KINEMATIC AND TEMPORAL ANALYSIS OF OVERARM THROWING IN FINNISH BASEBALL PLAYERS UNDER DIFFERENT INSTRUCTIONS

Peter Alway

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Department of Biology of Physical Activity

University of Jyväskylä

Supervisor: Janne Avela

ABSTRACT

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The velocity-accuracy trade-off in overarm throwing has been well studied, but has presented conflicting results. The cause of the velocity-accuracy trade-off is poorly understood. The present study therefore aimed: to determine if a velocity-accuracy trade-off exists in Finnish baseball players, and to determine if there was any difference in kinematics, timing of movements, and intra-subject movement variability between three different throwing instructions. Eight elite Finnish baseball players (mean age = 25.00yr, mean height = 1.82m, mean body mass = 86.65kg) threw 10 times in accuracy, velocity and combination instructions towards a 0.07m target, from a distance of 20m. A 3-D motion analysis system measured ball velocity and kinematics. Relative ball velocity significantly differed between groups (84.15%, 96.69% and 91.01% of maximum ball velocity, in accuracy, velocity and combination instructions respectively), while no significant differences were observed between groups in accuracy scores (total error = 52.18cm, 60.18cm and 54.54cm in accuracy, velocity and combination instructions respectively). A velocity-accuracy trade-off was not present, attributed to the demands of the sport, and the skill level of the participants. A trade-off between velocity and the task prioritization of accuracy was present. Great ball velocity when emphasizing accuracy questions the application of the velocity-accuracy trade-off in elite sports. No significant difference in movement variability and timing of maximum joint rotations between instructions suggests that technique is consistent across near-maximum and maximum throws. Further, this result suggests that the impulse-variability theory is too simplistic for complex multijoint movements. Multiple significant differences in kinematics were observed between instructions, suggesting that in greater velocity throws, concentric contractions of the shoulder are facilitated by increased use of the stretch shortening cycle.

Key words: Overarm Throwing, Velocity, Accuracy, Kinematics, Movement variability, Motor control, Timing

CONTENTS

1 INTRODUCTION

Overarm throwing, a complex, fast, discrete skill, is a critical component in many sports, including baseball, softball, Finnish baseball, cricket, handball, water polo and American football (Abernethy et al. 2013). Overarm throwing is divided into six main phases: wind-up, stride, arm cocking, arm acceleration, arm deceleration and follow-through (Fleisig et al. 2000). However, these phases differ depending on the sport. For example, in Finnish baseball, softball and cricket there is no wind up phase, instead replaced with a fielding and step phase (Fleisig, 2010; Cook & Strike, 2000).

The success of overarm throwing is defined by a combination of two performance outcomes: accuracy and ball velocity (BV) (Van den Tillaar & Ettema, 2003a). It has been suggested that accuracy and velocity cannot be optimized simultaneously, where accuracy peaks between 75-85% of maximum BV, and decreases with greater or reduced BV. This velocity-accuracy trade-off (VATO) has been observed in: untrained students (Indermill & Husak, 1984), novice, sub-elite and elite dart players (Etnyre, 1998), elite and sub-elite cricketers (Freeston et al. 2007; Freeston & Rooney, 2014), elite baseball players (Freeston & Rooney, 2014; Freeston et al. 2015), and novice handball players (Garcia et al. 2013). However, no VATO was observed in novice (Van den Tillaar & Ettema, 2006) and elite handball players (Van den Tillaar & Ettema, 2003a; Van den Tillaar & Ettema, 2006), and skilled and unskilled participants (Urbin et al. 2012). The VATO phenomenon has been described in a range of populations, but not in Finnish baseball. Little is known, however, about the underlying mechanisms of the VATO.

The finding of a VATO opposes a popular theory in motor control, the impulse-variability theory. This theory suggests that movement variability increases linearly with force production up until 65% of maximum force, at which point a linear decrease in movement variability is observed to maximum force (Sherwood & Schmidt, 1980; Schmidt & Sherwood, 1982). Therefore, greatest accuracy should occur at maximum force, however, no such results have been recorded. Increased inaccuracy of throwing at greater BV is suggested to be related to the launch window hypothesis, where increased

BV of the throw reduces the time in which ball release (BR) must occur to achieve the accuracy goal (Calvin, 1983; Freeston et al. 2015). A window of < 0.002s has been observed to achieve 'very great' accuracy (Fleisig et al. 2009a, Chowdhary & Challis, 1999), therefore, movement variability must be minimized to achieve optimal timing of release. Alternatively, the VATO could be explained through functional movement variability, where movements at distal joints compensate for proximal movement errors (Bernstein, 1967, Bootsma & Van Wieringen, 1990, Bartlett, 2007), explaining why accuracy is greatest between 75-85%. The greater movement time of lower velocity throws (Fleisig et al. 2009a), could give greater time for the sensorimotor system to unconsciously position distal limbs, or alter the timing of release, in response to proximal movement errors (Urbin, 2012), resulting in an increase in accuracy.

Great BV is characterized by optimal throwing mechanics. Several studies have reported on the relationship between BV and throwing mechanics in baseball and handball. Results from these studies display that, at the knee, between 38 degrees of flexion is optimal at front foot contact (FFC) (Werner et al. 2008; Stodden et al. 2005; Fleisig et al. 2006; Escamilla et al. 2007), while a more extended knee at BR contributes to BV (Werner et al. 2008, Escamilla et al. 2002). Further throwing mechanics that contribute to BV include: maximum pelvis angular velocity (AV) (Stodden et al. 2001; Wagner et al. 2011; Escamilla et al. 2002; Fleisig et al. 1999), maximum trunk rotation AV (Stodden et al. 2001; Werner et al. 2008; Wagner et al. 2011), greater trunk flexion at BR (Stodden et al. 2005, Werner et al. 2008; Matsuo et al. 2001), greater shoulder horizontal abduction at FFC (Escamilla et al. 2001; Escamilla et al. 2002), greater external rotation at FFC (Escamilla et al. 2001; Escamilla et al. 2002), greater internal rotation at BR (Wagner et al. 2011, Whiteley, 2007), maximum elbow flexion, greater elbow flexion at FFC (Werner et al. 2008; Roach et al. 2013), maximum elbow extension AV (Wagner et al. 2011), and greater stride length (Montgomery & Knudson, 2002). Additionally, the timing of maximum AVs (Matsuo et al. 2001; Aguinaldo et al. 2007) must be optimised through rapid, sequential activation of many muscles, starting in the legs and progressing through the hips, trunk, shoulder, elbow and wrist, to attain maximum BV (Dillman et al. 1993; Matsuo et al. 2001; Aguinaldo et al. 2007; Hirashima et al. 2002). No study to date has attempted to quantify kinematics or temporal variables when throwing under different instruction, and the effect that they may have upon accuracy of overarm throws.

The aim of this experiment is three-fold. Firstly, to determine if there is a VATO in elite Finnish baseball players. Secondly, to determine the kinematic and temporal differences of throwing under different instructions. Finally, to analyse movement variability of kinematic and temporal variables that contribute to BV and accuracy. These variables are measured to attempt to provide explanation for the VATO in overarm throwing.

