal of Sport Science*, *7*(3), 135–141.

Oudejans, R., & Pijpers, J. (2010). Training with mild anxiety may prevent choking under higher levels of anxiety. *Psychology of Sport and Exercise, 11*(1), 44-50.

Owings, T. M., & Grabiner, M. D. (2004). Variability of step kinematics in young and older adults. *Gait and Posture*, *20*(1), 26–29.

Palmieri-Smith, R. M., Ingersoll, C., Stone, M. B., & Krause, B. (2002). Center-of-pressure parameters used in the assessment of postural control. *Journal of Sport Rehabilitation*, *11*(1), 51–66.

Pellegrini, B., & Schena, F. (2005). Characterization of arm-gun movement during air pistol aiming phase. *Journal of Sports Medicine and Physical Fitness*, *45*, 467–475.

Preatoni, E., Hamill, J., Harrison, A. J., Hayes, K., van Emmerik, R. E. a., Wilson, C., & Rodano, R. (2013). Movement variability and skills monitoring in sports. *Sports Biomechanics*, *12*(2), 69–92.

Raymakers, J. A., Samson, M. M., & Verhaar, H. J. J. (2005). The assessment of body sway and the choice of the stability parameter(s). *Gait and Posture*, *21*(1), 48–58.

Schmidt, R., Zelaznik, H., & Frank, J. (1978). Sources of inaccuracy in rapid movement. In *Information processing in Motor Control and Learning* (pp. 183–202). London: Academic Press Inc.

Scholes, C. J., McDonald, M. D., & Parker, A. W. (2012). Single-subject analysis reveals variation in knee mechanics during step landing. *Journal of Biomechanics*, *45*(12), 2074–2078.

Scholz, J. P., & Schöner, G. (1999). The uncontrolled manifold concept: Identifying control variables for a functional task. *Experimental Brain Research*, *126*(3), 289– 306.

Scholz, J. P., Schoner, G., & Latash, M. L. (2000). Identifying the control structure of multijoint coordination during pistol shooting. *Experimental Brain Research*, *135*(3), 382–404.

Stergiou, N. (2004). *Innovative Analyses of Human Movement*. Champaign, IL: Human Kinetics.

Stoffregen, T. A., Pagulayan, R. J., Bardy, B. G., & Hettinger, L. J. (2000). Modulating postural control to facilitate visual performance. *Human Movement Science*, *19*(2), 203–220.

Su, F., Wu, W., & Lee, W. (2000). Stance stability in shooters. *Journal of Medical and Biological Engineering*, *20*(4), 187–192.

Tang, W.-T., Zhang, W.-Y., Huang, C.-C., Young, M.-S., & Hwang, I.-S. (2008). Postural tremor and control of the upper limb in air pistol shooters. *Journal of Sports Sciences*, *26*(14), 1579–1587.

Termoz, N., Halliday, S. E., Winter, D. A., Frank, J. S., Patla, A. E., & Prince, F. (2008).
The control of upright stance in young, elderly and persons with Parkinson’s disease. *Gait and Posture*, *27*(3), 463–470.

Tseng, Y.-W., Scholz, J. P., & Schöner, G. (2002). Goal-equivalent joint coordination in pointing: affect of vision and arm dominance. *Motor Control*, *6*(2), 183–207.

Tseng, Y.-W., Scholz, J. P., Schöner, G., & Hotchkiss, L. (2003). Effect of accuracy constraint on joint coordination during pointing movements. *Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale*, *149*(3), 276– 288.

Tucker, C. B., Anderson, R., & Kenny, I. C. (2011). A method to quantify movement variability of highly skilled golfers performing driver swings. *Portuguese Journal of Sport Sciences*, *11*(2), 411–413.

Van Beers, R. J., Haggard, P., & Wolpert, D. M. (2004). The role of execution noise in movement variability. *Journal of Neurophysiology*, *91*(2), 1050–1063.

Vereijken, B., Emmerik, R., Whiting, H., & Newell, K. (1992). Free(z)ing degrees of freedom in skill acquisition. *Journal of Motor Behavior*, *24*(1), 133–142.

Wagner, H., Pfusterschmied, J., Klous, M., von Duvillard, S. P., & Müller, E. (2012). Movement variability and skill level of various throwing techniques.

Human Movement Science, *31*(1), 78–90.

Wilson, C., Simpson, S. E., van Emmerik, R. E. A, & Hamill, J. (2008). Coordination variability and skill development in expert triple jumpers. *Sports Biomechanics*, *7*(1), 2–9.

Windolf, M., Götzen, N., & Morlock, M. (2008). Systematic accuracy and precision analysis of video motion capturing systems-exemplified on the Vicon-460 system. *Journal of Biomechanics*, *41*(12), 2776–2780.

Winter, D. (1990). *Biomechanics and Motor Control of Human Movement* (2nd ed.). New York: Wiley.

Winter, D. (2005). *Biomechanics and Motor Control of Human Movement* (3rd ed.). New York: Wiley.

Winter, D., Patla, A., & Prince, F. (1998). Stiffness Control of Balance in Quiet Standing Stiffness Control of Balance in Quiet Standing. *Journal of Neurophysiology*, *80*, 1211–1221.

Wulf, G., Mercer, J., McNevin, N., & Guadagnoli, M. A. (2004). Reciprocal influences of attentional focus on postural and suprapostural task performance. *Journal of Motor Behavior*, *36*(2), 189–199.

Yur'yev, A. A. (1985). *Competitive Shooting: Techniques and Training for Rifle, Pistol and Running Game Target Shooting.* Fairfax, Virginia: National Rifle Association.

Zatsiorsky, V. M., & Aktov, A V. (1990). Biomechanics of highly precise movements: the aiming process in air rifle shooting. *Journal of Biomechanics*, *23(1)*, 35–41.

Appendix 1 – Centre of Pressure Calculations

1.1 Equations used to calculate centre of pressure (CoP) location for each force Plate.

Axis conventions: x = mediolateral; y = anterior-posterior; z = vertical

$$\mathrm{CoP}xx = \frac{\mathrm{M}yy + (\mathrm{Z}oooooo * FFFF)}{FFFF} \square * (-1)$$

Equation 1.1. Calculation of mediolateral centre of pressure (CoPxx) location for each force plate

$$\mathrm{CoP}yy = \square \quad \frac{MMFF - (ZZoooooo * FFyy)}{FFFF} \square * (-1)$$

Equation 1.2. Calculation of anterior-posterior centre of pressure (CoPyy) location for each force plate

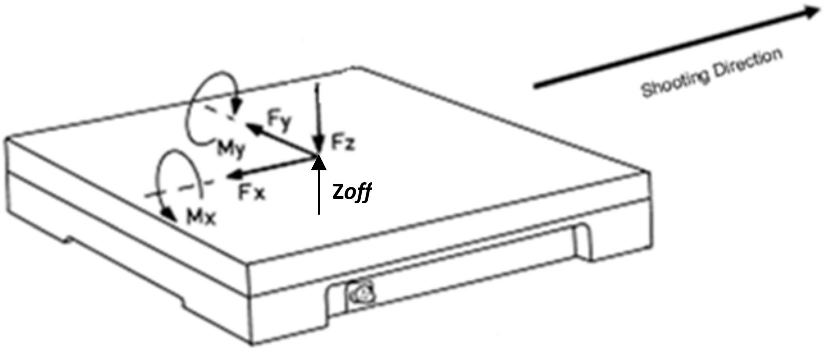
CoP(x): x coordinate of the centre of pressure, representing mediolateral movement.

CoP(y): y coordinate of the centre of pressure, representing anterior-posterior movement.

Z*off* : Vertical offset from the top of the plate to the origin of the force platform (origin set in the centre of each platform)

F*x,* F*y,* F*z* : Force along the X, Y and Z axis

1.2 Axis Convention used for each AMTI Force Platform.



1.3 Equations used to Calculate Whole Body Mediolateral Centre of Pressure (CoPxx) Location using the Values Obtained for each Force Plate in Appendix 1.1.

a: Percentage of vertical force () on force platform 1:

$$\boxed{?}\,\frac{\mathrm{Fz1}}{FFFF1 + FFFF2}\,\boxed{?}$$

b: Distance between CoPxx location on each force plate:

$$xx_1 - xx_2$$

c: Displacement of whole body CoP from CoPxx_1:

$$(1 - aa) * bb$$

d: Overall body CoPxx location in relation to origin of force platform 1:

$$cc + {}_1$$

$FF1$ = vertical force on force platform 1
$FF2$ = vertical force on force platform 2
xx_1= xx coordinates of CoP on force platform 1
xx_2= xx coordinates of CoP on force platform 2

1.4 Equations used to Calculate Whole Body Anterior-Posterior Centre of Pressure (CoPyy) Location using the Values Obtained for each Force Plate in Appendix 1.1.

a: Percentage of vertical force () on force platform 1:

$$\boxed{?}\ \frac{\text{Fz1}}{FFFF1 + FFFF2}\ \boxed{?}$$

b: Distance between CoPyy location on each force plate:

$$yy_2 - yy_1$$

c: Displacement of whole body CoP from CoPyy_1:

d: Overall body CoPyy location in relation to origin of force platform 1:

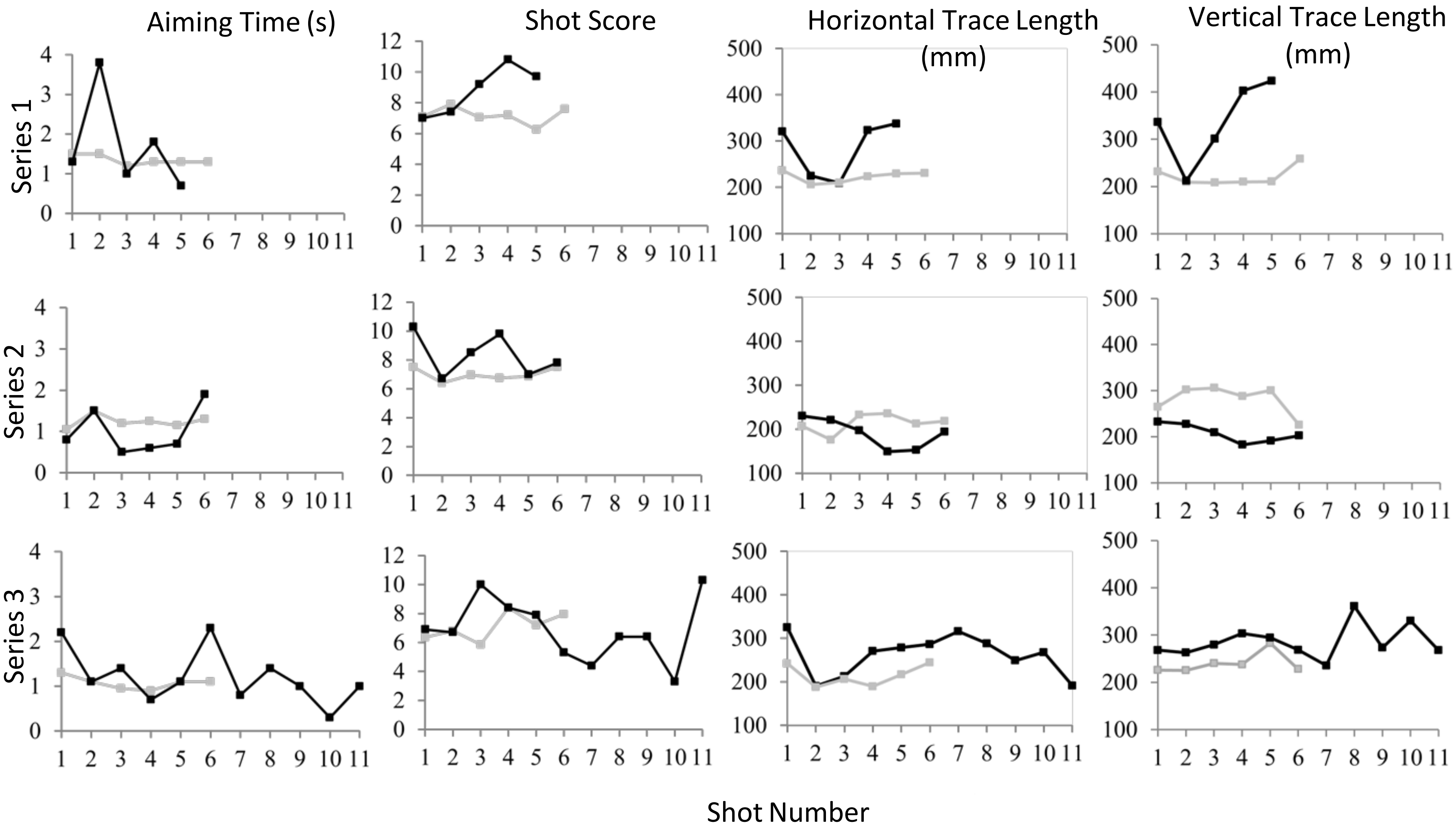
$$cc + {}_1$$

FF1 = vertical force on force platform 1

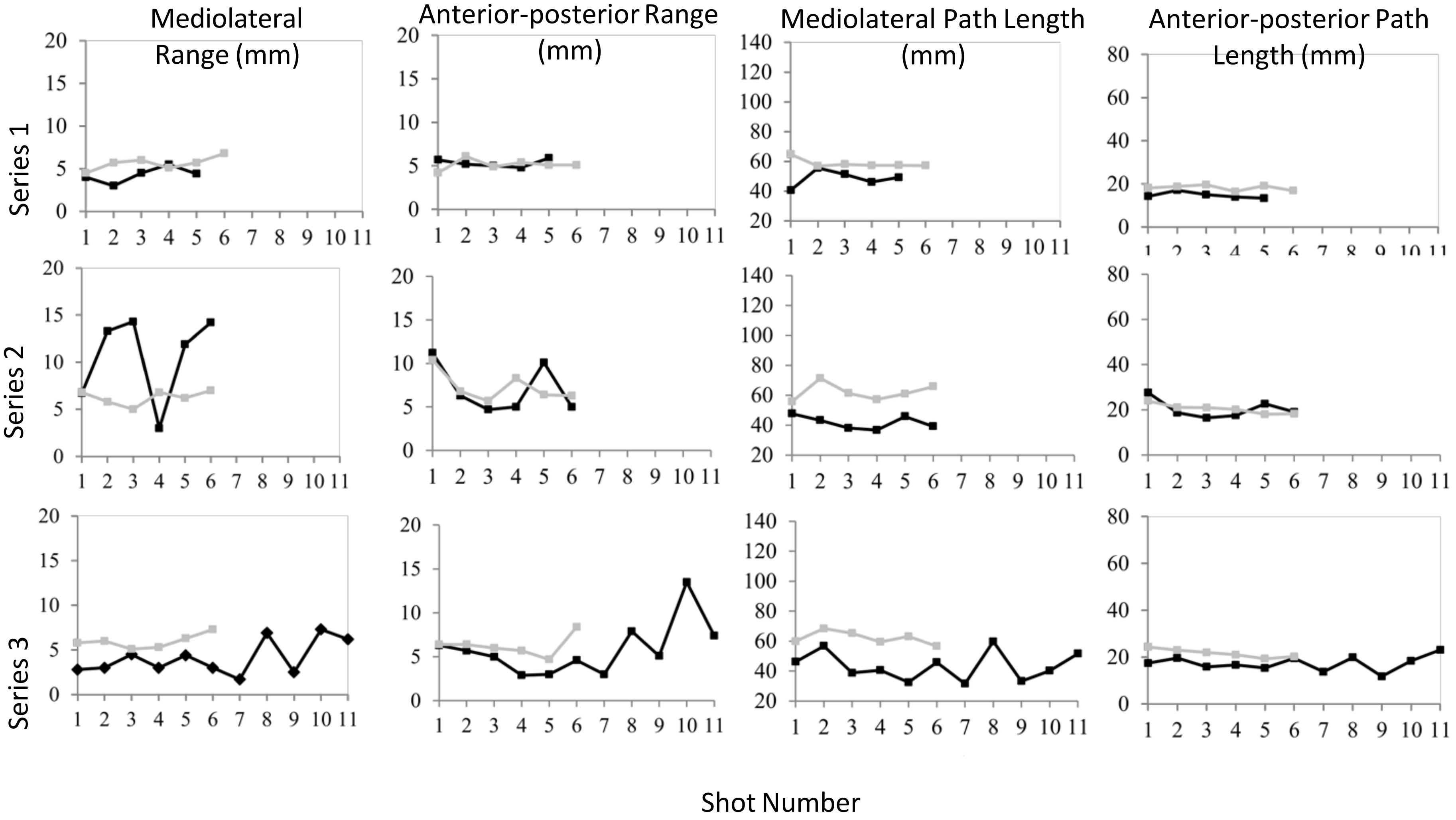
FF2 = vertical force on force platform 2

yy_1= yy coordinates of CoP on force platform 1

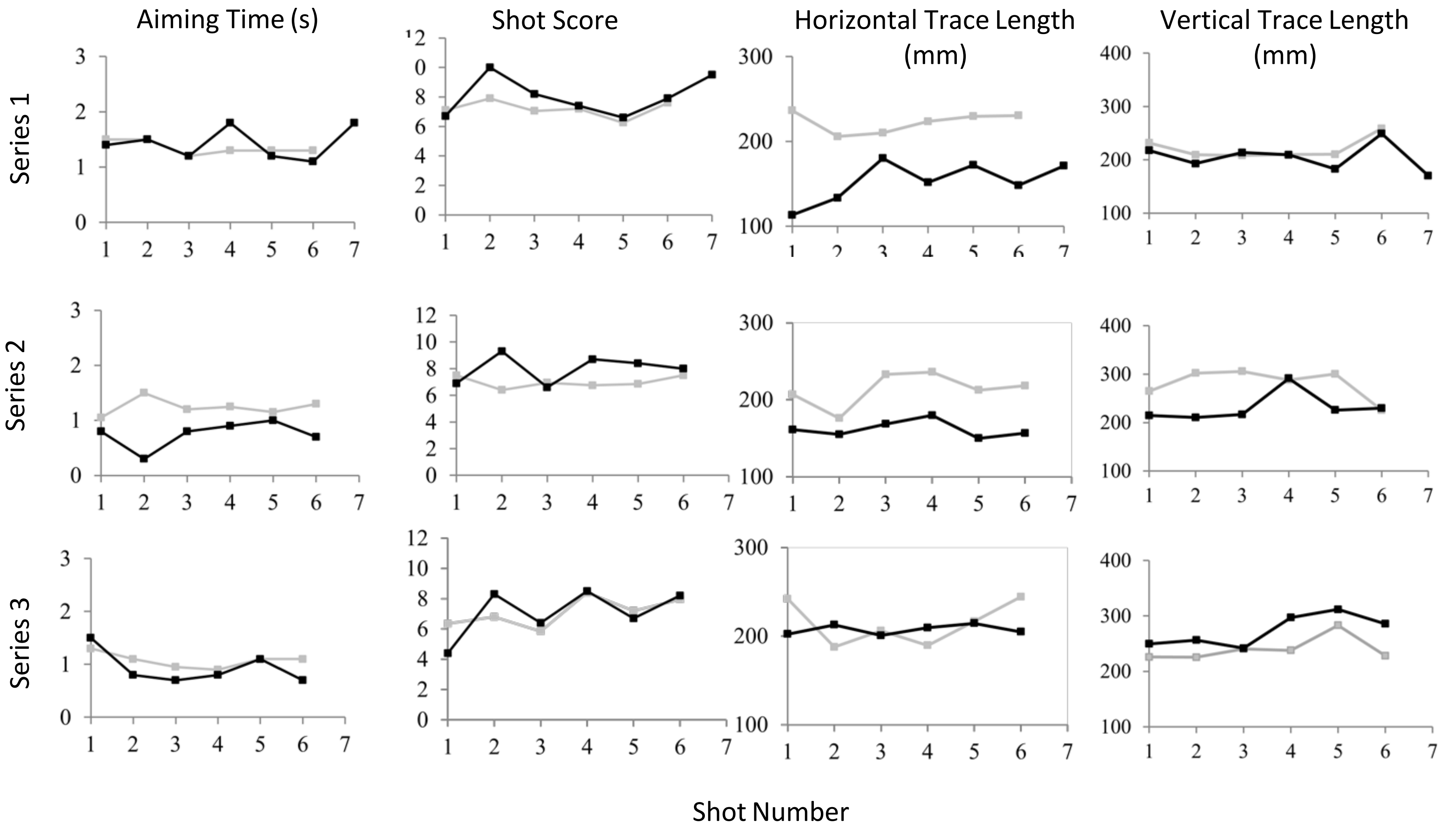
yy_2= yy coordinates of CoP on force platform 2