2 PHASES OF OVERARM THROWING

2.1 Fielding phase

To execute an overarm throw, the fielder must align himself to catch the ball, off the ground or in the air, typically with two hands, and generate momentum towards the ball. The feet are positioned either side of the ball so that the athlete's trunk is perpendicular to the target for the following phases of the throw (Fleisig, 2010, Figure 1a).

2.2. Step phase

After fielding the ball, the fielder steps or skips towards the target so that the back foot is closer to the target than the front foot (Fleisig, 2010, Figure 1b).

FIGURE 1. The phases of throwing: A) Fielding phase B) Step Phase C) Stride Phase D) Arm-Cocking Phase E) Arm Acceleration F) Arm Deceleration G) Follow Through. Taken from Fleisig, 2010.

2.3. Stride phase

The athlete lowers the centre of gravity through eccentric contraction of the stance leg hip flexors, and strides his leading leg (stride leg) towards the target to generate linear velocity (Dillman et al. 1993, Fleisig et al. 1998), initiated by stance leg hip adduction, and further enhanced through knee and hip extension (Weber et al. 2014). Hip abductors isometrically contract to maintain a level pelvis (Fleisig et al. 1998). Meanwhile, the back (stance) foot remains in contact with the ground (Fleisig, 2010), in slight knee flexion through isometric quadriceps contraction (Weber et al. 2014). While the stride leg is still in mid-air, the stride hip begins to externally rotate, while the stance hip internally rotates (Weber et al. 2014). The stance leg continues to extend through eccentric contraction of the hip extensors (Weber et al. 2014), and hip flexion in the stance leg is maintained through eccentrically and isometrically contracting the hip extensors (Fleisig et al. 1998). The trunk and upper body rotate greater than 90 degrees, in coordination with flexion and elevation of the leading leg (Dillman et al. 1993), which is a result of concentric activation of the rectus femoris, pectineus, iliopsoas and sartorius (Fleisig et al. 1998). Following this, the athlete separates his hands and swings them down, apart, and up through shoulder external rotation, and horizontal abduction, initiated by the contractions of the deltoid and supraspinatus (Fleisig et al. 1996b, a selection of upper body muscle activity can be found in figure 2). Serratus anterior and upper trapezius contracts to bring the scapula into internal rotation (scapular protraction), anterior tilt (scapular forward tilt), and upward rotation (scapular lateral rotation), necessary to initiate the upcoming phases of throwing (Meyer et al. 2008). The trunk continues to extend away from the target while the torso begins to rotate towards the target (Dillman et al. 1993, Keeley et al. 2008). The elbow begins to flex, controlled by eccentric and isometric contractions of the elbow flexors (Fleisig et al. 1996b), and the wrist hyperextends (Fleisig et al. 2000). The phase ends with the knee flexing to absorb the impact of FFC (Giodano & Limpisvasti, 2012, Figure 1c). At the moment when the stride leg impacts the ground, the throwing arm should be in a semi-cocked, abducted position (Dillman et al. 1993), as this position is of optimal potential energy as the thrower's body is maximally stretched, creating elastic-like energy (Weber et al. 2014). The stance leg, stride leg, and target should all be in line with one another, and the stride distance should be approximately the same length as the athlete's height (Dillman et al. 1993; Eckenrode et al. 2012).

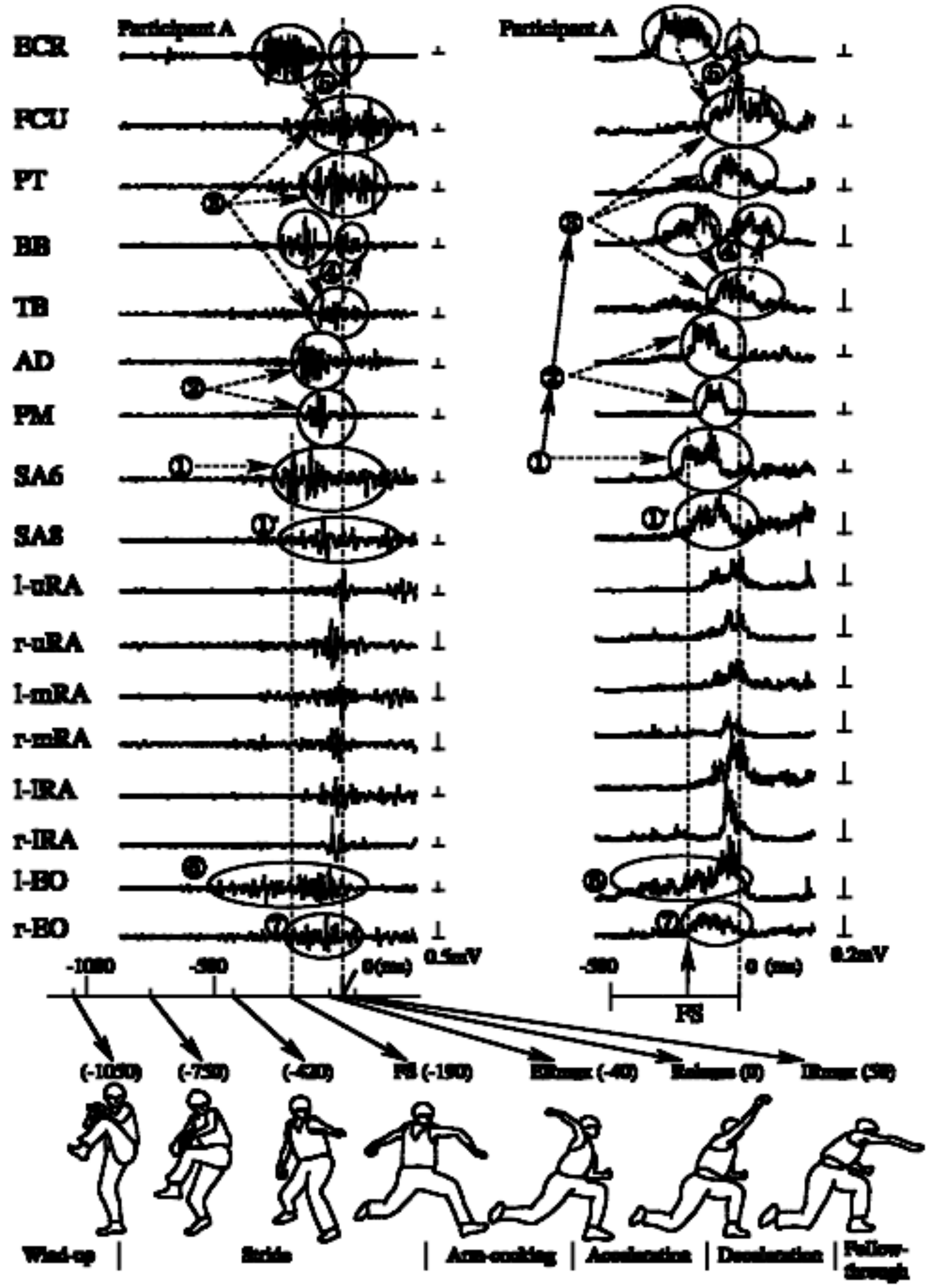

FIGURE 2: High pass filtered (left) and rectified and averaged (right) EMGs of: extensor carpi radialis (ECR), flexor carpi ulnaris (FCU), pronator teres (PR), biceps brachii (BB), lateral head of the triceps brachii (TB), anterior deltoid (AD), pectoralis major (PM), serratus anterior (6th rib, SA6 and 8th rib, SA8), and left and right upper (uRA) middle (mRA) and lower (lRA) parts of the rectus abdominis, and external obliques (EO) during a baseball pitch. FS = footstrike. Taken from Hirashima et al. 2002.