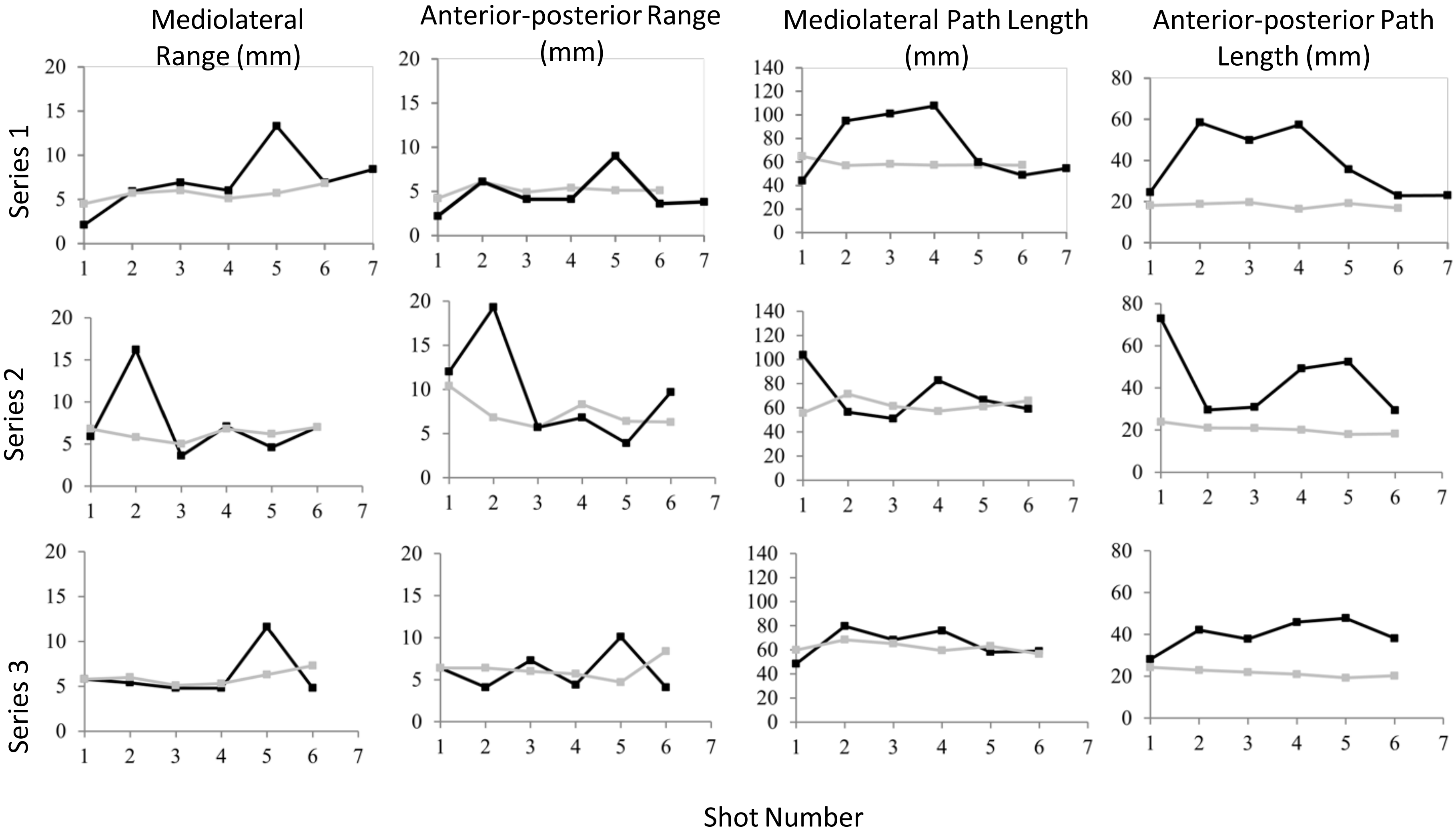
Appendix 2.1a. Aiming time, score and pistol movement produced by participant 1 for each shot in every series. Data (shown in black) are presented in relation to the group median (shown in grey).



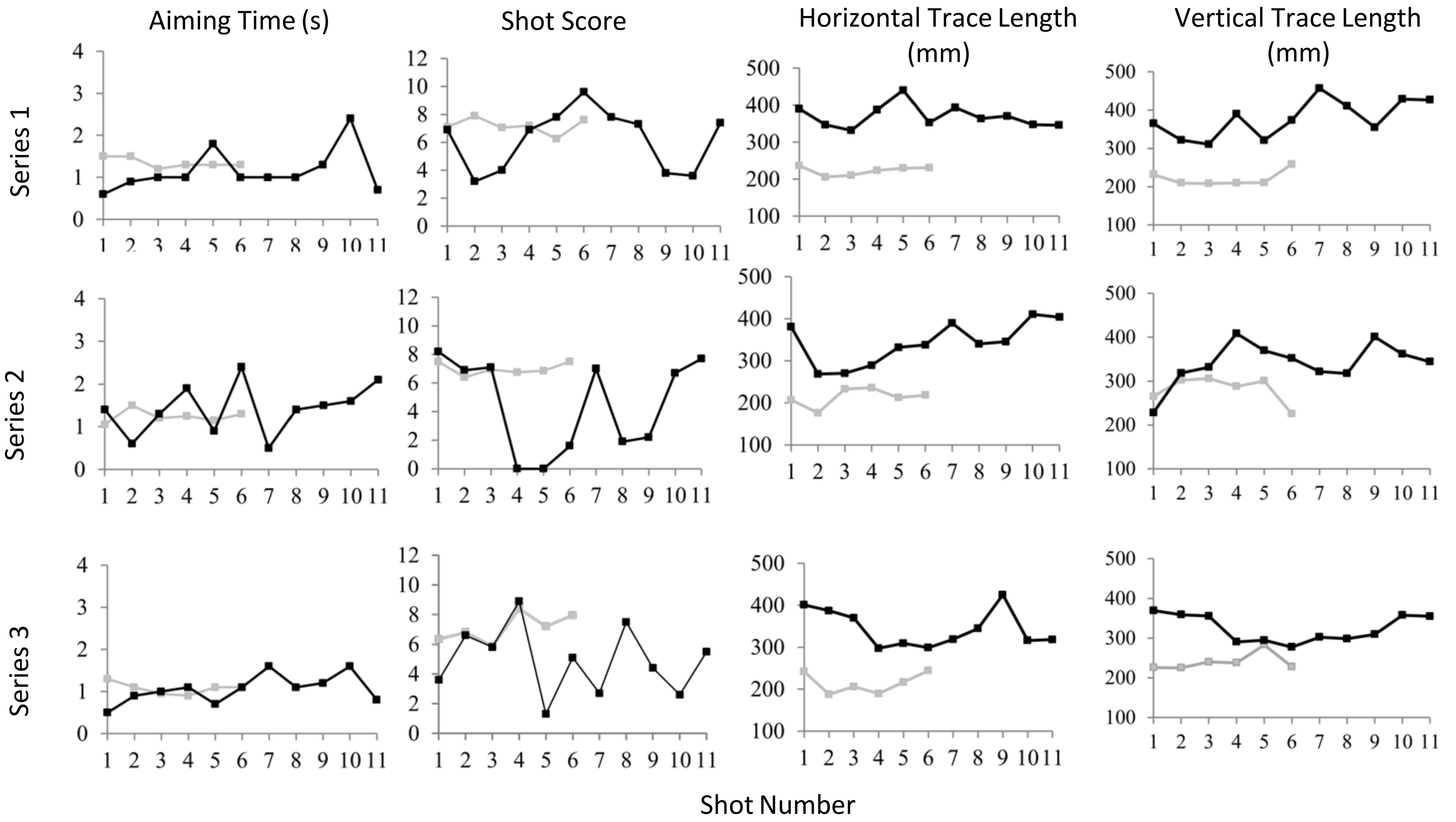
Appendix 2.1b. Centre of pressure movement produced by participant 1 for each shot in every series. Data (shown in black) are presented in relation to the group median (shown in grey).



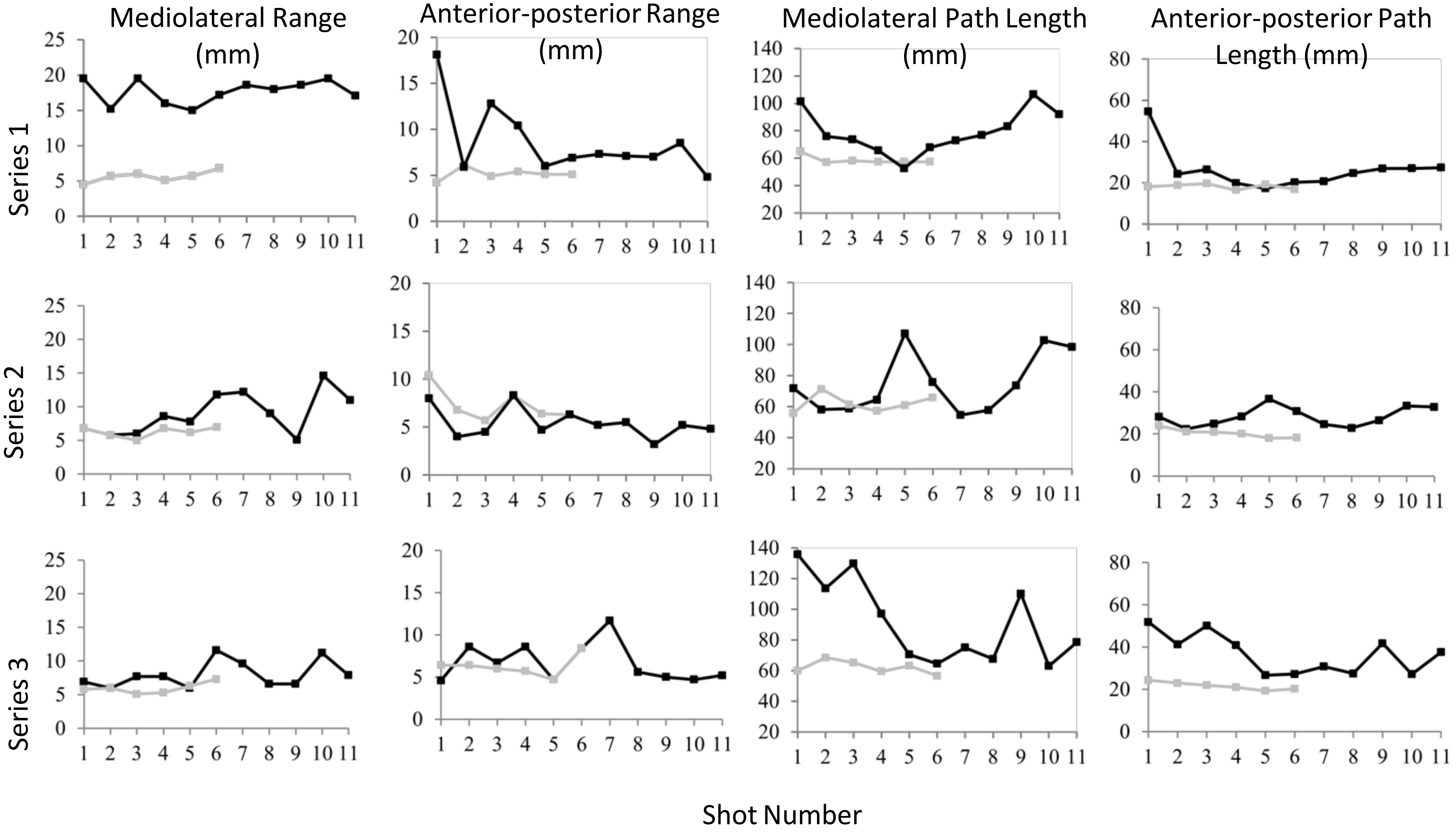
Appendix 2.2a. Aiming time, score and pistol movement produced by participant 5 for each shot in every series. Data (shown in black) are presented in relation to the group median (shown in grey).



Appendix 2.2b. Centre of pressure movement produced by participant 5 for each shot in every series. Data (shown in black) are presented in relation to the group median (shown in grey).



Appendix 2.3a. Aiming time, score and pistol movement produced by participant 14 for each shot in every series. Data (shown in black) are presented in relation to the group median (shown in g

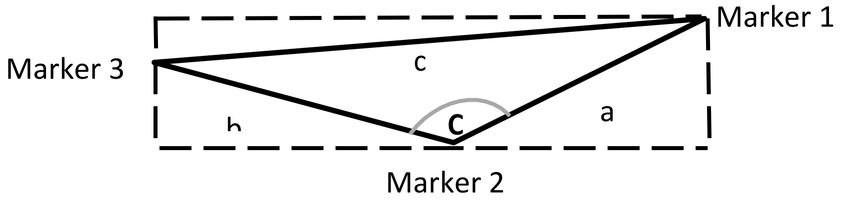


Appendix 2.3b. Centre of pressure movement produced by participant 14 for each shot in every series. Data (shown in black) are presented in relation to the group median (shown in grey).

Appendix 3 – Angle Calculations and Individual Variability Graphs

3.1 Each torso, upper limb and pistol angle was calculated using a combination of trigonometric equations as follows:

Movements in a vertical plane, perpendicular to the target:



a = $\sqrt{(MMaaMMMMMMMM\ 1zz - MMaaMMMMMMMM\ 2zz)^2 + (MMaaMMMMMMMM\ 1xx - MMaaMMMMMMMM\ 2xx)^2}$

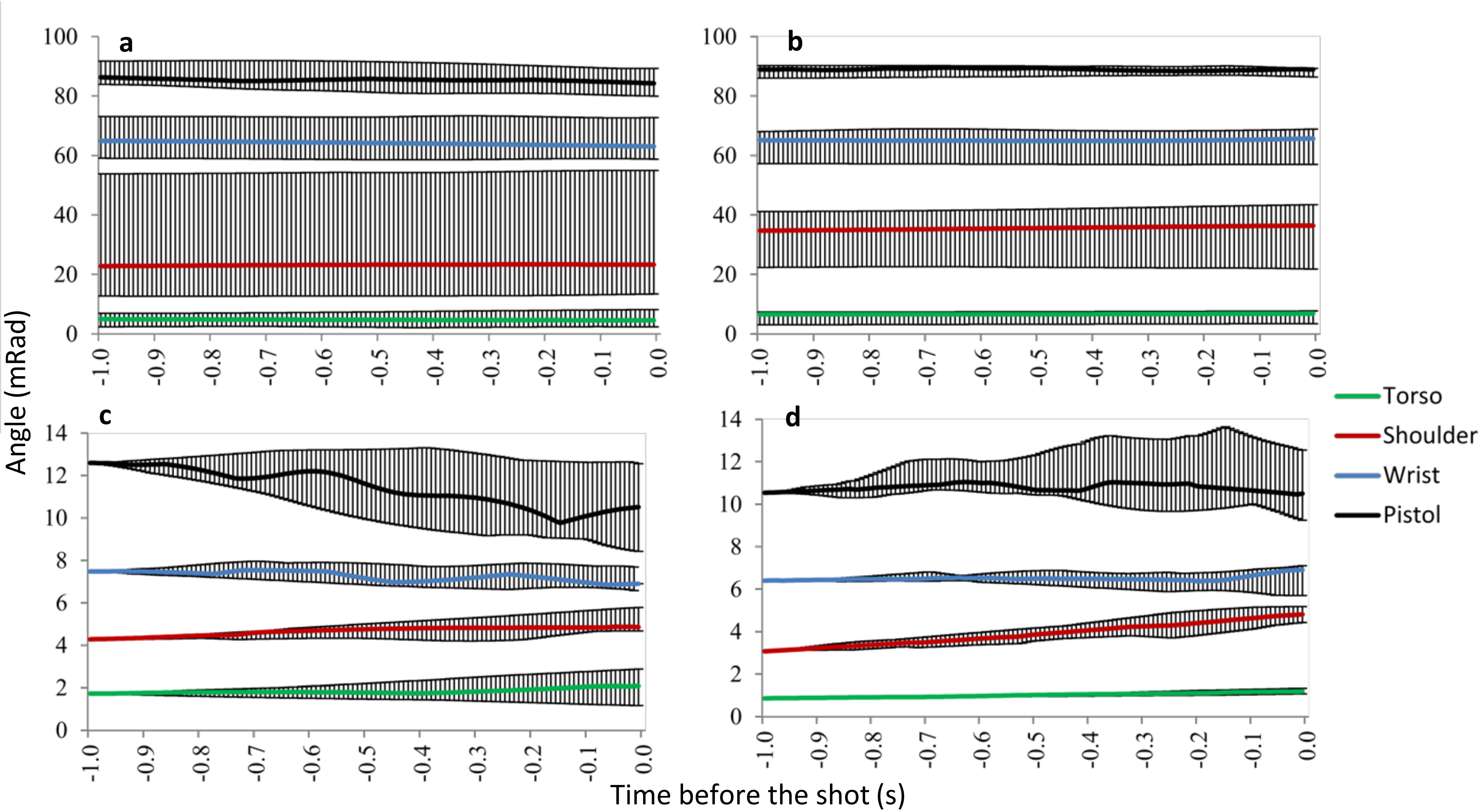
b = $\sqrt{(MMaaMMMMMMMM\ 2zz - MMaaMMMMMMMM\ 3zz)^2 + (MMaaMMMMMMMM\ 2xx - MMaaMMMMMMMM\ 3xx)^2}$

c = $\sqrt{(MMaaMMMMMMMM\ 1zz - MMaaMMMMMMMM\ 3zz)^2 + (MMaaMMMMMMMM\ 1xx - MMaaMMMMMMMM\ 3xx)^2}$