2.4. Arm cocking phase

Following FFC, knee flexion decelerates, aided by eccentric quadriceps contractions, then isometric contractions to stabilize the stride leg (Fleisig et al. 1996b). As the stride leg flexes, the centre of gravity lowers (Weber et al. 2014). The pelvis maximally rotates towards the target and is swiftly followed by lumbar spine hyperextension and trunk maximum rotation towards the target (Fleisig et al. 2000; Fleisig et al. 1996b). The pelvis and the trunk rotation put the abdominal and oblique muscles on stretch (Fleisig et al. 1996b) and the trunk begins to flex towards the target (Fleisig, 2010). As the trunk begins to accelerate towards the target, the positioning of the shoulder, with maximum external rotation, horizontal abduction, abduction, along with the elbow flexion (figure 1d), increases the mass moment of inertia around the long axis of the humerus, causing the forearm and wrist to lag behind the accelerating torso (Roach et al. 2013; Fleisig et al. 1994; Dillman et al. 1993; Pappas et al. 1985; Werner et al. 1993; Fleisig et al. 1998; Hess et al; 2005; Fleisig et al. 2000). The flexed elbow enables passive inertial forces to counter-rotate the arm, stretching the tendons, ligaments, and elastic components of muscles which cross the shoulder, storing elastic energy in the large cross-sectional areas of these elastic structures (Roach et al. 2013).
At maximum external rotation and maximum horizontal adduction, the extreme rotational AV on the shoulder during arm cocking creates larges forces and torques, of up to 770N on the shoulder (Fleisig et al. 1995, Feltner & Dapena, 1986), which are balanced by muscle contractions of the rotator cuff muscles around the shoulder, providing stability to the joint (Hess et al. 2005; Weber et al. 2014). The first rotator cuff muscle activated during arm cocking is subscapularis, occurring 50ms before external rotation is initiated (Hess et al. 2005, a summary of shoulder muscularate activity can be found in Table 1), likely due to improved shoulder joint stability and increasing the tension in the middle and inferior shoulder ligaments (Keeley et al. 2008). This is followed by eccentric contractions of latissimus dorsi and pectoralis muscles to further decelerate the shoulder joint (Fleisig et al. 1994; Glousman et al. 1988; Gowan et al. 1987; Digiovine et al. 1992). Simultaneously, infraspinatus and teres minor muscles also contract to increase joint stability, through decreasing the anterior translation of the humeral head as the shoulder approaches maximum external rotation (Jobe et al. 1983; Cain et al. 1987). The combination of muscle force and passive

restraints produce torques of up to 80Nm of internal rotation, and 100Nm of horizontal adduction to resist posterior translation of the arm, and keep the throwing arm moving forward with the trunk (Fleisig et al. 1995; Feltner & Dapena, 1986).

TABLE 1: Shoulder activity (% maximum voluntary isometric contraction) by muscle and phase during overarm throwing (adapted from DiGiovine et al. 1992)

	Phase				
Muscle	**Stride**	**Arm-cocking**	**Arm acceleration**	**Arm deceleration**	**Follow-through**
Upper trapezius	64	37	69	53	14
Middle trapezius	43	51	71	35	15
Lower trapezius	39	38	76	78	25
Serratus anterior (6th rib)	44	69	60	51	32
Serratus anterior (4th rib)	40	106	50	34	41
Rhomboids	35	41	71	45	14
Leavtor scapulae	35	72	76	33	14
Anterior deltoid	40	28	27	47	21
Middle deltoid	44	12	36	59	16
Posterior deltoid	42	28	68	60	13
Supraspinatus	60	49	51	39	10
Infraspinatus	30	74	31	37	20
Teres minor	23	71	54	84	25
Subscapularis (lower 3rd)	26	62	56	41	25
Subscapularis (upper 3rd)	37	99	115	60	16
Pectoralis major	11	56	54	29	31
Latissimus dorsi	33	50	88	59	24
Triceps branchii	17	37	89	54	22
Biceps Branchii	22	26	20	44	16

At maximum external rotation and horizontal abduction, the scapula is positioned with maximum external rotation, upward rotation, and maximum posterior tilt (Meyer et al. 2008). The scapular rotation is critical for maintaining adequate subacromial space, and preventing dynamic outlet impingement, as the throwing shoulder and humerus are elevated at this moment in the throwing motion. Scapular rotation is enabled by activation of the levator scapulae, serratus anterior, trapezius, rhomboids, and pectoralis minor muscles (Dillman et al. 1993; Fleisig et al. 1999; Kibler, 1998). To conclude the arm cocking phase, the legs, hips, and trunk have complete their acceleration (Dillman et al. 1993). The distal limbs are in position to begin their acceleration towards the target as a result of the shoulder being at maximum external rotation, aided by scapulothoracic rotation and lumbar hyperextension (Dillman et al. 1993).

Elite throwers experience a critical moment at maximum external rotation, due to the tremendous force imparted on the shoulder joint (Fleisig et al. 1995), which is implicated in the pathologic and adaptive changes associated with the shoulder and the elbow (Burkhart & Morgan, 1998; Kibler et al. 2013; Ryu et al. 2003). The adaptive changes of repetitive overarm throwing occur as a result of an increase in shoulder external rotation, and a decrease in shoulder internal rotation, while maintaining the rotational range of motion seen in the contralateral shoulder (Burkhart et al. 2003; Chant et al. 2007; Crockett et al. 2002; Drakos et al. 2010; Myers et al. 2009; Reagan et al. 2002). The gain in shoulder external rotation with a loss of internal rotation is an adaptive change resulting from alterations in bony (Crockett et al. 2002; Reagan et al. 2002; Meister et al. 2005) capsuloligamentous (Burkhart et al. 2003; Thomas et al. 2011) and muscular (Proske & Morgan, 1999; Whitehead et al. 2001) structures in and around the shoulder, facilitating greater BV and accuracy (Kibler et al. 2013; Burkhart et al. 2003). However, when the shoulder internal rotation deficit is greater than 20 degrees, the adaptive change alters the shoulder kinematics and increases the risk of injury at the shoulder and the elbow (Burkhart et al. 2003; Dines et al. 2009; Wilk et al. 2011). The increase in shoulder external rotation has been attributed to superior labrum anterior to posterior tears (Kuhn et al. 2003; Pradhan et al. 2001; Shepard et al. 2004), rotator cuff impingement, and partial articular-sided rotator cuff tears (Ryu et al. 2002; Jobe, 1995; Walch et al. 1992). The critical moment of maximum external rotation at the shoulder also places great valgus torque on the elbow (Fleisig et al. 1995; Werner et al. 1993; Aguinaldo & Chambers, 2009; Glousman et al. 1992), which can be exacerbated by early trunk rotation, increased maximum external rotation and decreased elbow flexion (Aguinaldo & Chambers 2009). The increased valgus stress at the elbow can result in tensile force on the medial elbow, causing attritional changes to the ulnar collateral ligament, compressive force on the radiocapitellar joint (which can result in osteochonral damage), and shear force on the posterior compartment of the elbow leading to chondromalacia and osteophyte formation (Fleisig et al. 1995; Ahmad et al. 2004; Takahara et al. 2008).