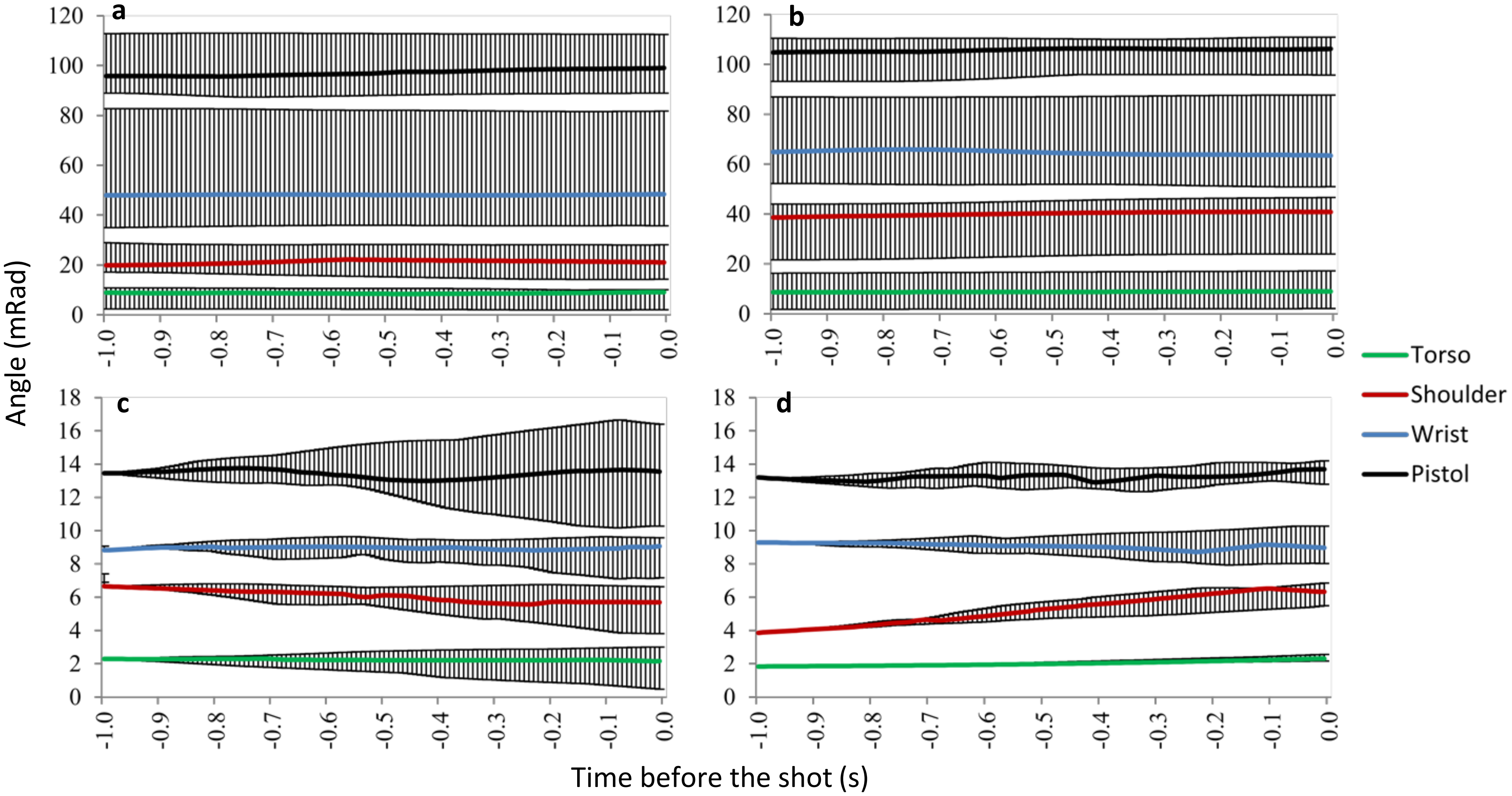
Angle C = ARCCOS $\frac{aa^2+bb^2-cc^2}{2aabb}$

- If markers 1, 2 and 3 represent the C7, shoulder and elbow markers respectively, angle C in this example is referred to as shoulder angle, and movement described as either abduction or adduction. Mediolateral torso sway followed the same equations, with the x coordinates substituted for y coordinates.

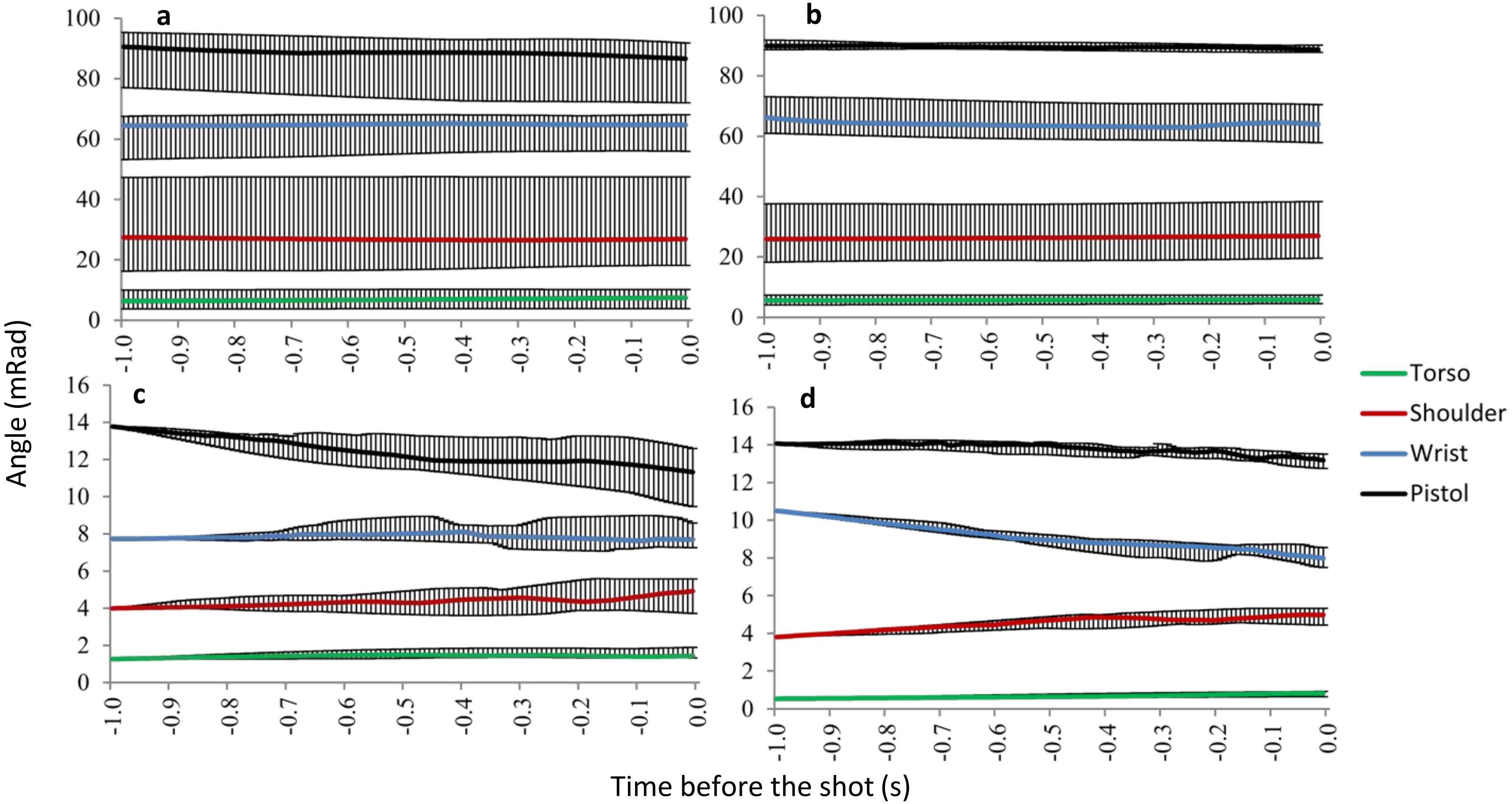
- Movements in a horizontal plane, parallel to the target, were calculated as detailed, but with x and y coordinates replacing the x and z coordinates.



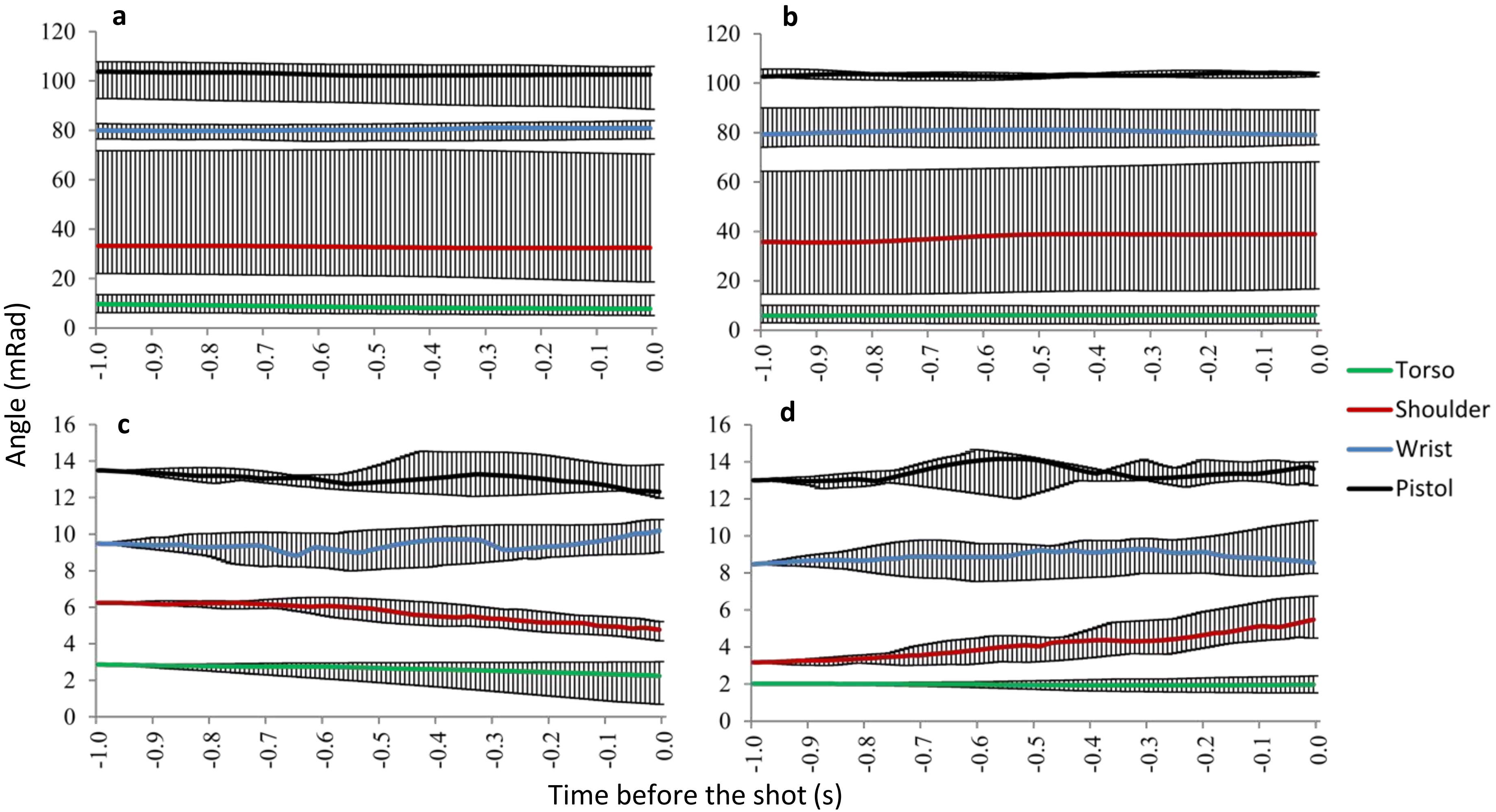
Appendix 3.2. (a) Positional and (c) movement variability of anterior-posterior torso sway and horizontal upper limb movements for participant 1. (b) Positional and (d) movement variability of mediolateral torso and vertical upper limb movements. Coloured lines represent the median angle over twenty shots and black vertical lines represent standard deviation.



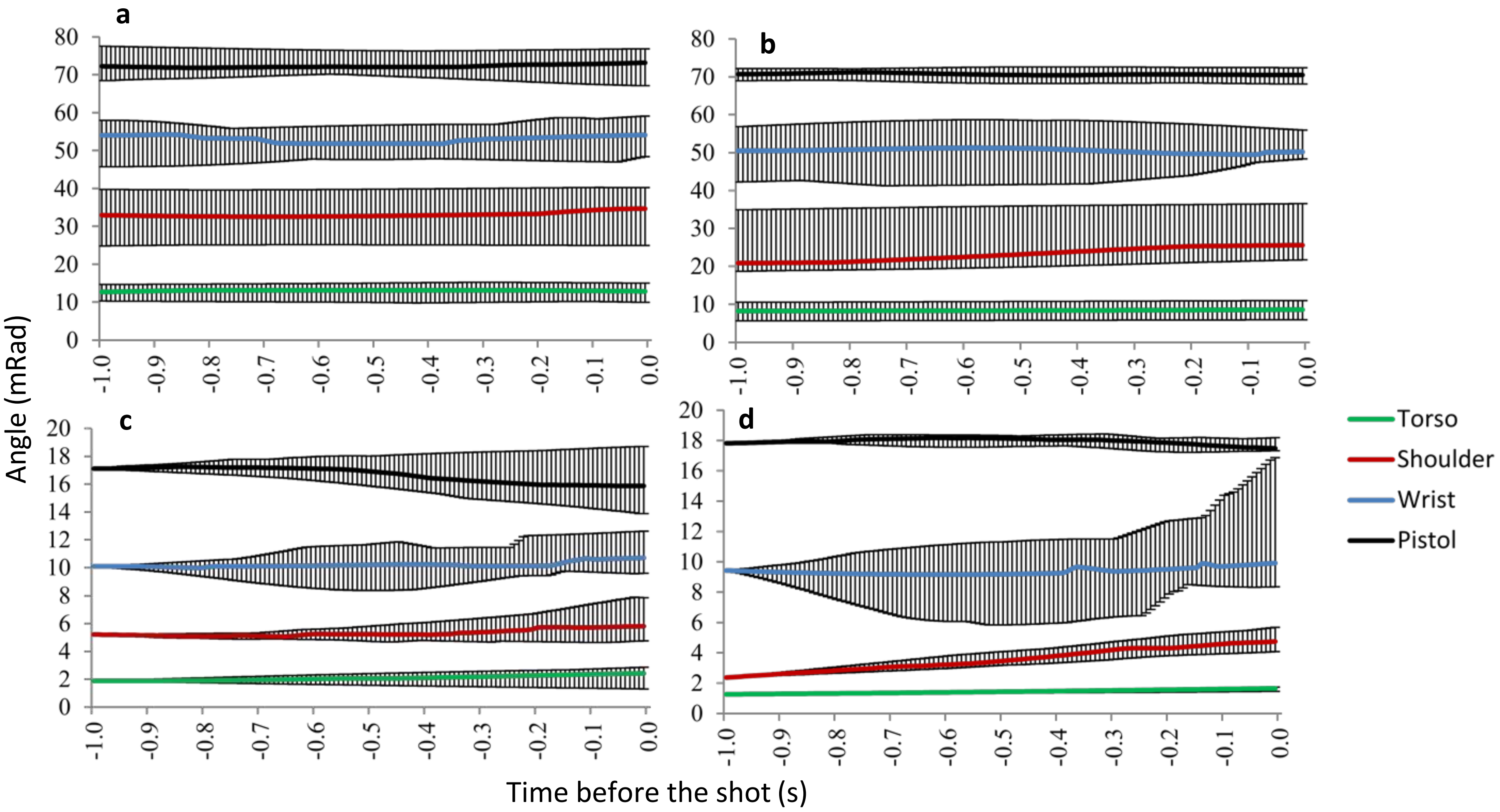
Appendix 3.3. (a) Positional and (c) movement variability of anterior-posterior torso sway and horizontal upper limb movements for participant 2. (b) Positional and (d) movement variability of mediolateral torso and vertical upper limb movements. Coloured lines represent the median angle over twenty shots and black vertical lines represent standard deviation.



Appendix 3.4. (a) Positional and (c) movement variability of anterior-posterior torso sway and horizontal upper limb movements for participant 3. (b) Positional and (d) movement variability of mediolateral torso and vertical upper limb movements. Coloured lines represent the median angle over twenty shots and black vertical lines represent standard deviation.



Appendix 3.5. (a) Positional and (c) movement variability of anterior-posterior torso sway and horizontal upper limb movements for participant 4. (b) Positional and (d) movement variability of mediolateral torso and vertical upper limb movements. Coloured lines represent the median angle over twenty shots and black vertical lines represent standard deviation.



Appendix 3.6. (a) Positional and (c) movement variability of anterior-posterior torso sway and horizontal upper limb movements for participant 5. (b) Positional and (d) movement variability of mediolateral torso and vertical upper limb movements. Coloured lines represent the median angle over twenty shots and black vertical lines represent standard deviation.

Appendix 3.7. Scores achieved by participants in official competitions close to the time of testing.

	Testing session (1st 10 / 2nd 10)	CSFC (2013)	SAPOC (2013)	SAPOC (2014)	CG (2014)	EC (2014)
1	96 / 92	97 / 92 / 93 / 96	-		94 / 92 / 92 / 87	94 / 94 / 90 / 91
2	87 / 92	-	-	86 / 93 / 95 / 98	91 / 94 / 92 / 90	-
3	92 / 92	-	90 / 92 / 94 / 94	89 / 90 / 93 / 93	75 / 88 / 92 / 96	90 / 92 / 91 / 88
4	93 / 96	92 / 92 / 89 / 93	90 / 90 / 85 / 87	88 / 88 / 88 / 93	-	-
5	92 / 85	90 / 93 / 93 / 91	-	92 / 91 / 89 / 93	-	-

CSFC – Commonwealth Shooting Federation Championships
SAPOC – Scottish Air Pistol Open Championships
CG – Commonwealth Games
EC – European Championships

Appendix 4 – Shot Score for Individual Participants and Case Study Graphs

4.1 Scores and shot distribution achieved in each stance position for participant 1.

	Stance Position	Score	Shot Distribution (mm)	
			Horizontal	Vertical
1	Narrow, Foot in Front	102.7	19	13
2	Narrow, Current	100.1	20	29
3	Current, Current	99.5	24	26
4	Wide, Foot in Front	98.7*	30	21
5	Narrow, Inline	97.0*	30	20
6	Wide, Current	96.3*♦	25	35
7	Current, Inline	96.0*♦	10	39
8	Wide, Inline	93.9*♦	33	29
9	Current, Foot in Front	93.4	30	27

* significantly different to Narrow Foot in Front stance position (*p*<.007)
♦ significantly different to Narrow Current stance position (*p*<.007)

4.2 Scores and shot distribution achieved in each stance position for participant 2.

	Stance Position	Score	Shot Distribution (mm)	
			Horizontal	Vertical
1	Wide, Foot in Front	102.2	16	21
2	Current, Foot in Front	101.5	19	26
3	Narrow, Inline	100.1	21	30
4	Narrow, Current	99.8*	29	21
5	Wide, Current	98.3	24	18
6	Narrow, Foot in Front	97.6*	34	29
7	Wide, Inline	96.6*	31	34
8	Current, Inline	95.5*	22	30
9	Current, Current	88.7*♦	45	29

* significantly different to Wide Foot in Front stance position (*p*<.007)
♦ significantly different to Current Foot in Front stance position (*p*<.007)

4.3 Scores and shot distribution achieved in each stance position for participant 3.

	Stance Position	Score	Shot Distribution (mm)	
			Horizontal	Vertical
1	Wide, Current	102.8	16	19
2	Narrow, Foot in Front	101.9	21	18
3	Current, Foot in Front	98.9*♦	21	26
4	Wide, Foot in Front	97.9*♦	30	21
5	Narrow, Inline	97.0*♦	22	25
6	Narrow, Current	96.8*♦	26	30
7	Wide, Inline	96.7*♦	32	28
8	Current, Current	96.1*♦	31	26
9	Current, Inline	95.0*♦†	30	30

* significantly different to Wide Current stance position (*p*<.007)

♦ significantly different to Narrow Foot in Front stance position (*p*<.007)

† significantly different to Current Foot in Front stance position (*p*<.007)

4.4 Scores and shot distribution achieved in each stance position for participant 4.

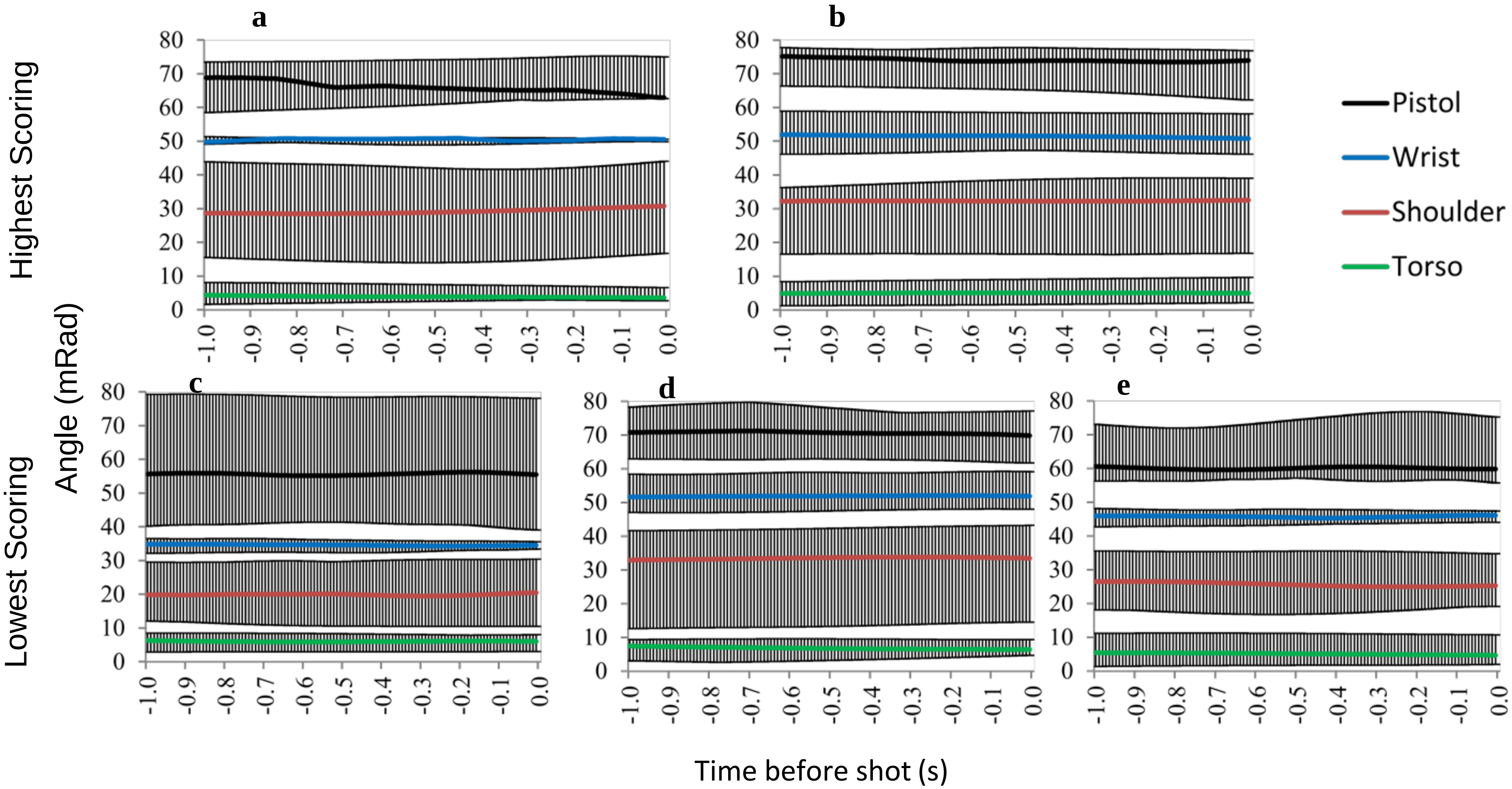
	Stance Position	Score	Shot Distribution (mm)	
			Horizontal	Vertical
1	Current, Foot in Front	100.5	21	18
2	Narrow, Foot in Front	98.9	30	21
3	Wide, Foot in Front	97.2	35	26
4	Current, Inline	96.6	30	30
	Narrow, Current	96.6*	31	26
6	Current, Current	96.5	21	26
	Wide, Inline	96.5*	22	25
8	Narrow, Inline	96.1*	26	30
9	Wide, Current	95.0*	32	28

* significantly different to Current Foot in Front stance position (*p*<.007)

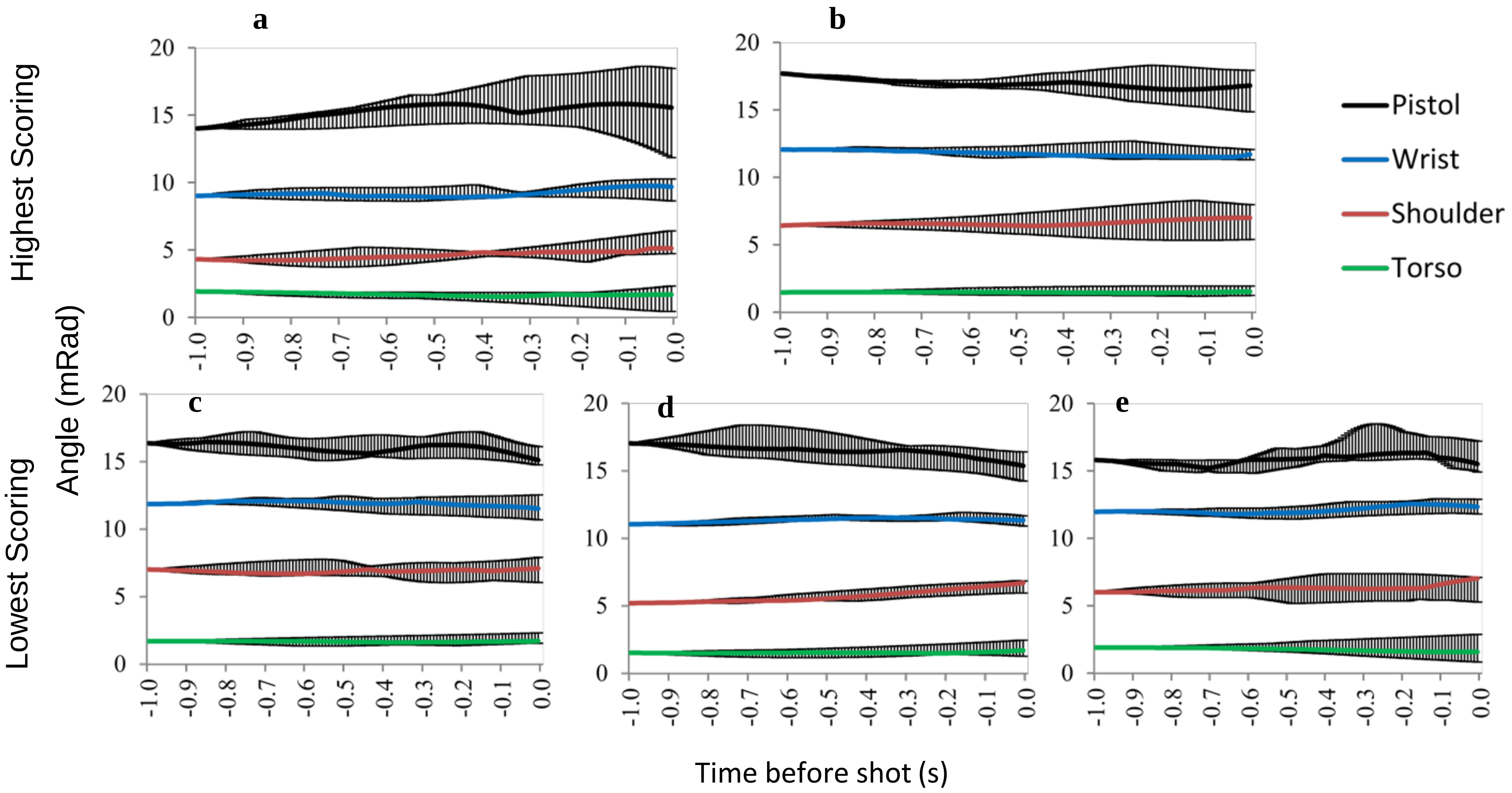
4.5 Scores and shot distribution achieved in each stance position for participant 5.

	Stance Position	Score	Shot Distribution (mm)	
			Horizontal	Vertical
1	Narrow, Inline	99.4	17	29
2	Current, Current	97.8	34	18
3	Wide, Inline	97.1*	25	26
4	Wide, Current	96.8*	29	22
5	Current, Inline	96.3*	33	33
6	Current, Foot in Front	94.1*	30	30
7	Narrow, Current	92.9*	22	39
8	Narrow, Foot in Front	91.9*	36	39
9	Wide, Foot in Front	88.6*	46	30

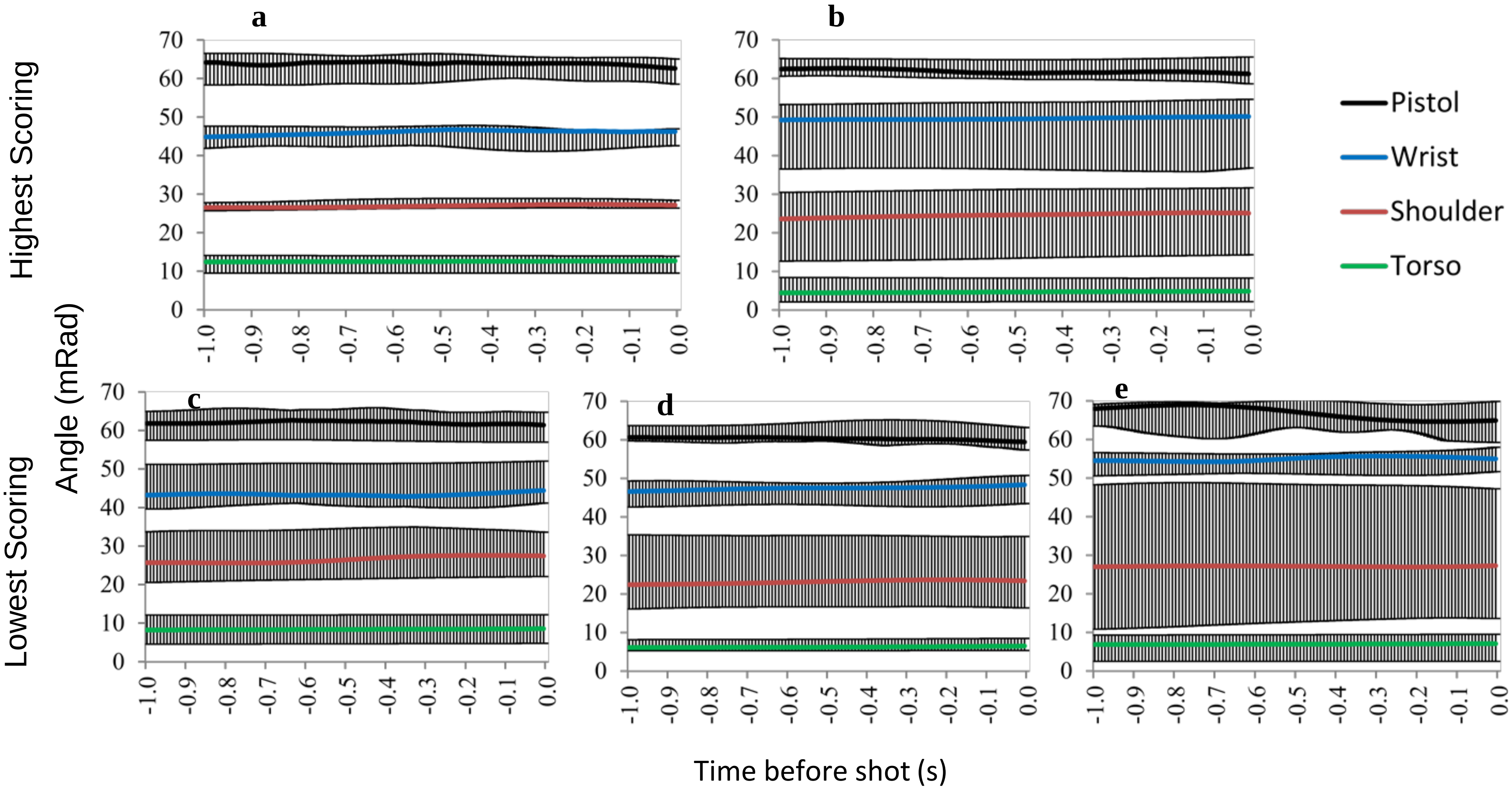
* significantly different to Narrow Inline stance position (*p*<.007)



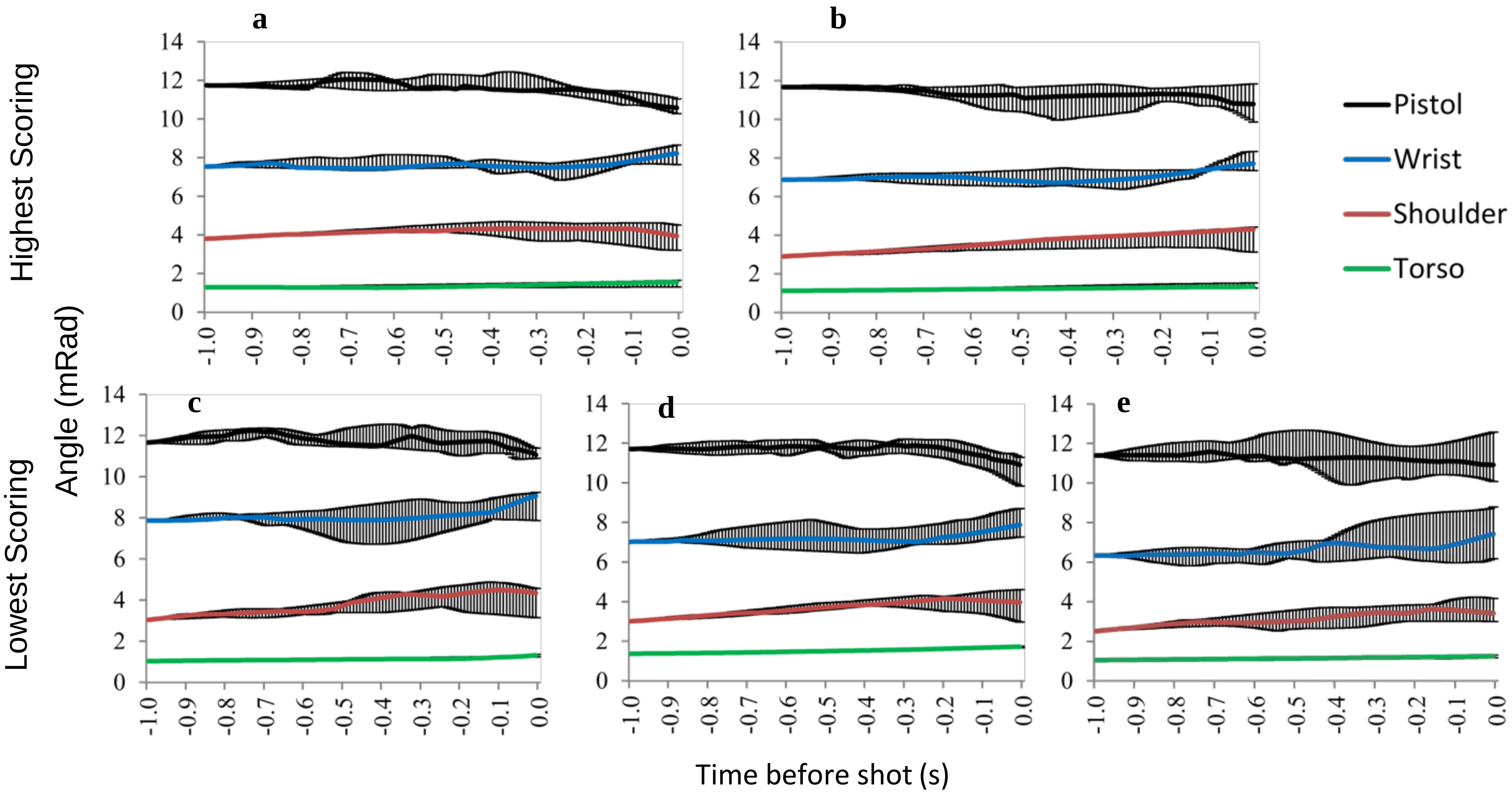
Appendix 4.6. Positional variability of anterior-posterior sway and horizontal upper limb movements over the final second for the highest scoring (a – Narrow Foot in Front; b – Narrow Current) and lowest scoring (c – Current Inline; d – Wide Current; e – Wide Inline) stance positions for participant 1. Coloured lines represent the median angle over ten shots and vertical black lines represent standard deviation.



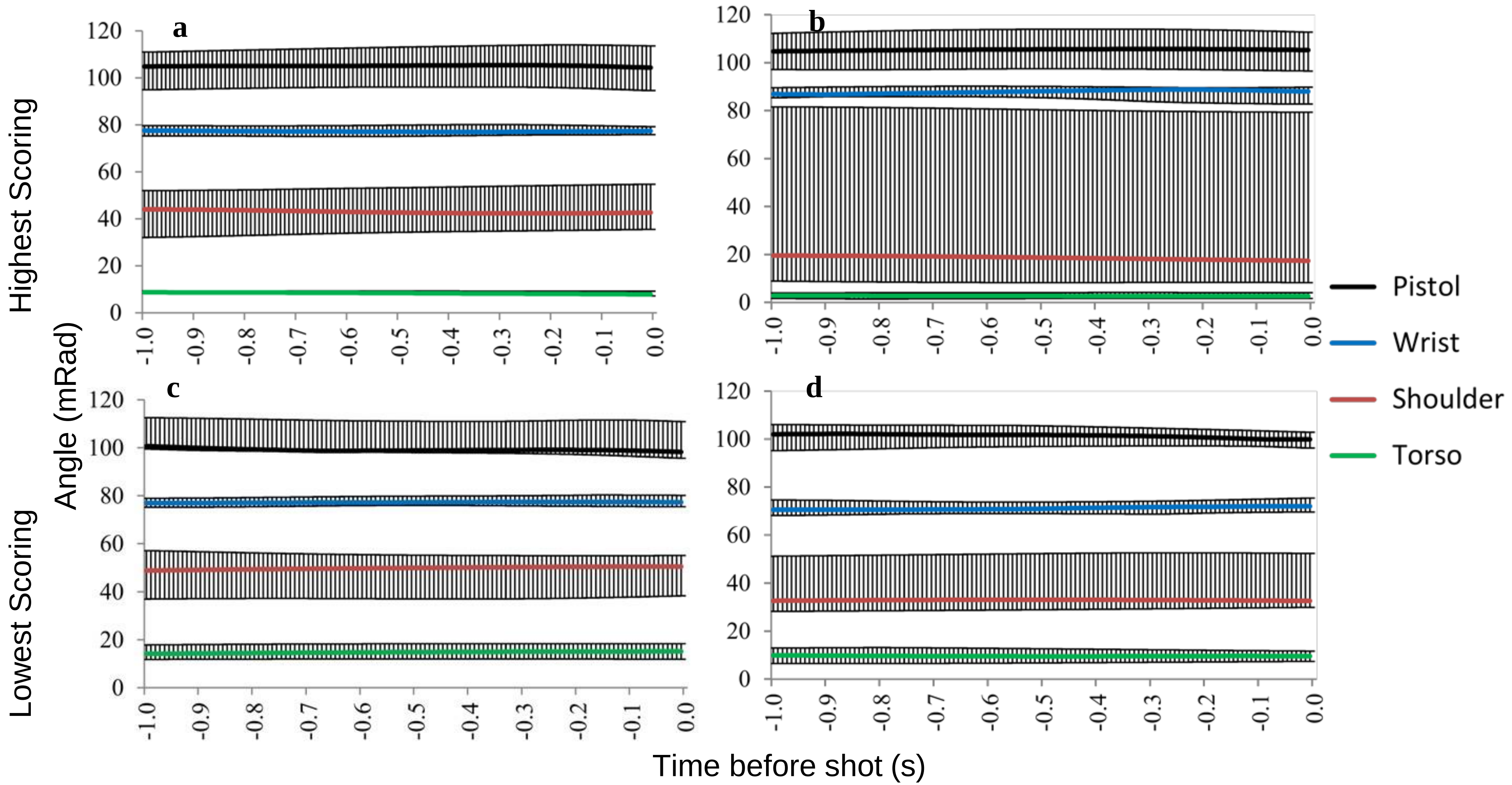
Appendix 4.7. Movement variability of anterior-posterior sway and horizontal upper limb movements over the final second for the highest scoring (a – Narrow Foot in Front; b – Narrow Current) and lowest scoring (c – Current Inline; d – Wide Current; e – Wide Inline) stance positions for participant 1. Coloured lines represent the median angle over ten shots and vertical black lines represent standard deviation.