2.5. Arm acceleration

The arm acceleration phase begins at maximum external rotation of the shoulder. The elbow rapidly extends and is swiftly followed by the shoulder rapidly internally rotating (Fleisig, 2010). Rapid internal rotation of the shoulder is caused by concentric contractions of the triceps, pectoralis major, latissimus dorsi and serratus anterior, which reverses their antagonistic activity observed in the arm cocking phase (Jobe et al. 1983). The gap in time between onset of elbow extension and internal rotation of the shoulder allows the athlete to decrease the arm's rotational resistance about the longitudinal axis, permitting the stretched structures of the shoulder to recoil, releasing their stored elastic energy, resulting in an increased magnitude of shoulder internal rotational AV, and therefore greater BV (Roach et al. 2013; Fleisig et al. 2009b; Dillman et al. 1993). These AVs can be up to 8000 degrees per second (Dillman et al. 1993; Fletner & Dapena, 1986; Pappas et al. 1985; Fleisig et al. 1999). The shoulder horizontally adducts from approximately 20 degrees at maximum external rotation, to 9 degrees at BR, as a result of the elbow being positioned slightly in front of the trunk at maximum external rotation, and the hand moving forward during arm acceleration, forcing the elbow backwards (Fleisig et al. 2009b). At BR, the combination of shoulder abduction and lateral trunk tilt creates the "arm slot," usually positioned at approximately 90 degrees of shoulder abduction at BR, which maximizes functional stability (Poppen & Walker, 1978), and reduces load upon the throwing arm (Matsuo et al. 2002). Throughout arm acceleration, the lead knee extends to allow the trunk to rapidly move from a hyperextended position to a forward flexed position as the throwing arm accelerates (Fleisig et al. 1995). This combination of movements to maximize the efficiency of the kinetic chain coincides with BR, where the wrist and fingers are rapidly flexed (Fleisig et al. 2000, Figure 1e).

2.6. Arm deceleration

After BR, the throwing arm horizontally adducts across the torso as the shoulder continues to internally rotate to maximum (Dillman et al. 1993). The trunk continues to flex towards the target, and the elbow maximally extends, potentially even hyper-extending (Fleisig, 2010). Great eccentric loads are needed to decelerate the shoulder and the elbow. The large internal rotation torque on the shoulder joint is countered by contraction of the rotator cuff external rotators (infraspinatus and teres minor, Weber et al. 2014). These contractions, coupled with the posterior capsule are responsible for limiting excessive anterior humeral translation in relation to the glenoid (Fleisig et al. 1995; Dillman et al. 1993). The force required to decelerate the throwing arm may be up to 1200N (Fleisig et al. 1995; Feltner & Dapena, 1986). To resist horizontal adduction and decelerate the arm, a posteriorly directed shoulder force of 400N is also required (Fleisig et al. 1995). Further, the shoulder passive restraints also create a horizontal abduction torque to resist anterior translation of the humerus in relation to the glenoid (Fleisig et al. 1995). The passive restraints in conjunction with the shoulder musculature also resist abduction and superior humeral head translation, through producing adduction torque, and a maximum inferiorly directed force (Fleisig et al. 1995). Deceleration of elbow extension is facilitated by eccentric contraction of the elbow flexors (Weber et al. 2014). The scapula de-rotates from an upward position and returns to an anteriorly tilted position as the arm decelerates (Meyer et al. 2008). The knee continues to extend throughout this phase (Fleisig et al. 2000, Figure 1f).

2.7. Follow-through

The trunk continues to flex towards the target until the maximum level over the stride leg, which extends until it is straight, enhancing stability (Fleisig et al. 2000; Weber et al. 2014). The stance leg is brought to the ground also, for further stability (Fleisig et al. 1996b). The throwing shoulder continues to decelerate, through eccentric contractions of the deltoid and rotator cuff muscles (Digiovine et al. 1992). Further, deceleration of the scapula also occurs through eccentric contractions of the serratus anterior, middle trapezius and rhomboids (Digiovine et al. 1992). In addition, the elbow and forearm are decelerated by biceps contraction (Weber et al. 2014). When the athlete is in a balanced position, the skill is complete (Fleisig et al. 2000, Figure 1g). The deceleration and follow through phases are critical to preventing overuse injuries at the posterior arm or trunk (Fleisig et al. 1995; Fleisig et al. 1996b), as the energy created to accurately and forcefully throw the projectile must be dissipated safely (Weber et al. 2014).

3 SEQUENTIAL PATTERN OF THROWING

It is critical to overarm throwing performance that the movement is performed in a specific, coordinated, sequential motion, with correct timing of movements, including acceleration and deceleration of joints. This allows a smooth, efficient flow of kinetic energy, from heavier, stronger proximal joints, to smaller, distal joints (Hirashima et al. 2002), (except internal shoulder rotation occurring after elbow extension, Wagner et al. 2012b), using joint torques, velocity-dependent torques, centrifugal or Coriolis forces to enhance BV (Joris et al. 1985; Herring & Chapman, 1992; Putnam, 1993; Hirashima et al. 2008). The optimum transfer of forces to the distal segment occurs when the proximal segment is at its maximum AV, thus allowing greater kinetic energy to be transferred via angular momentum with each transfer, ultimately resulting in greater BV (Putnam, 1991; Neal et al. 1991; Herring & Chapman, 1992; Hirashima et al. 2007). The great AVs of the elbow and the wrist at BR are a result of elbow extension and wrist flexion being driven primarily by velocity-dependent forces, generated by trunk rotation and shoulder internal rotation (Hirashima et al. 2008). Additionally, wrist flexion is further aided by elbow extension. Effective synchronous activity of specific muscle groups maximizes the efficiency of the kinetic chain (Seroyer et al. 2010; Fleisig et al. 1994, Fleisig et al. 1998, Kibler, 1998). In the shoulder girdle and the upper extremity this can be observed, as the serratus anterior (6^{th} rib), serratus anterior (8^{th} rib), anterior deltoid, pectoralis major, triceps branchii, pronator teres and flexor carpi ulnar is activate in sequence (Hirashima et al. 2002). The proximal to distal chain can utilize the stretch shortening cycle (SSC) of muscle groups between adjacent segments. As the proximal segment accelerates, the distal segment lags behind, eccentrically stretching the muscle group between the two segments, thus facilitating greater concentric contraction (Bosco & Komi, 1979; Komi & Gollhofer, 1997). For example, the non-throwing external oblique activates sooner than the throwing external oblique, as it prevents the trunk rotating together with the pelvis and stretches a large number of muscles in the trunk (Hirashima et al. 2002).