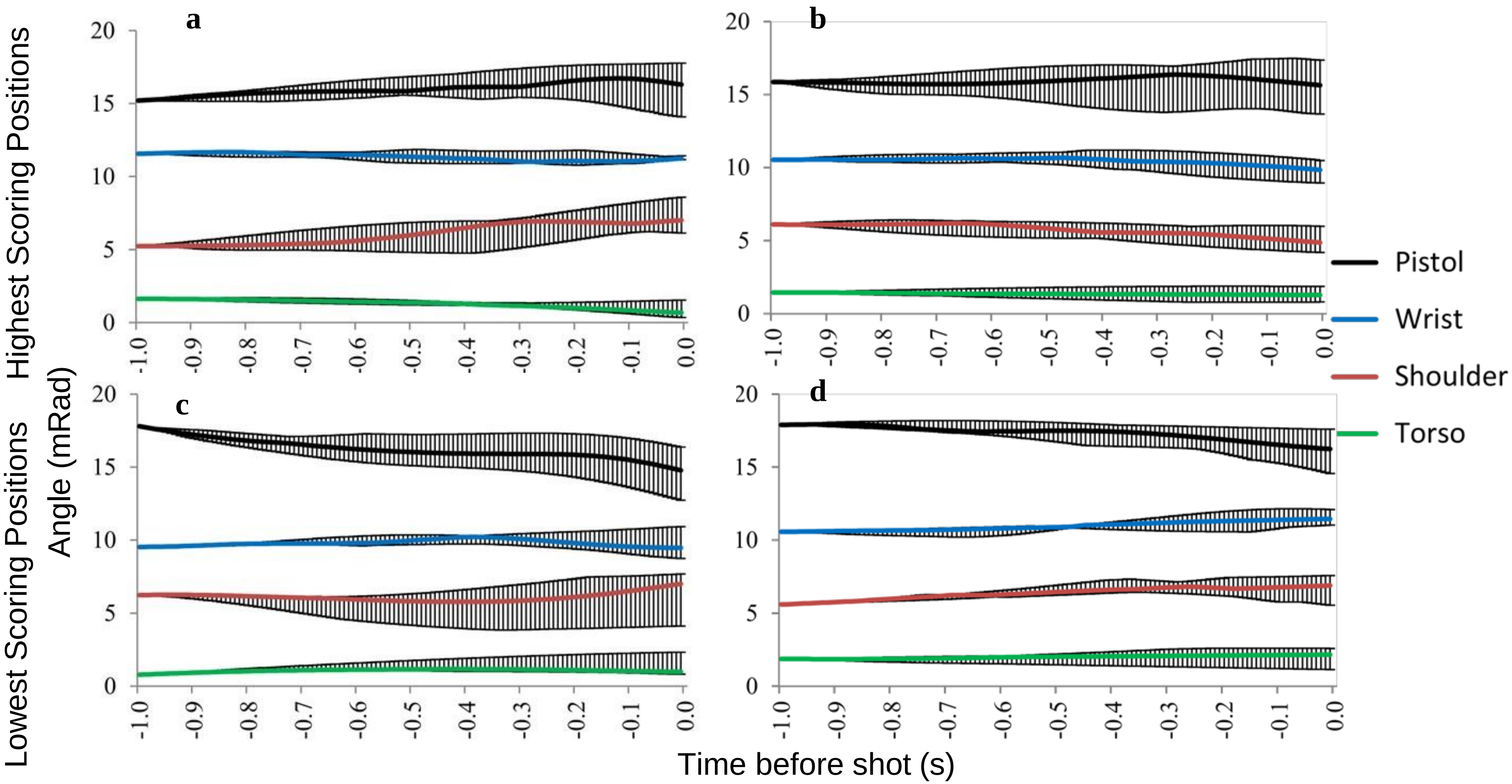
Appendix 4.8. Positional variability of mediolateral sway and vertical upper limb movements over the final second for the highest scoring (a – Narrow Foot in Front; b – Narrow Current) and lowest scoring (c – Current Inline; d – Wide Current; e – Wide Inline) stance positions for participant 1. Coloured lines represent the median angle over ten shots and vertical black lines represent standard deviation.



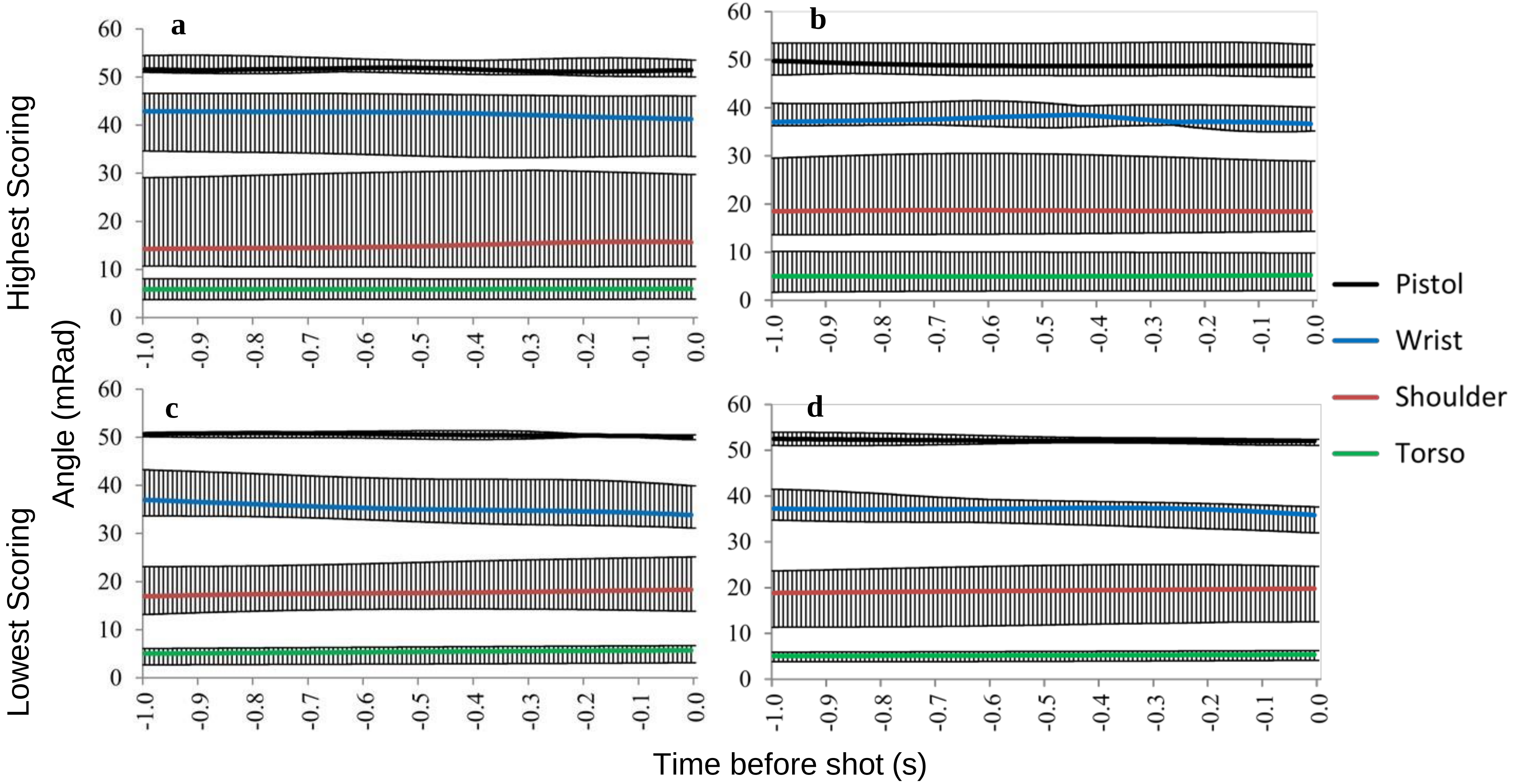
Appendix 4.9. Movement variability of mediolateral sway and vertical upper limb movements over the final second for the highest scoring (a – Narrow Foot in Front; b – Narrow Current) and lowest scoring (c – Current Inline; d – Wide Current; e – Wide Inline) stance positions for participant 1. Coloured lines represent the median angle over ten shots and vertical black lines represent standard deviation.



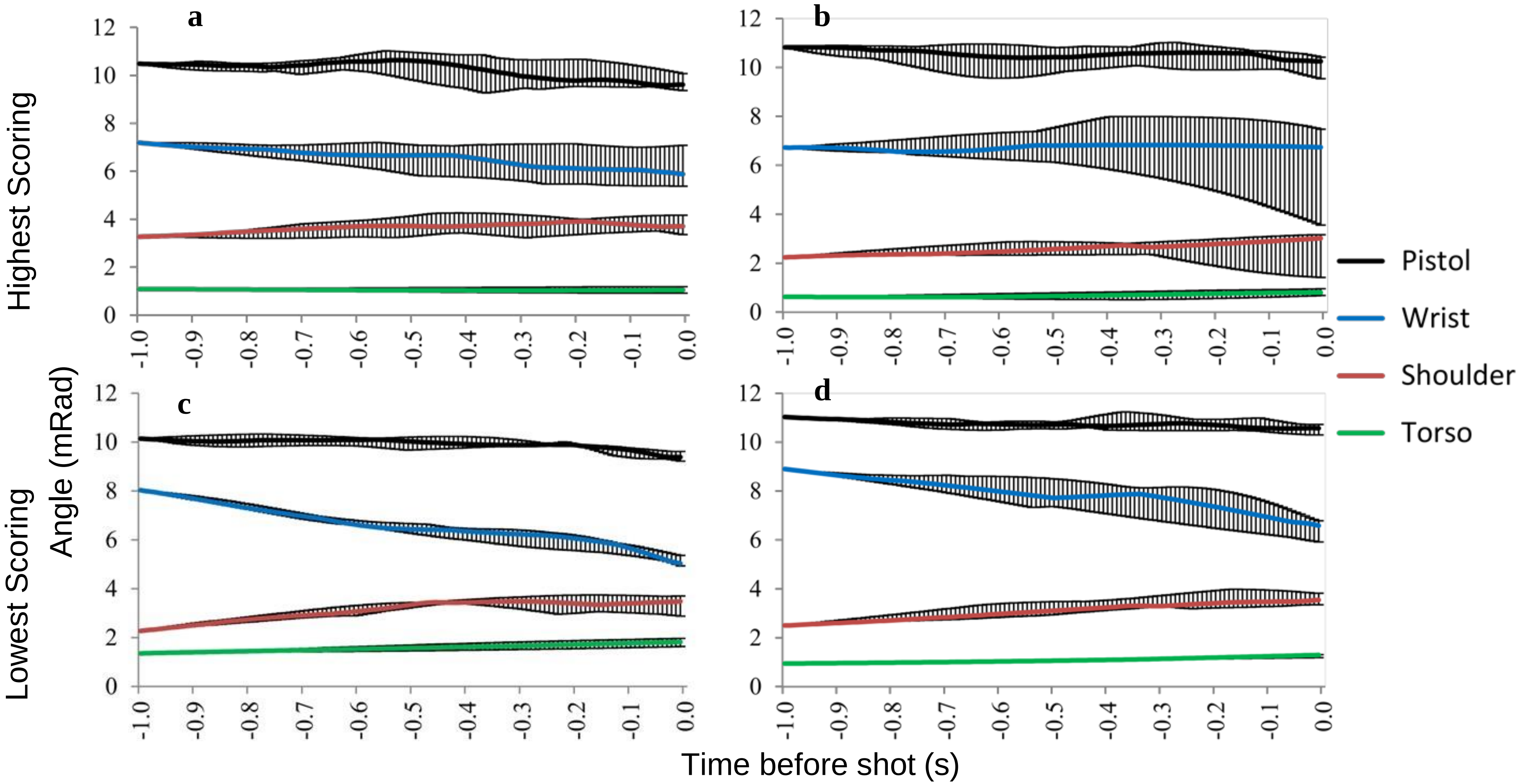
Appendix 4.10 Positional variability of anterior-posterior sway and horizontal upper limb movements over the final second for the highest scoring (a – Wide Current; b – Narrow Foot in Front) and lowest scoring (c – Current Current; d – Current Inline) stance positions for participant 3. Coloured lines represent the median angle over ten shots and vertical black lines represent standard deviation.



Appendix 4.11. Movement variability of anterior-posterior sway and horizontal upper limb movements over the final second for the highest scoring (a – Wide Current; b – Narrow Foot in Front) and lowest scoring (c – Current Current; d – Current Inline) stance positions for participant 3. Coloured lines represent the median angle over ten shots and vertical black lines represent standard deviation.



Appendix 4.12. Positional variability of mediolateral sway and vertical upper limb movements over the final second for the highest scoring (a – Wide Current; b – Narrow Foot in Front) and lowest scoring (c – Current Current; d – Current Inline) stance positions for participant 3. Coloured lines represent the median angle over ten shots and vertical black lines represent standard deviation.



Appendix 4.13. Movement variability of mediolateral sway and vertical upper limb movements over the final second for the highest scoring (a – Wide Current; b – Narrow Foot in Front) and lowest scoring (c – Current Current; d – Current Inline) stance positions for participant 3. Coloured lines represent the median angle over ten shots and vertical black lines represent standard deviation.

Journal of Sports Sciences, 2013
Vol. 31, No. 12, 1294–1301, http://dx.doi.org/10.1080/02640414.2013.777762

Biomechanical analysis of the change in pistol shooting format in modern pentathlon

CLARE ELIZABETH DADSWELL, CARL PAYTON, PAUL HOLMES, &
ADRIAN BURDEN

Manchester Metropolitan University, Exercise and Sport Science, Crewe, United Kingdom

(*Accepted 15 February 2013*)

Abstract

Despite the importance of the Combined Event to the modern pentathlon competition, little is known about performance in the event. This study aimed to (i) identify the key variables affecting Combined Event shooting performance, and the extent to which these corresponded with those identified for precision shooting and (ii) investigate the impact of changing shooting format, and whether more successful precision shooters were also more successful in the Combined Event. Seven modern pentathletes and three pistol shooters completed precision and Combined Event trials. An opto-electronic shooting system recorded score and pistol movements, whilst force platforms recorded centre of pressure movements 1 s prior to every shot. Intra-individual analysis revealed that the extent of associations between variables was participant-specific, highlighting the need for individual analysis of performance. No participants displayed matching associations between variables for precision and Combined Event shooting, emphasising the difference between performances in the two events. Both groups experienced significantly reduced scores, and increased pistol and body movements for Combined Event shooting ($P < 0.05$). Despite the pistol shooters' greater precision shooting ability, no significant differences were evident between the groups' Combined Event performances ($P > 0.05$). This implies that experience in one event does not guarantee success in the other, indicating the importance of event specific training.

Keywords: *combined event, pistol movement, body sway*

Introduction

Modern pentathlon has traditionally consisted of five separate disciplines: pistol shooting, fencing, swimming, horse riding, and running. A rule change in 2009, however, resulted in the formation of a new discipline: the Combined Event, in which two existing events, precision pistol shooting and the 3 km run, were merged. Athletes now complete the following tasks within the Combined Event:

20 m Run → Shooting Series 1 → 1 km Run → Shooting Series 2 → 1 km Run → Shooting Series 3 → 1km Run

In each shooting series, athletes attempt to hit five targets as quickly as possible within a maximum time limit of 70 s. Targets are 5.95 cm in diameter; equivalent to the 7 ring of a precision target. The number of shots taken within each series is unlimited, and athletes who hit all five targets before the time limit is reached can immediately begin the next running phase. In contrast, under previous precision rules, athletes aimed at a target with a 10 ring of only 1.15 cm, and had 40 s available per shot. The Combined Event forms the final stage of the competition, with the overall competition winner being the first to complete the final running stage.

Following the rule change, the focus of pistol shooting has changed from achieving high scores in a relatively time-unlimited environment, to an event where athletes attempt to complete each series as quickly as possible whilst maintaining sufficient accuracy. Le Meur, Hausswirth, Abbiss, Baup, and Dorel (2010) reported that shooting performance remains essential to success in modern pentathlon, with faster event times attributed primarily to greater shooting accuracy and not faster running phases. Correlations between rankings in each of the four disciplines and overall World Cup ranking revealed that Combined Event performance was more influential to the overall result than swimming or fencing.

Other than Le Meur et al. (2010), previous shooting research has focused on precision shooting (Ball, Best, & Wrigley, 2003; Era, Konttinen, Mehto, Saarela, & Lyytinen, 1996; Heimer, Medved, & Spirelja, 1985; Mason, Cowan, & Gonczol, 1990). Most studies have identified two main factors affecting performance; pistol movement and body sway.

Correspondence: Adrian Burden, Manchester Metropolitan University, Exercise and Sport Science, Crewe, United Kingdom. Email: a.burden@mmu.ac.uk

Opto-electronic shooting systems have been used to measure movement of the pistol aim-point and the distance of the shot from the centre of the target. Centre of pressure measures have been used to represent body sway.

Previous rifle shooting research has reported that higher ability shooters have smaller rifle and centre of pressure movements than lower ability shooters (Era et al., 1996; Heimer et al., 1985; Zatsiorsky & Aktov, 1990), although differences in technique between rifle and pistol disciplines mean these findings should be used carefully. Mason et al. (1990) and Ball et al. (2003) focused specifically on pistol shooting performance. Mason et al. reported that horizontal pistol movements of elite and junior shooters accounted for 37% of the variability in horizontal accuracy, whilst vertical pistol movement accounted for just 13% of the variability in vertical accuracy. Anterior-posterior body sway accounted for just 8% of the variability in horizontal accuracy, while mediolateral body sway accounted for 40% of the variance in vertical accuracy. Thus, while both pistol and body movements influence accuracy to some extent, each has a greater impact on accuracy in one particular direction. This illustrates the importance of breaking down variables into directional components rather than one resultant value.

Most previous studies have used group-based designs (Hoffman, Gilson, Westenburg, & Spencer, 1992; Mason et al., 1990), however, Ball et al. (2003) included intra-participant analysis of elite shooters, with each type of analysis producing different results. Group analysis revealed that pistol movements were positively associated with accuracy, whereas intra-individual analysis identified three out of five individuals with significant negative correlations between accuracy and pistol movements ($P < 0.05$). Body sway was only significantly associated with accuracy for one participant. Consequently movement variables can clearly have both positive and negative impacts on score, with the specific effect varying between participants.