4 VELOCITY ACCURACY-TRADE OFF

The VATO is an important application of Fitts' Law (1954), which describes an inverse relationship between the speed of a movement, and the accuracy of the movement. In overarm throwing, the VATO is an important factor in determining the success of overarm throws, suggesting that increases in BV result in improved performance until a critical BV is reached, at which point further increases in BV result in a decrease in throwing accuracy (Freeston et al. 2007). Recent studies, however, conflict with the VATO in overarm throwing.

Research by Indermill & Husak (1984) suggested that when throwing, the VATO was an inverted U. The authors divided undergraduate students into 3 velocity conditions: 50%, 75% and 100% of maximum BV. Participants were instructed to throw 12.19m at an archery target and distance was measured from the centre of the target. Results found that 75% of maximum BV was the most accurate (Table 2). The result was attributed to the learning effect, the authors suggesting that, as most practice had occurred at 75%, accuracy was greatest at this level. In addition, the authors suggest that throws of 100% suffer reduced accuracy as a result of disproportionate firing of muscles (Indermill & Husak, 1984).

Similar findings to Indermill & Husak (1984) were found in beginner, intermediate and advanced dart players, who were instructed to throw with normal force and to throw at maximum force at a standard dartboard bullseye (Etnyre, 1998). Results found that maximum BV reduced accuracy, demonstrating a VATO (Table 2). Furthermore, the author suggested that increased projectile release timing errors, related to significantly greater variability measured in maximum force throws caused the decrease in accuracy (Etnyre, 1998).

Freeston et al. (2007) found similar results to Indermill & Husak (1984) when the authors studied the VATO in 110 elite, sub-elite and youth male cricketers. The participants were asked to throw cricket balls 20.12m at one cricket stump, surrounded by five 0.14m zones, so throws could be measured for accuracy. Participants were asked to throw 10 times at 50%, 75%, 100% and a self selected BV. Results displayed greater accuracy between 75-85% of the participants' maximum throw, but were not always significant (Freeston et al. 2007, Table 2). The authors suggested accuracy was enhanced through a greater volume of training at their self selected BV, compared with other BV.

TABLE 2. Summary of literature of the velocity-accuracy trade-off. * denotes significantly different to 50%, ** denotes significantly different to 100%, *** significantly different to 50% and 100%.

Study	Accuracy method	Population	Ball velocity 50%	75%	100%	Self - selected
Indermill & Husak, 1984	Zoned point system	Undergraduates	1.79	2.33***	1.73	
Etnyre, 1998	Total error (cm)	Beginner darts			14.87	8.68**
		Intermediate darts			11.24	6.8**
		Advanced darts			8.54	4.04**
	Variable error (cm)	Beginner darts			6.5	3.60**
		Intermediate darts			4.71	2.86**
		Advanced darts			4.01	1.97**
Freeston et al. 2007	Inverse zoned point system	Elite male cricket	18	14	20	13*
		Sub-elite male cricket	26	21	22	20**
		Elite u19 male cricket	24	21	23	18*
		Elite u17 male cricket	22	20	24	19
		Elite female cricket	24	22	22	19
		Elite u19 female cricket	33	22*	25*	23*

Freeston & Rooney (2014) studied 20 baseball pitchers and 20 cricket players throwing over 20.00m at a cricket stump (0.71 x 0.04m) with a cricket ball, at both 80% and 100% of maximum BV. Accuracy was reported as the total error, horizontal and vertical error, absolute constant error (a measure of bias, ACE) and variable error (a measure of consistency). Total error and horizontal error was found to be significantly reduced at 80% of maximum BV than at 100% maximum BV in both cricketers and baseball players (Table 3). Further, ACE, variable error, and vertical error were significantly lower in cricketers, but not baseball players, when throwing at 80% of maximum throwing BV. A second study was also conducted, only using the baseball players, where the participants threw towards a 0.07m diameter circular target, positioned 0.70m above the ground, from 20.00m away. Ten throws were performed at 70%, 80%, 90% and 100% of maximum BV. Linear regression showed a significant speed effect with total error, horizontal error, and ACE, increased significantly with increases in speed between 70% and 100% of maximum BV. Further analysis revealed that ACE increased significantly between 70 and 90% of maximum BV, while variable error increased significantly between 90% and 100% of maximum BV (Table 3). The authors attributed the increased total error at 100% BV to errors in the timing of BR, in addition to the increase in lateral trunk movement, which potentially shifts the hand path.

In a study of 9 elite junior baseball players throwing 20.00m, Freeston et al. (2015) found a significant VATO between 80% and 100% of maximum throwing BV, when throwing at a 0.07m target. Greater BV displayed a significantly greater total error and average constant error (Table 3). Significantly increased vertical error was observed rather than in the horizontal direction during maximum throwing, which was also observed in sub-elite baseball and cricket players (Freeston & Rooney, 2014). The increase in vertical error when throwing at maximum 100% was attributed to a decreased launch window, increasing the number of BR timing errors, and is suggested to be the cause of the VATO (Freeston et al. 2015).

Van den Tillaar & Ettema (2003a) studied the VATO in 9 elite male handball players throwing 7.00m, at a 0.50 x 0.50m target. The participants were instructed to throw in 5 different instruction conditions: maximum BV, maximum BV and try to hit the target, hit the target and throw as fast as possible, hit the target and try to throw as fast as possible, and hit the target. Results found that when accuracy was emphasized (‘hit the target’ condition), BV was 85% of the maximum BV, however, no significant differences were observed between instructions (Table 3). The authors explained that elite players may have optimized their overarm throwing technique, and overcome the VATO, suggesting that no VATO exists in elite performers (Van den Tillaar & Ettema, 2003a).

TABLE 3. Summary of literature of the velocity-accuracy trade-off. * denotes significantly different to 90% ** denotes significantly different to 100%

			Ball velocity			
Study	**Accuracy Method**	**Population**	**70%**	**80%**	**90%**	**100%**
Freeston & Rooney 2014	Total error (cm)	Elite baseball		34**		39
		Elite cricket		37**		52
	Horizontal error (cm)	Elite baseball		9**		15
		Elite cricket		5**		16
	Vertical error (cm)	Elite baseball		28		29
		Elite cricket		34**		44
	Variable error (cm)	Elite baseball		41		45
		Elite cricket		41**		53
	ACE (cm)	Elite baseball		16		19
		Elite cricket		17**		29
Freeston & Rooney 2014	Total error (cm)	Elite baseball	49	53	57	60
	Horizontal error (cm)		27	31	29	33
	Vertical error (cm)		35	36	42	44
	Variable error (cm)		42	43	43**	51
	ACE (cm)		23*	30	36	34
Freeston et al. 2015	Total error (cm)	Elite baseball		50**		68
	Horizontal error (cm)			34		31
	Vertical error (cm)			34**		54
	Variable error (cm)			40		49
	ACE (cm)			31**		48

Additionally, research by Van den Tillaar and Ettema (2006) also suggested that the VATO is not present in elite and novice handball players, discovering that accuracy was maintained regardless of BV, agreeing with the findings of Van den Tiillar (2003a). The participants were instructed to throw 7.00m at a 0.50m x 0.50m target, with the same set of instructions seen in Van den Tillaar & Ettema (2003). Similar to the findings of Freeston (2007), Indermill & Husak (1984), Etnyre (1998) and Van den Tillar (2003a), when accuracy was prioritized, accuracy was measured at 85% of maximum in both experts and novices, however, when BV was increased, accuracy did not significantly differ, conflicting with the VATO (Table 4). The authors suggested that there is a trade-off between velocity and task prioritization of accuracy, as there was a reduction in BV when accuracy was emphasized in both elite and novice groups. The authors further suggested that the characteristics of the task, rather than the skill level of the athlete, govern the lack of the appearance of the VATO in overarm throwing (Van den Tillaar &

Ettema, 2006). The absence of a VATO at great BV was attributed to the impulse-variability theory, as force tasks have shown greatest, most consistent and least variability in accuracy at near maximum force generation (Sherwood & Schmidt, 1980).

TABLE 4. Summary of literature of the velocity-accuracy trade-off when throwing under different instruction (A=Accuracy, Av = emphasis on accuracy, AV = equal emphasis on accuracy and BV, Va = emphasis on velocity). * denotes significantly different to A

			Instruction			
Study	**Accuracy method**	**Population**	**A**	**Av**	**AV**	**Va**
Van den Tillaar & Ettema, 2003a	Total error (cm)		29	29	28	33
	Variable error (cm)	Elite handball	26	23	26	29
	ACE (cm)		16	16	11	17
Van den Tillaar & Ettema, 2006	Total error (cm)		29	29	28	33
	Variable error (cm)	Elite handball	26	23	26	29
	ACE (cm)		16	16	11	17
	Total error (cm)		42	46	40	50
	Variable error (cm)	Novice handball	39	43	38	42
	ACE (cm)		23	19	20	22
Garcia et al. 2013	Total error (cm)		35			35
	Variable error (cm)	Elite handball	44			44
	ACE (cm)		15			16
	Total error (cm)		50			62*
	Variable error (cm)	Novice handball	79			91*
	ACE (cm)		35			37

Garcia et al. (2013) studied the VATO in 18 elite and 24 novice handball players. The players were instructed to throw two series of 10 throws 7.00m, at 10 0.40m x 0.40m targets positioned within the goal. In the first series, participants were instructed to throw with an emphasis on accuracy, and in the second series were instructed to throw as hard as possible whilst maintaining accuracy. In the accuracy instruction, elite players attained 76% of maximum BV, while novices attained 70%. In the speed instruction, elite players attained 93% of maximum BV, while novices attained 92%. The authors discovered that there was significant difference between the two BV conditions in both ability groups, similar to previous research (Van den Tillaar & Ettema, 2003a; Van den Tillaar & Ettema, 2006). No significant difference was observed in experts' accuracy scores when throwing in the speed instruction, agreeing with the findings of Van den Tillaar & Ettema (2003) and Van den Tillaar & Ettema

(2006), while novice performers' accuracy scores were significantly reduced when BV was increased, conflicting with the findings of Van den Tillaar & Ettema (2006) and suggesting a VATO exists in novice performers (Table 4). The authors attributed the lack of VATO in elite athletes to impulse-variability theory, and attributed the VATO in novices due to the multi-targeted nature of the task.

5 KINEMATIC VARIABLES ASSOCIATED WITH BALL VELOCITY

5.1 The knee

Knee flexion at FFC has been found to significantly contribute to BV in college baseball pitchers (Werner et al. 2008), through absorbing ground reactions forces upon impact (Matsuo et al. 2001). Optimum values for knee flexion at FFC are 38-50 degrees, stabilizing the front leg for trunk rotation and flexion (Stodden et al. 2005; Fleisig et al. 2006; Escamilla et al. 2007). However, these findings were not replicated in handball players (Van den Tillaar & Ettema, 2007), within baseball players (Stodden et al. 2005), or between international and elite and college baseball pitchers, despite there being significant differences in BV's between pitchers (Escamilla et al. 2001; Escamilla et al. 2002; Fleisig et al. 1999; Kageyama et al. 2014), likely due to the similarities in ability (Table 5). Inadequate knee flexion at BR can cause poor force generation, and create instability. Instability can compromise energy transfer to the distal kinetic chain, which can cause a decrease of throwing velocity and/or accuracy, and contributes to overuse injuries in the shoulder and the elbow (Eckenrode et al. 2012; Anderson & Alford, 2010; Patel et al. 2013; Fleisig et al. 1995; Fleisig et al. 1996b).

Decreased knee flexion at BR has also been found to significantly contribute to BV in college baseball pitchers, throwing 15 metres (Werner et al. 2008). Additionally, significantly less knee flexion at BR was also observed in American baseball pitchers when being compared to South Korean baseball pitchers, and between high and low baseball pitchers (Escamilla et al. 2002; Kageyama et al. 2014). Further, greater knee extension AV has been observed in high-BV pitchers compared with low-BV pitchers (Matsuo et al. 2001; Kageyama et al. 2014). A more extended knee at BR contributes to greater trunk flexion at BR, resulting in improved potential energy flow in the kinetic chain as the body accelerates over the front leg (Werner et al. 2008). However, no significant correlation was found between knee flexion at BR and BV in handball players (Van den Tillaar & Ettema, 2007). Further, no significant differences were observed between international baseball pitchers, or between elite and college baseball pitchers, despite significant differences in BV (Escamilla et al. 2001; Fleisig et al. 1999, Table 5).