Previous precision shooting research has provided useful information regarding levels of pistol and body movement associated with high level performers (Ball et al., 2003; Mason et al., 1990). These findings are, however, of limited relevance to the Combined Event. Previous research has identified that as movement speed increases, as is necessary with the Combined Event, accuracy decreases (Duarte & Freitas, 2005; Fernandez & Bootsma, 2004; Goonetilleke, Hoffman, & Lau, 2009; Walmsley & Williams, 1994). Furthermore, as target size increases, movement speed also increases (Berrigan, Simoneau, & Martin, 2006; Fernandez & Bootsma, 2004). Therefore, the greater target size and reduced shot times associated with the Combined Event may influence shot accuracy when compared to precision shooting techniques, making it difficult to compare between events. This research indicates that accuracy may be sacrificed for speed, although most studies considering this phenomenon have analysed simple pointing tasks rather than more ecologically valid shooting performance. Research should, therefore, identify whether similar effects are seen with the change from precision to Combined Event shooting.

Research aims and hypotheses

There are few research studies that have considered pistol shooting as it currently occurs in modern pentathlon. Therefore, the main aims of this research were to:

(i) Identify key kinematic variables associated with Combined Event shooting performance, and determine whether these correspond to those associated with the precision event;
(ii) Identify the impact of changing from precision to Combined Event shooting, and whether ability level in precision shooting influences shooting performance in the Combined Event.

To achieve the first aim, athletes' shooting performance under both Combined Event and precision rules was monitored. Correlations between shot score, pistol movements, and body sway were used to identify any variables influential to success in either event. To achieve the second aim, performances of modern pentathletes and elite pistol shooters were compared between shooting conditions, and between groups to identify whether athletes of greater precision shooting ability also showed greater ability in the Combined Event. As this research considered changes in performance as a result of the altered shooting format, participants completed all shooting and running phases of the event, but only the first shooting series was analysed. This removed the additional effects that each running phase could have on performance in later series.

There are three hypotheses for this research. First, the variables significantly associated with score will differ between precision and Combined Event shooting due to the different shooting formats. Second, pistol shooters will achieve significantly higher scores and smaller pistol and body movements than the modern pentathletes in both events. Finally, both groups will experience increased movements and decreased scores with the Combined Event. Consequently the differences between groups will be smaller than for precision shooting.

Methods

Participants

Seven Modern Pentathlon World Class Development athletes (3 male, 4 female) (mean age 17.3 ± 3.1 years, mass 58.6 ± 7.6 kg), and three elite pistol shooters (3 female) (mean age 19.3 ± 4.2 years, mass 48.3 ± 5.6 kg), comprised the two participant groups. Throughout all testing sessions participants wore the clothes in which they would normally compete. All athletes used their own training/competition pistol (4.5 mm calibre compressed or CO_2 single shot air pistol, weighing less than 1500 g). Written consent was obtained from all participants prior to testing, which was approved by the University ethics committee.

Tasks

Testing took place in a specially designed shooting range within the University's Biomechanics Laboratory which met all International Shooting Sport Federation shooting regulations. Each participant completed live fire shooting tasks under two conditions; precision rules, and Combined Event (CE) rules. For each testing session, participants stood behind a firing line 10 m from the target. A table was placed in front of the line on which participants rested the pistol, pellets, and any other equipment they were using. Under precision conditions participants completed 20 shots with a maximum of 40 s per shot, aiming at a standard air pistol target (17 cm × 17 cm), and attempting to achieve the highest possible score. An opto-electronic target was positioned on the target to allow more accurate measurement of pistol movement and score. The commands "Load", "Start", and "Stop" were issued in accordance with modern pentathlon precision shooting regulations. The Combined Event condition was completed in the same laboratory, but a Combined Event target with five targets was used, with the opto-electronic target positioned in front of the centre target. Each shooting series lasted 70 s with participants attempting to hit the centre target (5.95 cm diameter) five times within that period. Conditions were designed to replicate competition conditions, so when a participant successfully completed the shooting series or reached the 70 s time limit, they continued with the subsequent running and shooting sections as they would in competition. Only the first Combined Event shooting series was analysed.

Centre of pressure measurements

Two AMTI OR6-7-2000 force platforms (Advanced Mechanical Technology, Inc. (AMTI), Massachusetts), each measuring 46.7 × 51.0 cm were used, with both platforms recording ground reaction force throughout the aiming period of each shot. The platforms were linked through a Data Translation 3002 12-bit A-D converter to an RM Expert 3010 computer, using AMTI Netforce (Version 2.1.0, Advanced Mechanical Technology, Inc.) software, sampling at 100 Hz, for data acquisition. For both conditions, participants positioned themselves with one foot fully on each force plate whilst shooting. This made little or no change to their normal shooting stance. Vertical ground reaction force and centre of pressure co-ordinate data from each platform were exported through BioAnalysis software (Biosoft Version 2.3.0, AMTI), and used to calculate the centre of pressure location for the whole body during the 1 s prior to each shot.

Pistol movements and shot location

Pistol movements and shot score were recorded using a SCATT USB opto-electronic shooting system (SCATT, Moscow), linked to SCATT Professional software (version 5.63), recording at 100 Hz. A microphone positioned near the pistol detected the noise from the trigger pull. This was recorded as a pulse on the centre of pressure trace via the DataTranslation 3002 A-D convertor, enabling synchronisation of the centre of pressure and pistol movement data.

Data analysis

Decimal shot score was reported by the SCATT system to a maximum of 10.9. Trace Length, calculated as the distance (mm) moved by the aiming point of the pistol on the target along the X (horizontal) and Y (vertical) axes was used to represent pistol movement. Aim-point refers to the precise location on the target at which the pistol is pointing. Therefore, trace length represented changes in aim-point location that were brought about by movements of the pistol. Trace length is a common measure of pistol movement, used regularly within elite shooting training, which can accurately discriminate between different ability level athletes (Ball et al., 2003; Mason et al., 1990). Consequently trace length was chosen as an appropriate measure of pistol movement for this initial evaluation of Combined Event performance.

Two factors, both separated into anterior-posterior and mediolateral components, were selected to represent centre of pressure movement: "range", calculated as the difference between the maximum and minimum co-ordinates of the centre of pressure (mm); and "path length", calculated as the distance travelled by the whole body centre of pressure. For each parameter, data were obtained for 1 s prior to trigger pull, in accordance with previous shooting research (Ball et al., 2003; Mason et al., 1990).

Statistical analysis

Due to relatively small sample sizes, non-parametric tests were selected. Spearman's rank order correlation coefficients revealed the extent of associations between score, pistol movements (trace length) and centre of pressure movements (range and path length). Correlations were performed for both groups and for each individual's data using median values from each data set. A Wilcoxon test identified changes in score, pistol movements, and centre of pressure movements as a result of changing from precision to Combined Event shooting for both groups. A Mann-Whitney U test compared variables between the participant groups. For all comparisons, $P < 0.05$ was considered statistically significant.

Results

Group median values and the results of statistical comparisons between the two participant groups for each shooting condition are shown in Table I. Table II details the results of statistical comparisons between precision and Combined Event shooting for each group.

Shot score

Pistol shooters achieved significantly greater scores than modern pentathletes under precision conditions (Table I), with a median score of 9.7 for pistol shooters, compared to 8.8 for modern pentathletes. All median precision scores for both groups were greater than 8.0, demonstrating that all participants were capable of consistently scoring a "hit" on the Combined Event target (equivalent to scoring 7.0 or higher). Median scores reduced significantly for both groups when changing to Combined Event shooting (Table II), reducing by 1.1 points for modern pentathletes and 1.7 points for pistol shooters. This reduction was greater, but not significantly, for pistol shooters than modern pentathletes resulting in a non-significant difference between groups of 0.3.

Pistol movements

Under precision conditions median horizontal trace length was significantly greater for modern pentathletes than pistol shooters (Table I). When changing to Combined Event shooting, both groups experienced significant increases in horizontal trace length of 166 mm for modern pentathletes and 119 mm for pistol shooters (Table II). As a result, between-group differences became non-significant.

Vertical trace length was also significantly greater for modern pentathletes than pistol shooters under precision conditions (Table I). Values significantly increased by 76 mm for modern pentathletes and 120 mm for pistol shooters with Combined Event shooting (Table II). Again, between-group differences became non-significant.

Centre of pressure movements

Under precision conditions, modern pentathletes had significantly greater anterior-posterior and mediolateral range and anterior-posterior path length than pistol shooters. Both groups experienced significantly increased body sway for Combined Event conditions (Table II). Mediolateral and anterior-posterior range increased by 2.2 mm and 1.9 mm respectively for modern pentathletes. For pistol shooters, mediolateral and anterior-posterior range

Table I. Group medians and interquartile range (IQR) for all dependent variables, and statistical results of comparisons between the modern pentathlon and pistol shooter groups.

	Precision				Combined Event			
	Group median (IQR)				Group median (IQR)			
	MP	Pistol	Statistic (U)	p value	MP	Pistol	Statistic (U)	p value
Score	8.8 (1.7)	9.7 (0.9)	8.0	0.003	7.7 (1.9)	8.0 (2.3)	6.0	0.571
Horizontal TL (mm)	115.8 (18.5)	71.2 (28.8)	24.0	<0.001	281.9 (120.2)	190.4 (52.2)	2.0	0.071
Vertical TL (mm)	132.8 (29.7)	88.4 (28.8)	53.0	<0.001	209.5 (72.1)	209.3 (50.6)	5.0	0.286
M-L Range (mm)	3.6 (0.7)	2.6 (1.1)	10.0	0.006	5.8 (0.8)	8.0 (4.0)	2.5	0.060
A-P Range (mm)	2.7 (0.8)	1.4 (0.7)	5.0	<0.001	4.6 (2.8)	4.1 (6.3)	8.5	0.488
M-L PL (mm)	66.1 (30.9)	52.0 (11.7)	16.0	0.172	75.7 (15.1)	59.7 (26.6)	3.0	0.083
A-P PL (mm)	32.4 (11.7)	24.7 (8.0)	7.0	0.015	49.3 (23.3)	35.7 (23.1)	5.0	0.190

Group: MP = Modern pentathletes; Pistol = Pistol shooters; TL = Trace Length; PL = Path Length; M-L = Mediolateral; A-P = Anterior-posterior.

Table II. Statistical results of comparisons for each participant group between precision and Combined Event shooting conditions for all dependent variables.

	MP		Pistol	
	Statistic (T)	p value	Statistic (T)	p value
Score	2	0.003	0	0.016
Horizontal TL	0	<0.001	0	0.008
Vertical TL	0	<0.001	0	0.008
M-L Range	0	0.006	0	0.016
A-P Range	0	<0.001	0	0.016
M-L PL	0	0.172	0	0.016
A-P PL	8	0.015	0	0.016

Group: MP = Modern pentathletes; Pistol = Pistol shooters; TL = Trace Length; PL = Path Length; M-L = Mediolateral; A-P = Anterior-posterior.

increased by 5.4 mm and 2.7 mm respectively. Consequently, between-group differences became non-significant. Between-group differences remained non-significant for mediolateral path length, with movement increasing by 27.7 mm for modern pentathletes and 17.0 mm for pistol shooters. Differences also became non-significant for anterior-posterior path length, with movements increasing by 7.5 mm for modern pentathletes and 10.7 mm for pistol shooters.

Correlations between shot score and pistol and centre of pressure movement

Under precision conditions, group analysis revealed one significant correlation with score for each group; mediolateral path length for modern pentathletes ($r_s = –0.386$, $P < 0.05$, $R^2 = 0.15$) and vertical pistol movements for pistol shooters ($r_s = –0.408$, $P < 0.05$, $R^2 = 0.17$). Intra-individual analysis identified significant correlations between movement variables and score for three modern pentathletes and all pistol shooters (Table III). Changes in centre of pressure movements, particularly mediolateral path length, were commonly associated with changes in score for precision shooting, while pistol movements showed few significant correlations.

Under Combined Event conditions, group analysis revealed no significant correlations with score for either group, and only two participants showed significant associations for intra-individual analysis (Table III). None of these associations were with centre of pressure path length despite the multiple correlations for precision shooting. No participants showed the same correlations for both shooting conditions.

Correlations between pistol and centre of pressure movements

Group precision shooting analysis revealed no significant associations between pistol and centre of pressure movement for pistol shooters. Significant correlations for modern pentathletes were between horizontal pistol movement and anterior-posterior path length ($r_s = –0.385$, $P < 0.05$, $R^2 = 0.15$), and vertical pistol movement and mediolateral range ($r_s = –0.391$, $P < 0.05$, $R^2 = 0.15$). Intra-individual analysis (Table IV) significantly associated only one centre of pressure variable with pistol movements for each modern pentathlete and up to three for pistol shooters. Few modern pentathletes showed any significant associations so no clear trend was identified, while mediolateral centre of pressure movements had the greatest influence on pistol movement for pistol shooters.

Combined Event group analysis revealed no significant correlations between pistol and centre of pressure movements for modern pentathletes, whilst pistol shooters had significant correlations between horizontal trace length and both mediolateral range ($r_s = 0.886$, $P < 0.01$, $R^2 = 0.78$) and anterior-posterior range ($r_s = 0.829$, $P < 0.05$, $R^2 = 0.69$). Intra-individual analysis identified only one modern pentathlete with a significant correlation between

Table III. Significant intra-individual correlations with shot score under precision and Combined Event conditions. R^2 values are included in brackets.

Event	Group	Participant	Vertical TL	Horizontal TL	M-L Range	A-P Range	M-L PL
Precision	MP	1					−.405** (0.16)
		3	.713* (0.51)				
		5					.310** (0.10)
	Pistol	1					−.295** (0.09)
		2			−.294** (0.09)	−.283** (0.08)	−.373* (0.14)
		3					.592* (0.35)
Combined Event	MP	1			.949* (0.90)	.949* (0.90)	
		2		.949* (0.90)			

Group: MP = Modern pentathletes; Pistol = Pistol shooters; TL = Trace Length; PL = Path Length; M-L = Mediolateral; A-P = Anterior-posterior; *= significant correlations between variable and score at $p < 0.01$; ** = significant correlations between variable and score at $p < 0.05$.

Table IV. Significant intra-individual correlations between pistol and centre of pressure movements under precision conditions. R^2 values are included in brackets.

Group	TL	Participant	M-L Range	A-P Range	M-L PL	A-P PL
MP	Horizontal TL	2		−.432** (0.19)		
	Vertical TL	3			−.405** (0.16)	
		4		−.402** (0.16)		
Pistol						
	Horizontal TL	1	.340** (0.12)			.438** (0.19)
		2	.522* (0.27)	.269** (0.07)	.305** (0.09)	
		3	.575* (0.33)		.404* (0.16)	
	Vertical TL	1	.424* (0.18)	.281** (0.08)	.438** (0.19)	
		3	.317** (0.10)			

Group: MP = Modern Pentathletes; Pistol = Pistol Shooters; TL = Trace Length; PL = Path Length; M-L = Mediolateral; A-P = Anterior-posterior; * = significant correlations between variables at $p < 0.01$; ** = significant correlations between variables at $p < 0.05$.

Table V. Significant intra-individual correlations between pistol and centre of pressure movements under Combined Event conditions. R^2 values are included in brackets.

Group	TL	Participant	M-L Range	A-P Range	M-L PL	A-P PL
MP	Vertical TL	5			.949* (0.90)	
Pistol	Vertical TL	3		.821** (0.67)		
	Horizontal TL	2	.714** (0.51)			

Group: MP = Modern Pentathletes; Pistol = Pistol Shooters; TL = Trace Length; PL = Path Length; M-L = Mediolateral; A-P = Anterior-posterior; * = significant correlations between variables at $p < 0.01$; ** = significant correlations between variables at $p < 0.05$.

pistol movements and body sway (Table V). In accordance with group analysis, one pistol shooter showed a significant association between horizontal trace length and mediolateral range. These variables were also correlated for this participant under precision conditions, but the strength of the association was much greater for Combined Event shooting; 51% for Combined Event compared to 27% for precision.

Discussion

This study aimed to identify the key variables affecting shooting performance in the Combined Event, and highlight any similarities with precision shooting. A further aim was to identify whether pistol shooters who had a higher precision shooting ability than modern pentathletes were also more successful in the Combined Event.

Precision scores recorded for the pistol shooters compared well with other elite groups (Ball et al., 2003; Heimer et al., 1985; Mason et al., 1990; Tang, Zhang, Huang, Young, & Hwang, 2008), supporting their status as elite shooters. Modern pentathletes scored lower than the pistol shooters in this study and other elite groups, but higher than groups previously identified as less skilled shooters (Heimer et al., 1985; Tang et al., 2008).

Group analysis revealed few significant associations between score and any other variable for either shooting condition. Individual analysis identified a greater number of significant correlations with score, the strength and direction of which were participant specific. Individual variation was particularly evident for precision shooting, where six participants displaying significant correlations with score were identified. Of these, one displayed an association between score and pistol movements, with score increasing as vertical pistol movement decreased. Despite this movement accounting for over half of the variation in score, no other participant displayed any significant correlations between these two variables. All other associations were with centre of pressure movements, most commonly with mediolateral range. Within these results, an increased mediolateral range was associated with greater scores for two participants but reduced scores for three others. The extent to which this movement influenced shot score varied from 9% to 35% between participants. Variation was also apparent for Combined Event shooting, where despite three significant positive correlations with score, none were with the same movement variable. This supports the findings of Ball et al. (2003) that group analysis masks important individual trends. Consequently, the outcomes of individual analysis will be considered as a means of identifying key variables affecting performance.

The limited number of significant Combined Event correlations means that no single variable could be identified as most influential to Combined Event performance. Under precision conditions only one participant displayed more than one movement variable significantly associated with score. This highlights how other variables not investigated here, such as movement of individual body segments, must also influence performance. No participants displayed the same correlations for both conditions, demonstrating the new demands that the Combined Event has placed on athletes. In relation to the first aim, there are few similarities regarding key variables affecting performance in the two events. This difference between events is particularly apparent when comparing mediolateral centre of pressure movements. These movements were commonly identified as having a significant influence on both shot score and pistol movements under precision conditions. In contrast, only two associations with mediolateral centre of pressure movements were evident under Combined Event conditions. This supports the hypothesis that the variables significantly associated with score would differ between the two shooting events. These findings imply that experience in one event does not guarantee success in the other, indicating the importance of Combined Event specific training.

Intra-individual analysis also identified that body sway accounted for some, but not all of the variability in pistol movements, with centre of pressure movements accounting for up to 33% of the variance in pistol movement for precision shooting. This supports the concept of a more complex system than simply centre of pressure movements being transferred through the body to the pistol and ultimately reducing score (Ball et al., 2003; Pellegrini & Schena, 2005). While some correlations between pistol and centre of pressure movements were expected, it is unsurprising that these associations were not greater. Between the centre of pressure at ground level and the hand holding the pistol there are many potential sources of movement, such as movements of the upper extremity. These may affect pistol movement but not be represented by centre of pressure motion. This theory is supported by Pellegrini and Schena (2005) who reported that vertical arm movements increased from proximal to distal segments. Furthermore, Arutyunyan, Gurfinkel, and Mirskii (1968) reported that pistol movement was not determined solely by postural stability, but was further influenced by the compensatory actions of the upper extremity joints. Strong correlations were identified between movement of the shoulder and wrist; the combination of which contributed to much of the pistol movement. Such findings demonstrate that while centre of pressure movements influence performance, they are not the only variable to consider.