TABLE 5. Summary of literature of BV and knee angle/AV at FFC & BR. * Significant differences between groups *** Significantly correlated towards ball velocity

Study	Sport (Baseball unless stated otherwise)/ Ability	BV (m/s)	Knee angle/AV FFC (°)	BR (°)	Max extension AV (°/s)
Matsuo et al. 2001	High-BV pitcher	38*			-243*
	Low-BV pitcher	33			-124*
Stodden et al. 2001	Elite pitcher	35			
Stodden et al. 2005	Elite pitcher	35	41		
Werner et al. 2008	College pitcher	35	47***	58***	
Escamilla et al. 2001	Australian pitcher	36*	64	67	
	Italian pitcher	36*	61	62	
	Dutch pitcher	35*	68	67	
	Japanese pitcher	37	63	66	
	S. Korea pitcher	37	65	65	
	USA pitcher	39*	63	60	
	Cuban pitcher	39*	67	67	
	Nicaragua pitcher	36	58	66	
Escamilla et al. 2002	USA pitcher	38*	49	32*	
	Korean pitcher	35*	50	48*	
Wagner et al. 2011	Elite handball	24			
Fleisig et al. 1999	High-BV pitcher	35*	48	39	
	Low-BV pitcher	37*	46	38	
Escamilla et al. 2007	Elite pitcher	35	47	41	
Van den Tiillar & Ettema, 2007	Elite handball	22		42	-299
Van den Tillaar & Cabri, 2012	Elite handball	21			
Fleisig et al. 2011	Elite pitcher	37	47	37	
	Elite 33m throw	37	46	36	
Escamilla et al. 1998	Elite pitcher	35	48	46	
Cook & Strike, 2000	Elite cricket	26			
Kageyama et al. 2014	High-BV pitcher	37	46	28*	-267*
	Low-BV pitcher	33	44	42*	-164*
Fleisig et al. 1996a	College pitcher	35*	51*	40*	
	College QB	21*	39*	28*	

5.2 The pelvis

Greater maximum pelvis AV has been significantly correlated to BV in a within-subjects study of 19 baseball pitchers (Stodden et al. 2001), and in elite handball throwers, who threw maximum BV penalty shots from 7 metres (Wagner et al. 2011). Additionally, a comparison of elite baseball pitchers from the USA and South Korea showed that USA pitchers threw at a greater BV, with significantly greater maximum pelvis AV, suggesting that maximum pelvis AV contributes to increased BV (Escamilla et al. 2002; Kageyama et al. 2014, Table 6). However, no significant differences were observed between high-BV and low-BV pitching groups, or between college and elite pitchers despite significant differences in BV (Matsuo et al. 2001). Curiously, in a study between college and elite baseball pitchers, the elite baseball pitchers threw at a greater BV, however, the college pitchers produced greater maximum pelvis AV (Fleisig et al. 1999). Greater pelvis AV results in a greater transference of energy from the legs into the trunk and the throwing arm, facilitating BV.

5.3. The trunk

Greater trunk flexion at BR is significantly correlates to greater BV in elite baseball pitchers throwing greater than 35.50m/s (Stodden et al. 2005), college pitchers maximally throwing 15 metres (Werner et al. 2008), and is significantly greater in elite high-BV pitch groups compared with low-BV pitch groups (Matsuo et al. 2001; Kageyama et al. 2014, Table 6). Greater trunk flexion at BR results in the ball travelling a greater distance during the acceleration phase, allowing more time for force to be imparted to the ball (Matsuo et al. 2001; Stodden et al. 2005). Greater trunk flexion at BR also results in facilitating greater shoulder external and internal rotation (Matsuo et al. 2001), which significantly contributes to BV (Whiteley, 2007). However, no significant correlation was observed in handball players maximally throwing from 7 metres, or significant differences between Olympic baseball pitchers, international baseball pitchers, or between elite and college baseball pitchers, despite significant differences in BV (Van den Tillaar & Ettema, 2007; Escamilla et al. 2001; Escamilla et al. 2002; Fleisig et al. 1999).

TABLE 6. Summary of Literature of kinematics of the pelvis and the trunk. * Significant differences between groups **significantly different within subject *** Significantly correlates to ball velocity

Study	Max pelvis rotation AV (°/s)	BR(°)	Trunk angle/AV Max flexion AV (°/s)	Max rotation AV (°/s)
Matsuo et al. 2001	637	37*	406	1227
	633	29*	391	1179
Stodden et al. 2001	490**			920**
Stodden et al. 2005		32**		
Werner et al. 2008		55***		1052***
Escamilla et al. 2001		37		1318
		31		1432
		32		1369
		33		1650
		34		1381
		45		1501
		29		1358
		29		1392
Escamilla et al. 2002	673*	36		1248
	611*	26		1212
Wagner et al. 2011	586***			870***
Fleisig et al. 1999	670*	33		1190
	620*	33		1200
Escamilla et al. 2007	626	34		1205
Van den Tillaar & Ettema, 2007	508		279	866
Van den Tillaar & Cabri, 2012	378	35	246	785
Fleisig et al. 2011	568	34		1120
	586	27		1141
Escamilla et al. 1998	640	28	250	1220
Kageyama et al. 2014	738*	28*	338	1361*
	638*	19*	308	1120*
Fleisig et al. 1996a	660*			1170*
	500*			950*

No significant results have been found in maximum trunk flexion AV, between high-BV and low-BV baseball pitchers (Matsuo et al. 2001; Kageyama et al. 2014) or significant correlation in handball players (Van den Tillaar & Ettema, 2007). However, there was a 8% difference in BV between high- and low-BV baseball groups, which the authors suggest may be important, due to the summative effects of slightly increased

AVs throughout the knee, pelvis, and trunk, manifesting into significant distal AVs, resulting in greater BV (Matsuo et al. 2001, Table 6).

Significant correlation between maximum trunk rotation AV and BV has been observed in elite baseball pitchers (Stodden et al. 2001), college baseball pitchers (Werner et al. 2008) and handball players (Wagner et al. 2011). High BV baseball pitchers also have greater trunk rotation AV than low-BV baseball pitchers (Kageyama et al. 2014). Greater trunk rotational AV results in greater efficiency in the transference of kinetic energy from the trunk into the throwing arm, and significantly contributes to elastic energy storage in the shoulder, resulting in greater shoulder internal rotation AV, and therefore BV (Roach & Lieberman, 2014). However, no significant difference was observed between high and low-BV baseball pitching groups, international baseball pitchers, or elite and college baseball pitchers (Matsuo et al. 2001; Escamilla et al. 2001; Escamilla et al. 2002; Fleisig et al. 1999, Table 6).

5.4. The shoulder

Significantly greater horizontal shoulder abduction at FFC has been observed between international baseball pitchers (Escamilla et al. 2001, Escamilla et al. 2002), and may enhance the pre-stretch of the pectoralis major and anterior deltoids, resulting in greater force throughout the remainder of the pitch through the release of elastic energy (Escamilla et al. 2001; Escamilla et al. 2002, Table 7). Additionally, greater horizontal abduction at FFC causes the throwing arm to move behind the trunk, causing the trunk to rotate towards the throwing arm, therefore causing a pre-stretch in the rectus abdominis, internal and external obliques, and paraspinal musculature (Escamilla et al. 2001; Escamilla et al. 2002). This stored elastic energy can be released to enhance concentric trunk rotation and thus increase BV (Escamilla et al. 2001; Escamilla et al. 2002).

External rotation at FFC has been observed to be greater in higher-BV pitchers from different countries (Escamilla et al. 2001; Escamilla et al. 2002). Additionally, maximum external rotation is greater in high-BV pitchers (Matsuo et al. 2001), between international pitchers (Escamilla et al. 2002) and correlated to BV (Werner et al. 2008, Table 7).