Future Combined Event research would benefit from increased participant numbers. A greater number of significant individual correlations may become apparent, increasing the potential to uncover any factors influencing performance. Research should not only consider sources of variations in pistol movement, but also which aspects of pistol movement are most influential to performance. This study has identified that the amount of pistol movement can influence performance for some individuals, but research should now consider whether other factors, such as speed of movement are equally important.

Within each shooting condition, the performances of each participant group were compared to identify whether the greater precision shooting ability of the pistol shooters was also evident in the Combined Event. The difference in precision ability was evident by the significantly higher scores, and smaller pistol and body movements of the pistol shooters compared to modern pentathletes. Movements recorded for the pistol shooters were again more comparable with elite shooters (Ball et al., 2003), while modern pentathletes had similar movements to the elite and junior shooters of Mason et al. (1990) (Table VI). This supports past research which has reported greater ability shooters to display smaller pistol movements (Zatsiorsky & Aktov, 1990), and has associated greater centre of pressure movements with greater pistol movement and lower scores (Ball et al., 2003; Era et al., 1996; Heimer et al., 1985).

Under Combined Event conditions, score significantly decreased while pistol and some body movements significantly increased, for both groups. Consequently, scores were up to 2.0 points lower than all previous precision results, while pistol and centre of pressure movements were greater than all previous findings (Pellegrini & Schena, 2005; Tang

Table VI. Comparisons of movement variables with those from previous research.

	Current Study			
	MP	Pistol	Mason et al. (1990)	Ball et al. (2003)
Horizontal TL (mm)	115.8	71.2	108.9	76.1
Vertical TL (mm)	132.8	71.3	89.2	70.7
M-L Range (mm)	3.6	2.6	3.1	1.0
A-P Range (mm)	2.7	1.4	3.3	1.9

Group: MP = Modern Pentathletes; Pistol = Pistol Shooters; TL = Trace Length; M-L = Mediolateral; A-P = Anterior-posterior.

et al., 2008) (Table VI). This finding supports the third hypothesis that the Combined Event would result in significantly increased movements and decreased scores, and emphasises the different performance requirements of the Combined Event. This was expected as increased target size means that success is determined by achieving any score above 7.0; i.e. significantly lower than all precision scores. Increased target size, alongside the removal of any incentive to hit the centre of the target, means athletes could attempt to shoot more quickly with less consideration of exact shot placement or reducing their movement which might negatively affect performance. Therefore some accuracy may have been sacrificed to increase shooting speed. Previous research into the speed-accuracy trade-off supports this change in performance, with tasks with greater target sizes associated with faster movements (Berrigan et al., 2006; Duarte & Freitas, 2005; Fernandez & Bootsma, 2004). Le Meur et al. (2010) however, reported that the most successful Combined Event athletes had the shortest event times due to greater shooting accuracy and not quicker shot times or faster running phases. Increased accuracy meant that athletes achieved five hits in fewer shots, and could progress to the next running phase sooner than those who were less accurate. Consequently, minimising shot time may in fact be detrimental to performance. Less successful Combined Event athletes therefore need to determine the appropriate level of trade-off between accuracy and speed.

In this study, modern pentathletes' performances changed dramatically with the change to Combined Event rules. Scores decreased for all individuals and group scores reduced by 1.1 points. Furthermore, despite the pistol shooters' greater precision performances, there were no notable differences between groups in the Combined Event. This does not fully support the second hypothesis as pistol shooters were expected to achieve significantly greater scores in both events. This highlights the potential impact of the rule change, where athletes who were successful precision shooters will not necessarily be successful Combined Event shooters without specific training. Differences between conditions may also be a result of experience, where the pistol shooters had been shooting at a higher level than modern pentathletes in the precision event whereas neither group had any prior Combined Event experience. Future research with experienced participants would be useful as additional associations between variables may become apparent.

In conclusion, intra-individual analysis highlighted that while pistol movements and body sway can both be key factors influencing shot score, the strength of associations between variables is individual-specific. Associations differed between precision and Combined Event shooting for each individual, emphasising the different performance requirements of the two events. This conclusion is further supported by the lack of any significant difference between the performances of the two groups under Combined Event conditions despite the greater performance of the pistol shooters in the precision trials. Therefore, ability in precision shooting does not guarantee similar success in the Combined Event. This has important implications, as athletes who were successful under the old rules must find ways to adapt to the new demands of Combined Event shooting in order to remain successful in modern pentathlon.

References

Arutyunyan, G. A., Gurfinkel, V. S., & Mirskii, M. L. (1968). Investigation of aiming at a target. *Biofizika, 13*(3), 536–538.

Ball, K. A., Best, R. J., & Wrigley, T. V. (2003). Inter- and intra-individual analysis in elite sport: Pistol shooting. *Journal of Applied Biomechanics, 19,* 28–38.

Berrigan, F., Simoneau, M., & Martin, O. (2006). Coordination between posture and movement: Interaction between postural and accuracy constraints. *Experimental Brain Research, 170,* 255–264.

Duarte, M., & Freitas, S. M. S. F. (2005). Speed-accuracy trade-off in voluntary postural movements. *Motor Control, 9,* 180–196.

Era, P., Konttinen, N., Mehto, P., Saarela, P., & Lyytinen, H. (1996). Postural stability and skilled performance - a study on top-level and naive rifle shooters. *Journal of Biomechanics, 29*(3), 301–306.

Fernandez, L., & Bootsma, R. (2004). Effects of biomechanical and task constraints on the organisation of movement in precision aiming. *Experimental Brain Research, 159,* 458–466.

Goonetilleke, R. S., Hoffman, E. R., & Lau, W. C. (2009). Pistol shooting accuracy as dependent on experience, eyes being opened and available viewing time. *Applied Ergonomics, 40,* 500–508.

Heimer, S., Medved, V., & Spirelja, A. (1985). Influence of postural stability on sport shooting performance. *Kinezioliogija, 17*(2), 119–122.

Hoffman, M. D., Gilson, P. M., Westenburg, T. M., & Spencer, W. A. (1992). Biathlon shooting performance after exercise of different intensities. *International Journal of Sports Medicine, 13,* 270–273.

Le Meur, Y., Hausswirth, C., Abbiss, C., Baup, Y., & Dorel, S. (2010). Performance factors in the new combined event of modern pentathlon. *Journal of Sports Sciences, 28*(10), 1111–1116.

Mason, B. R., Cowan, L. F., & Gonczol, T. (1990). Factors affecting accuracy in pistol shooting. *EXCEL, 6,* 2–6.

Pellegrini, B., & Schena, F. (2005). Characterization of arm-gun movement during air pistol aiming phase. *Journal of Sports Medicine and Physical Fitness, 45*(4), 467–475.

Tang, W. T., Zhang, W. Y., Huang, C. C., Young, M. S., & Hwang, I. S. (2008). Postural tremor and control of the upper limb in air pistol shooters. *Journal of Sports Sciences, 26*(14), 2579–2587.

Walmsley, A., & Williams, L. R. T. (1994). Rapid-fire pistol shooting as a dynamic problem. *Perceptual and Motor Skills, 78,* 1019–1024.

Zatsiorsky, V. M., & Aktov, A. V. (1990). Biomechanics of highly precise movements: The aiming process in air rifle shooting. *Journal of Biomechanics, 23,* 35–41.

JOURNAL OF SPORTS SCIENCES, 2015
http://dx.doi.org/10.1080/02640414.2015.1088163

Routledge
Taylor & Francis Group

The effect of time constraints and running phases on combined event pistol shooting performance

Clare Dadswell, Carl Payton, Paul Holmes and Adrian Burden

Department of Exercise and Sport Science, Manchester Metropolitan University, Crewe, UK

ABSTRACT

The combined event is a crucial aspect of the modern pentathlon competition, but little is known about how shooting performance changes through the event. This study aimed to identify (i) how performance-related variables changed within each shooting series and (ii) how performance-related variables changed between each shooting series. Seventeen modern pentathletes completed combined event trials. An optoelectronic shooting system recorded score and pistol movement, and force platforms recorded centre of pressure movement 1 s prior to every shot. Heart rate and blood lactate values were recorded throughout the event. Whilst heart rate and blood lactate significantly increased between series ($P < 0.05$), there were no accompanying changes in the time period that participants spent aiming at the target, shot score, pistol movement or centre of pressure movement ($P > 0.05$). Thus, combined event shooting performance following each running phase appears similar to shooting performance following only 20 m of running. This finding has potential implications for the way in which modern pentathletes train for combined event shooting, and highlights the need for modern pentathletes to establish new methods with which to enhance shooting accuracy.

ARTICLE HISTORY
Accepted 25 August 2015

KEYWORDS
Modern pentathlon; body sway; pistol movement; fatigue

Introduction

The combined event is composed of 2 of the 5 disciplines that make up the modern pentathlon competition: pistol shooting and running. In its original format, as detailed by pre-2013 modern pentathlon rules, athletes must complete the following tasks:

20 m Run → Shooting Series 1 → 1 km Run → Shooting Series 2 → 1 km Run → Shooting Series 3 → 1 km Run

Within each shooting series, athletes attempt to hit 5 targets as quickly as possible. Once this is achieved, athletes immediately begin the next running phase. If 5 hits are not achieved within 70 s, then athletes automatically begin the next running phase. The rules of the combined event have since been modified further, with athletes required to complete four 800 m running phases interspersed by four 50 s shooting series. Thus, whilst the event has been adapted, the concept of shooting accurately following bouts of exercise remains the same.

To date, few researchers have considered which aspects of the combined event have the greatest influence on success. Current findings suggest that success is determined primarily by shooting performance and not running speed (Le Meur, Hausswirth, Abbiss, Baup, & Dorel, 2010, 2012). In their analysis of a World Cup competition, Le Meur et al. (2010) assigned athletes to 1 of 3 groups based on their overall combined event time. No significant differences in running times were found between any of the 3 groups. However, the athletes who completed the event in the shortest time took significantly fewer shots ($P < 0.05$), and finished each shooting series more quickly than those who took longer to complete the event.

The findings of Le Meur et al. (2010) highlighted the importance of each shooting series to the combined event. This was further emphasised in a subsequent analysis (Le Meur et al., 2012), which reported that the pace of each running phase had no significant effect on overall event time ($P > 0.05$). Moreover, by increasing the pace of the first two 1 km phases, athletes spent significantly longer shooting in the third series ($P < 0.05$). Thus, the benefits of quicker running phases were counteracted by the increase in shooting time. These findings are crucial, as they highlight the importance of a successful shooting performance and the need for athletes to direct training towards methods of improving combined event shooting technique.

Whilst the research of Le Meur et al. (2010, 2012) undoubtedly produced interesting findings regarding the temporal characteristics of performance, it is now important to advance this research area. By including the effects of the combined event on the kinematic and kinetic variables associated with shooting, it will be possible to examine the processes behind a successful combined event shooting performance. The understanding of these processes has previously been achieved for precision shooting (Ball, Best, & Wrigley, 2003; Dadswell, Payton, Holmes, & Burden, 2013; Heimer, Medved, & Spirelja, 1985; Mason, Cowan & Gonczo, 1990). One key finding from this research was the effect of movement on shooting performance, with pistol movement and body sway accounting for up to 37% and 40% of the variability in shooting accuracy, respectively (Mason et al., 1990). Combined event performance, however, differs from precision shooting (Dadswell et al., 2013), as it has a greater target size and reduced shot times (Berrigan, Simoneau, & Martin, 2006; Goonetilleke, Hoffman, & Lau, 2009).

To the authors' knowledge, only one study has compared the processes related to combined event and precision shooting performance (Dadswell et al., 2013). Comparisons between the 2 events revealed that pistol movements and body sway were significantly greater for the combined event than for precision shooting ($P < 0.05$). Correlations between pistol movements, body sway and shot score also differed between the 2 events, highlighting the different performance require-ments. Performance was, however, only analysed within the first shooting series of the combined event, prior to the run-ning phases. Each running phase, and its associated fatigue, is likely to further influence shooting performance and, thus, the effect of each running phase on combined event shooting performance should also be considered.

Whilst there has been limited research into combined event shooting, some researchers have considered the shooting performances of biathletes. Arguably, of all the shooting disciplines, biathlon is most similar to the combined event. Accepting the obvious performance differences between the 2 sports, biathlon can, therefore, provide an indication of the effect of exercise on shooting performance. In their analysis of biathlon, Hoffman, Gilson, Westenburg, and Spencer (1992) reported that increasing exercise intensity negatively influenced shooting performance. An increase in intensity resulted in reduced scores and significantly fewer shots on target, alongside significantly increased shot-group diameter and rifle movements. These findings supported a popular strategy in biathlon whereby athletes reduce skiing velocity in the final approach to each shooting phase in an attempt to reduce fatigue and enhance shooting performance (Hoffman et al., 1992).

If the effect of exercise on shooting performance is found to be similar between biathlon and the combined event, then the tactics employed by biathletes to enhance shooting performance could also prove beneficial to modern pentathletes. However, in their analysis of the effect of exercise on the shooting performance of police officers, Brown, Tandy, Wulf & Young (2013) reported no significant correlations between pistol shooting performance and heart rate following changes in heart rate of 60 bpm. As such, it is currently unclear whether the approach used by biathletes can transfer directly to the combined event.

Research aims and hypotheses

Previous research has considered the effect of biomechanical variables on shooting performance in the first series of the combined event (Dadswell et al., 2013). None, however, has considered the effect of either the 70 s time limit or the running phases on performance in each of the 3 shooting series. Therefore, the aims of this research were to: (i) identify any changes in performance-related variables within each shooting series and (ii) identify any changes in performance between each shooting series. There were 2 hypotheses for this research. First, as the time remaining to complete each series reduced, shot time and shot score would significantly reduce and pistol movements and body sway would significantly increase. Second, average shot score would significantly decrease with each successive shooting series, and average pistol movement and body sway would significantly increase.

Methods

Participants

Seventeen national development athletes (6 male, 11 female; mean age 17.4 ± 3.2 years, body mass 59.4 ± 8.7 kg, and height 172.9 ± 7.15 cm) completed the combined event task using their own pistol (4.5 mm calibre compressed air CO_2 single-shot air pistol, weighing less than 1500 g). Written informed consent was obtained from all participants prior to testing and also from participant's parents/guardians for those athletes under 18 years of age. The study was approved by the local research ethics committee.

Tasks

Testing took place in a shooting range, conforming to ISSF shooting regulations, within the university's biomechanics laboratory. The sequence of tasks followed the order detailed by pre-2013 modern pentathlon rules. Each running phase required participants to complete 2 circuits of a 500 m grass route directly outside the laboratory. Participants were instructed to complete each phase at a pace similar to that which they would use in competition. For each live-fire shoot-ing series, participants stood 10 m from a mechanical com-bined event target.

Pistol movements, shot location and shot time

Pistol movements over the final second before the shot, shot score and shot time were recorded using a SCATT USB opto-electronic shooting system (SCATT, Moscow) positioned in front of the centre of the mechanical target. Data were recorded using SCATT Professional software following the procedure used by Dadswell et al. (2013).

Centre of pressure measurements

Two AMTI OR6-7–2000 force platforms (Advanced Mechanical Technology, Inc. Massachusetts), were used to record ground reaction force data throughout the aiming period of each shot. Participants stood with one foot on each platform whilst data were recorded by following the procedure outlined by Dadswell et al. (2013). Centre of pressure location was calcu-lated over 1 s prior to every shot.

Physiological measurements

Three fingertip blood lactate (BLa) samples were obtained at the beginning of the event as well as immediately following completion of the second and third shooting series. Blood lactate concentration was used to indicate the reliance on anaerobic metabolism throughout the event. Each sample was taken from the 5th digit of the loading hand, and analysed using a YSI 1500 SPORT Lactate Analyzer (YSI UK Limited). Heart rate values were recorded throughout the event using an Activio Sport System (Activio AB, Stokholm: version 2.1) wireless heart rate monitor sampling at 1 Hz. This demonstrated how heart rate changed between each running and shooting series, in particular within each shooting series.

Data analysis

In the combined event, the number of shots an athlete can take in order to achieve 5 hits within the 70 s time limit is unlimited. Participants, therefore, took a varied number of shots within each series. Consequently, analysis was based on the first 6 shots of each series to ensure homogeneity and that appropriate data were available for comparisons.

Shot score is not recorded on a combined event style of target and, therefore, was obtained from the SCATT system to a maximum of 10.9. All athletes were instructed to zero the system prior to testing to ensure that scores were as accurate as possible. Trace length – the distance moved by the aiming point of the pistol on the target (mm) –, was recorded in the final second before triggering. This was separated into movement along both the horizontal and vertical axes of the target in accordance with previous research (Ball et al., 2003; Dadswell et al., 2013; Mason et al., 1990). Shot time (s), repre-senting the length of time that the participant spent aiming at the target, was defined as the moment that the aiming point was in alignment with the target until the instance of the shot. Time spent aiming has been previously reported to be corre-lated with shooting accuracy (Mason et al., 1990; Mononen, Konttinen, Viitasalo, & Era, 2007).

Two factors, separated into anteroposterior (movement parallel with the target) and mediolateral (movement perpendicular to the target) components, were selected to represent the centre of pressure movement: for each, range was calculated as the difference between the maximum and minimum co-ordinates of the centre of pressure (mm) over the final 1 s before the shot. Path length was calculated as the distance travelled by the whole-body centre of pressure (mm). Each parameter has previously been used as an indicator of body sway in pistol shooting (Ball et al., 2003; Dadswell et al., 2013; Mason et al., 1990). For each variable, data were obtained for 1 s prior to the shot.

Statistical analysis

Due to the relatively small sample size, non-parametric tests were used to analyse group median data for each dependent variable. Median values and interquartile range (IQR), represent-ing the middle 50% of values achieved across all participants, were selected as measures that would not be affected by skewed data. Where outliers were identified, the data were truncated. No gender differences were evident when comparing shooting performance; therefore, participants were analysed as a single group. Two sets of comparisons were performed, intra-series to identify the effect of the time remaining in which to achieve 5 hits, and inter-series to identify any changes in shooting performance following each running phase.

Wilcoxon tests were used for intra-series comparisons between the maximum and minimum heart rate within each shooting series. Friedman's ANOVA tests were used to identify any changes in shot score, shot time, pistol movements (trace length) and centre of pressure movements (range and path length) over the first 6 shots within each series. Friedman's ANOVA Tests were also used for inter-series comparisons of each variable. For all comparisons, $P < 0.05$ was considered statistically significant. Wilcoxon Tests using Bonferroni correc-tions were used for post hoc analysis of any significant results, with $P < 0.016$ considered statistically significant.

Spearman's rank order correlation coefficients were performed between all variables for each series (shot score, shot time, horizontal and vertical trace length, anterior and posterior centre of pressure range and path length), making it possible to identify the association between each variable and shot score. By comparing the correlations between each series, it was possible to further identify how performance changed between series. Group correlations were performed using data from the first 6 shots for all participants. The number of shots available for intra-individual correlations varied between participants. This was dependent on the minimum number of shots required to complete any of the 3 series for each participant. Due to the high number of correlations, Bonferroni corrections were used and, as such, $P < 0.007$ was considered statistically significant.

Results

Physiological variables

Each participant experienced similar heart rate patterns throughout the event (see Figure 1). Heart rate increased during each 1 km run phase, and then significantly reduced within each shooting series ($P < 0.05$) (see Table 2). Maximum and minimum heart rates were significantly greater for the second and third shooting series compared to series 1 ($P < 0.016$). Despite no significant changes in 1 km run time ($P > 0.05$), BLa concentration significantly increased between each series ($P < 0.016$) (see Table 2).

Intra-series comparisons

No significant changes were recorded for shot time within any of the shooting series ($P > 0.05$) (see Table 1). Each shot was completed within 0.9–1.5 s (see Figure 2); moreover, in series 3, whilst not significant, there was a progressive decrease in median shot time between shot 1 (1.3 s) and shot 4 (0.9 s). No significant changes in shot score were evident within any of the 3 shooting series ($P > 0.05$) (see Table 1). Scores varied considerably within each series, with no evidence of a decrease in score as the series progressed (see Figure 2). For instance, in series 3, despite the progres-sive decrease in shot time, there was no corresponding decline in scores.

Horizontal and vertical pistol movements did not change significantly within any series ($P > 0.05$). No significant

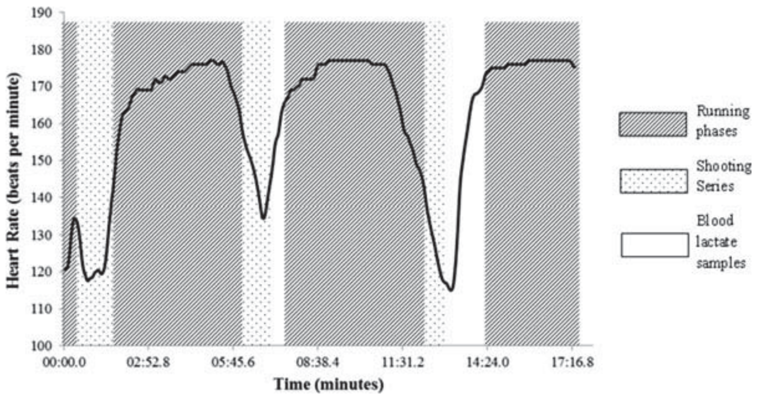


Figure 1. Heart rate from 1 participant throughout the combined event. This pattern is representative of the heart rate pattern for all participants.

Table 1. Statistical comparisons from Friedman's ANOVA (χ^2) between the first six shots within each shooting series for all dependent variables ($n = 17$).

	Series 1		Series 2		Series 3	
Dependent variable	χ^2	*P* value	χ^2	*P* value	χ^2	*P* value
Score	7.61	.268	3.83	.574	9.59	.088
Timings	4.95	.422	2.12	.833	9.53	.09
Horizontal trace length*	0.76	.985	4.57	.495	1.62	.917
Vertical trace length*	4.47	.513	2.19	.848	0.67	.990
Mediolateral range†	6.51	.260	5.07	.408	3.81	.577
Anteroposterior range†	1.74	.884	5.02	.413	5.75	.331
Mediolateral path length††	3.09	.685	4.37	.498	5.06	.409
Anteroposterior path length	5.39	.370	3.59	.610	8.75	.119

~~Notes: * Pistol movement variables~~.

† Centre of pressure movement variables.

changes were recorded for the anteroposterior or mediolateral components of centre of pressure range or path length within any series ($P > 0.05$) (see Figure 3).

Inter-series comparisons

Neither shot time nor score changed significantly between each series ($P > 0.05$) (see Table 2). Median shot time reduced by 0.2 s between series, while just 0.2 points separated each series' median score. IQR for shot score increased with each successive series as the success of participants varied more widely in the second and third series.

There were no significant changes in either horizontal or vertical pistol movements between series ($P > 0.05$). Although not significant, greater vertical movements were produced in series 2 and 3 than for series 1 (see Figure 2). This was not evident for horizontal pistol movements.

Neither mediolateral nor anteroposterior centre of pressure range changed significantly between series ($P > 0.05$) (see Table 2). Again, whilst not significant, the smallest movements were recorded in series 1 for the majority of shots. Changes in path length were minimal and non-significant ($P > 0.05$).

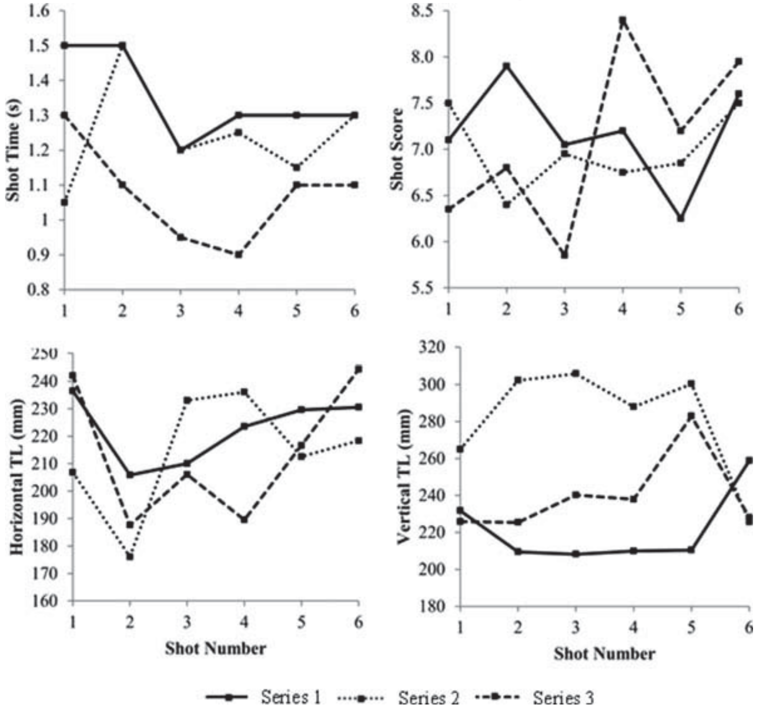


Figure 2. Median group shot time (a), shot score (b), horizontal trace length (c) and vertical trace length (d). Data are taken from the first 6 shots within each series.

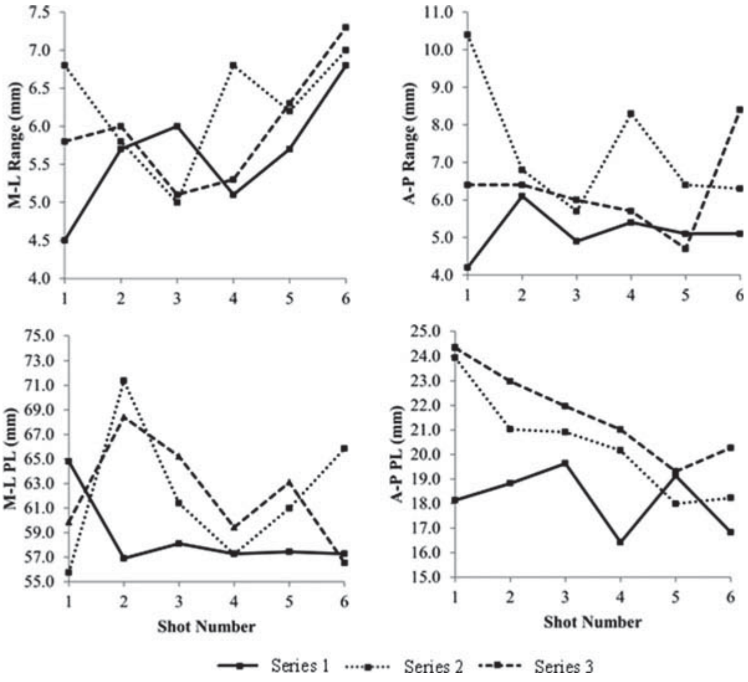


Figure 3. Median group mediolateral (a) and anteroposterior (b) centre of pressure range, and mediolateral (c) and anteroposterior (d) path length. Data are taken from the first 6 shots within each series.

Table 2. Comparisons of all dependent variables between each shooting series.

	Median group values (±IQR)				
Dependent variable	Series 1	Series 2	Series 3	χ^2	*P* value
Maximum HR (bpm) Minimum	142 (15.5)^{a,b}	181 (13.0)^{a}	185 (9.3)^{a}	18.13	<0.001
HR (bpm)	112 (39.0)^{b}	150 (28.5)	153 (25.5)	12.81	.002
BLa concentration (mMol·L^{-1})	1.1 (1.3)^{b}	5.9 (2.6)^{b}	6.7 (2.8)	26.53	<0.001
Shot time (s)	1.4 (0.1)	1.3 (0.1)	1.2 (0.1)	5.32	.070
Shot score	7.2 (0.5)	7.0 (0.6)	7.2 (1.3)	.93	.711
Horizontal trace length (mm)	272.6 (16.9)	227.9 (21.1)	248.2 (42.0)	2.18	.403
Vertical trace length (mm) M-L	238.5 (16.8)	280.9 (31.1)	264.4 (13.3)	5.63	.062
range (mm)	5.4 (0.7)	6.4 (0.9)	5.2 (0.8)	.760	.714
A-P range (mm)	5.8 (0.4)	6.5 (1.6)	5.4 (0.6)	1.06	.607
M-L path length (mm)	5.6 (0.7)	5.5 (6.6)	5.9 (5.1)	.462	.866
A-P path length (mm)	1.7 (1.9)	1.8 (2.3)	1.9 (2.3)	4.76	.098

Notes: HR = Heart rate, BLa = Blood lactate.
M-L = Mediolateral, A-P = Anteroposterior.
^{a}Significant reduction in heart rate within series ($P < 0.05$).
^{b}Significant difference between series ($P < 0.012$).

Correlations between variables

When correlations were performed using group data, no variables presented significant associations with score in any series ($P > 0.007$). Thus, all further analysis focused on intra-individual correlations. Few participants demonstrated significant correlations between kinematic variables and score. Two participants presented significant negative correlations between score and horizontal trace length in series 3 (Participant 8: r −.970 $P < 0.007$; Participant 10: r −.753, $P < 0.007$). A third participant produced a significant negative correlation with shot time in series 2 (Participant 9: r −.882, $P < 0.007$). These variables accounted for between 57% and 88% of the changes in score. However, the same correlations were not apparent in any of the other series for these participants. No other participants produced any significant correlations with shot score.

Discussion

This study had 2 aims: to identify changes in shooting performance within each series and to identify differences in shooting performance between each series following each additional 1 km run phase. The first hypothesis was rejected, as the time remaining to complete each series appeared to have little impact on shooting performance. No significant changes were evident for shot time, score, pistol movement or body movement within any series. The hypothesis was based on the assumption that, as the time remaining to achieve 5 hits reduced, participants would shoot more quickly, thereby reducing aiming time and leaving less time to complete aiming routines. However, with no evidence of reduced shot times, a consistent time period was available in which pistol and centre of pressure movement could be reduced. Thus, the degree of pistol movement across the target was comparable for each shot within every series.

Furthermore, the second hypothesis was rejected, as score, pistol movement or centre of pressure movement did not change significantly between series. Thus, despite an increasing reliance on anaerobic metabolism throughout the event, shooting performance remained similar. Whilst these findings fail to support the hypothesis, they do support the previous combined event research of Le Meur et al.(2010), who reported no significant change in shooting suc-cess or time per shot for any series ($P > 0.05$). As such, shooting performance following 1 km series running appears similar to performances achieved following only 20 m of running.

A potential explanation for the similarities in shooting performance across the 3 series is the increase in arousal associated with exercise. In their analysis of fatigue and shooting performance, Nibbeling, Oudejans, Ubink, and Daanaen (2014) reported that an increase in arousal has the potential to reduce the effect of anxiety. Thus, in the com-bined event, an increase in arousal may be sufficient to counteract any decrements in performance resulting from exercise-induced fatigue. This theory is further supported by the review of Lambourne and Tomporowski (2010), who reported consistent findings of an increase in cognitive test performance following exercise. Thus, factors which may have produced anxiety in series 1 may prove less influential to performance in series 2 and 3.

A further implication of the similarities between series is that, when developing shooting technique, shooting training in isolation could be effective in addition to combined run and shoot training. This is an important consideration, as greater shooting accuracy – not running performance – has been suggested to determine the most successful athletes (Le Meur et al., 2010). Many shots taken by participants in the current study were not on target and, therefore, athletes who can shoot accurately will have a considerable advantage over many of their competitors.

A key finding of the current research is the limited effect of each running phase on pistol shooting performance. This differs considerably to the effect of exercise on biathlon shooting performance (Hoffman et al., 1992), and indicates that reducing exercise intensity immediately prior to shooting, as used by biathletes, may not be an effective strategy in the combined event. Shooting performance appears to remain consistent throughout the combined event, despite the reduction in heart rate within each shooting series. This may be unsurprising, given the different methods of hold for a pistol and a rifle, with the rifle more susceptible to other physiological changes, such as heart rate. This seems likely, following the findings of Brown et al. (2013), who reported that, in pistol shooting, heart rate was not significantly correlated with either shooting accuracy or precision. Consequently, modern pentathletes should develop their own strategies when attempting to enhance shooting performance.

The limited effect of each running phase on centre of pressure movement was surprising and in contrast to previous findings. Previous investigations into centre of pressure movement following exercise have consistently reported an increase following exercise ($P < 0.05$) (Bove et al., 2007; Hoffman et al., 1992; Nardone, Tarantola, Giordano, & Schieppati, 1997; Niinimaa & McAvoy, 1983). It should be acknowledged, however, that not all studies were based on shooting performance, such as the research of Bove et al. (2007) and Nardone et al. (1997). Thus, the demands of combined event shooting are likely to be sufficient to destabilise the centre of pressure, even after minimal exercise, beyond that which occurs for the quiet stance tasks used by previous research (Bove et al., 2007; Nardone et al., 1997). Centre of pressure movements in series 1 of the combined event are significantly greater than those produced for the slower, precision event ($P < 0.05$) (Dadswell et al., 2013). Thus, as movement is already elevated in comparison to more simple stance tasks, any additional increases following exercise will be less apparent than those observed for the more simple stances.

Shooting performance characteristics have been shown to be highly individual (Ball et al., 2003; Dadswell et al., 2013; Mason et al., 1990). To ensure group analysis did not over-look individual variation, a supplementary statistical analysis was conducted using data from 4 participants who required different numbers of shots to complete a series. Only 1 participant produced the expected decline in score with each series, and none demonstrated a significant increase in pistol or centre of pressure movements. Thus, neither group nor individual analysis provided support for the expected reduction in shooting performance following each 1 km run phase.

The individual data, whilst not producing any significant findings, did support the intra-individual analysis of shooting performance (Ball et al., 2003; Dadswell et al., 2013; Mason et al., 1990). The performance of some participants varied little between series, consistent with the findings of the group analysis. However, none of the participants selected for individual analysis displayed the same trend as the group median for all dependent variables. For instance, score decreased with every series for 1 participant, with a reduction of 2.5 points between series 1 and 3. Thus, the highly individual nature of combined event pistol shooting means that the group median will rarely reflect each individual's response to the shooting task. Coaches should be cautious, therefore, when applying the findings from purely group-based analyses.

Intra-individual correlations revealed few significant associations between score and kinematic variables in any series. This suggests that there may be other performance variables not considered here, such as the location of the aim point on the target, which must also influence performance. In addition, the format of the event means that, while some participants took up to 11 shots to complete a series, most only required between 6 and 8. Thus, few shots were available for correlations. Future research in which participants take a greater number of shots using the combined event shooting format could increase the likelihood of uncovering correlations between different variables. This would further enhance the understanding of the factors most critical to combined event shooting success. This would, however, require consideration of an appropriate method in which to maintain validity.

This study has revealed, for the first time, the limited effect of each running phase, and of the time remaining to complete each series, on combined event shooting performance. Whilst time pressures did not cause any changes in performance within each series, an additional consideration should be the success of other athletes during competition. However, the testing format required participants to shoot whilst standing on force plates. Consequently, each participant had to com-plete the trial individually, albeit with a significant and large audience, including the experimenters and other participants, present throughout all trials. All other technical aspects of the event were identical to those in competition, but future research in which participants could compete alongside other athletes would be useful to investigate direct competi-tion effects.

In conclusion, neither time constraints nor the effects of each running phase caused any significant changes in com-bined event shooting performance. These findings have poten-tial implications for training, with the possibility that shooting training in isolation may be effective in addition to the com-plete event format. Furthermore, these results have highlighted the unique performance requirements of the combined event in comparison to other shooting disciplines, such as biathlon. Consequently, modern pentathletes must establish unique methods to enhance shooting accuracy. This is important if athletes wish to enhance not only their combined event, but also overall competition performance. Finally, whilst both group and individual analyses failed to support the hypotheses, it was apparent that group analysis alone is not sufficient to reflect the combined event shooting performances of all individuals.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Ball, K. A., Best, R. J., & Wrigley, T. V. (2003). Inter- and intra-individual analysis in elite sport: Pistol shooting. *Journal of Applied Biomechanics*, *19*, 28–38.

Berrigan, F., Simoneau, M., & Martin, O. (2006). Coordination between posture and movement: Interaction between postural and accuracy constraints. *Experimental Brain Research*, *170*, 255–264.

Bove, M., Faelli, E., Tacchino, A., Lofrano, F., Cogo, C. E., & Ruggeri, P. (2007). Postural control after a strenuous treadmill exercise. *Neuroscience Letters*, *418*, 276–281.

Brown, M. J., Tandy, R. D., Wulf, G., & Young, J. C. (2013). The effect of acute exercise on pistol shooting performance of police officers. *Motor Control*, *17*, 273–282.

Dadswell, C. E., Payton, C., Holmes, P., & Burden, A. (2013). Biomechanical analysis of the change in pistol shooting format in modern pentathlon. *Journal of Sports Sciences*, *31*(12), 1294–1301.

Goonetilleke, R. S., Hoffman, E. R., & Lau, W. C. (2009). Pistol shooting accuracy as dependent on experience, eyes being opened and available viewing time. *Applied Ergonomics*, *40*, 500–508.

Heimer, S., Medved, V., & Spirelja, A. (1985). Influence of postural stability on sport shooting performance. *Kinezioliogija*, *17*(2), 119–122.

Hoffman, M. D., Gilson, P. M., Westenburg, T. M., & Spencer, W. A. (1992). Biathlon shooting performance after exercise of different intensities. *International Journal of Sports Medicine*, *13*, 270–273.

Lambourne, K., & Tomporowski, P. (2010). The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain Research*, *1341*, 12–24.

Le Meur, Y., Dorel, S., Baup, Y., Guyomarch, J. P., Roudaut, C., & Hausswirth, C. (2012). Physiological demand and pacing strategy during the new combined event in elite pentathletes. *European Journal of Applied Physiology*, *112*(7), 2583–2593.

Le Meur, Y., Hausswirth, C., Abbiss, C., Baup, Y., & Dorel, S. (2010). Performance factors in the new combined event of modern pentathlon. *Journal of Sports Sciences*, *28*(10), 1111–1116.

Mason, B. R., Cowan, L. F., & Gonczol, T. (1990). Factors affecting accuracy in pistol shooting. *Excel*, *6*, 2–6.

Mononen, K., Konttinen, N., Viitasalo, J., & Era, M. (2007). Relationships between postural balance, rifle stability and shooting accuracy among novice rifle shooters. *Scandinavian Journal of Medicine and Science in Sports*, *17*, 180–185.

Nardone, A., Tarantola, J., Giordano, A., & Schieppati, M. (1997). Fatigue effects on body balance. *Electroencephalography and Clinical Neurophysiology*, *105*(4), 309–320.

Nibbeling, N., Oudejans, R. R. D., Ubink, E. M., & Daanaen, H. A. M. (2014). The effects of anxiety and exercise-induced fatigue on shooting accuracy and cognitive performance in infantry soldiers. *Ergonomics*, *57*(9), 1366–1379.

Niinimaa, V., & McAvoy, T. (1983). Influence of exercise on body sway in the standing rifle shooting position. *Canadian Journal of Applied Sport Sciences*, *8*(1), 30–33.