TABLE 7. Summary of literature of kinematics of shoulder rotations and horizontal adduction. *Significant differences between groups *** Significantly correlates to BV

	Shoulder rotation angles/AV			Shoulder horizontal adduction angle/AV			
Study	**FFC (°)**	**Max ER (°)**	**Max IRAV (°/s)**	**FFC (°)**	**Max (°)**	**BR(°)**	**Max AV (°/s)**
Matsuo et al. 2001		179*	7724				579
		166.3*	7350				544
Stodden et al. 2001							
Stodden et al. 2005	63	173		-17		12	
Werner et al. 2008		157***			21		
Escamilla et al. 2001	65*	187	6222	-25	10	8	
	39	182	5701	-22*	10	10	
	39	183	6102	-31	11	6	
	26*	187	6068	-18*	11	6	
	30	186	7087	-23*	12	11	
	47	191	5202	-20*	21	19	
	48	184	5919	-45*	12	10	
	72*	178	6721	-24*	15	12	
Escamilla et al. 2002	45*	181*	7844	-27*	16	8	
	68*	167*	8006	-14*	14	5	
Wagner et al. 2011			5864***				
Fleisig et al. 1999		173	7430		20	9	
		175	7240		17	9	
Escamilla et al. 2007	51	175	6772	-20	19	10	
Van den Tillaar & Ettema, 2007		130	3426		12	2	
Van den Tillaar & Cabri, 2012			2590				
Fleisig et al. 2011	53	174	7640	-21			
	56	174	7590	-19			
Escamilla et al. 1998	52	171	7550	-20	20	10	350
Cook & Strike, 2000		143					
Fleisig et al. 1996a	67*	173*	7550*	-17*	18*	7*	
	90*	164*	4950*	7*	32*	26*	

Greater maximum external rotation, and at FFC, causes the shoulder to move through a greater range of motion, enhancing the eccentric stretch of the internal rotators, used to control the rate of external rotation, which can facilitate shoulder internal rotation in arm acceleration, (Matsuo et al. 2001; Escamilla et al. 2002; Werner et al. 2008; Park et al. 2002), accounting for approximately 54% of the internal rotation work done (Roach et al. 2013).

TABLE 8. Summary of Literature of the kinematics of shoulder adduction and elbow angle. * Significant differences between groups *** Significantly correlates to BV

Study	Shoulder abduction FFC (°)	Elbow angle/AV FFC (°)	Max (°)	BR (°)	Max AV (°/s)
Matsuo et al. 2001					2537
					2353
Stodden et al. 2005		96		27	
Werner et al. 2008		86***			2251***
Escamilla et al. 2001	90	92	109	17	2578
	96	94	106	21	2469
	86	112	115	22	2847
	97	99	110	23	2818
	89	113	112	17	2990
	91	96	118	14	2767
	93	74	91	26	
	93	78	118	22	
Escamilla et al. 2002	88	89	104	21	2565
	104	96	104	20	2401
Wagner et al. 2011					1805***
Fleisig et al. 1999		85	99	23	2380
		87	98	23	2320
Roach et al. 2013					2434
Escamilla et al. 2007	93	96	110	31	2245
Van den Tillaar & Ettema, 2007	87		97	46***	1430
Van den Tillaar & Cabri, 2012			70	48	1346
Fleisig et al. 2011	96	78	101		2480
	98	79	103		2492
Escamilla et al. 1998	98	84	104	24	2440
Cook & Strike, 2000		58			1633
Fleisig et al. 1996a	93	98*	100*	22*	2340*
	96	77*	113*	36*	1760*

In addition, as the shoulder is more externally rotated, and, as in high-BV pitchers the trunk is more flexed at BR, the distance the ball travels is greater across a similar time period, which can cause greater AV of the shoulder and arm during arm acceleration as a result of the greater force applied to the ball (Matsuo et al. 2001; Werner et al. 2008). Consequently, maximum internal rotation AV has been significantly correlated to BV in elite handball players (Wagner et al. 2011; Whiteley 2007).

5.5. The elbow

At FFC, greater elbow flexion has been correlated to greater BV in baseball and handball players (Werner et al. 2008, Table 8), as the shorter segment is able to move quicker and more efficiently, positioning the joint in the correct position for the next phase of movement to occur (Werner et al. 2008). Greater maximum elbow flexion enables passive inertial forces to counter-rotate the arm, stretching the tendons, ligaments, and elastic components of muscles which cross the shoulder, storing elastic energy in the large cross-sectional areas of these elastic structures (Roach et al. 2013). Greater elbow extension AV has been significantly correlated to BV in handball and baseball players (Wagner et al. 2011; Werner et al. 2008, Table 8). Greater elbow extension AV results in decreased elbow flexion at BR and reduces the moment of inertia of the arm, thus allowing the stretched structures to recoil, releasing their stored energy, and facilitating shoulder internal rotation (Roach et al. 2013). Further, a more extended elbow at BR results in a longer trajectory path to accelerate the ball (Van den Tillaar & Ettema, 2007).

5.6 Stride length

Stride length (SL) shows no significant differences between any high and low-BV groups (Matsuo et al. 2001), countries (Escamilla et al. 2001; Escamilla et al. 2002), or ability levels (Fleisig et al. 1999), even when BV is significantly different, likely due to the highly trained nature of the athletes tested (Table 9). However, it is an important variable, as Montgomery & Knudson (2002) demonstrated that an increased SL results in an increased BV. Greater SL increases the distance over which angular and linear trunk movements can occur, which allows for greater energy to be transferred to the upper extremity (Dillman et al. 1993). Increasing SL can result in increased total body linear momentums, especially those directed anteriorly towards the target, through greater efficiency of the kinetic chain, as there is greater trunk momentum (Ramsey et al. 2014; Crotin et al. 2015). A shorter stride results in compensation mechanisms at shoulder and elbow (Ramsey et al. 2014), which predispose the athlete to medial elbow injuries through greater valgus stress (Fleisig & Escamilla, 1996). A shorter stride further reduces BV, as there is an earlier onset of FFC, reducing the time to generate forward momentum of the trunk over the front leg (Ramsey et al. 2014; Crotin et al. 2015). A longer period in double support also inhibits forward momentum to be inhibited through better braking (Ramsey et al. 2014).

TABLE 9. Summary of literature of stride length (%height) and time taken (s), * Significant difference between groups *** Significantly correlates to ball velocity

Study	SL	Time taken
Matsuo et al. 2001	87	
	86	
Stodden et al. 2005		0.150
Escamilla et al. 2001	78-86	
Escamilla et al. 2002	91	
	85	
Fleisig et al. 1999	85	0.145
	86	0.145
Escamilla et al. 2007	76	
Montomgery & Knudson, 2002	88***	
Crotin et al. 2015	67	
Fleisig et al. 2011	80	
	79	
Escamilla et al. 1998	84	
Cook & Strike, 2000	58	
Kageyama et al. 2014	85	0.200
	85	0.200
Fleisig et al. 1996a	74*	0.145*
	61*	0.207*

6 TEMPORAL VARIABLES ASSOCIATED WITH BALL VELOCITY

6.1 Time taken

No significant correlation has been found between time taken and BV (Stodden et al. 2005, Table 9). This is likely to be because all subjects were of a high standard, and will have been taught "proper" pitching mechanics (Fleisig et al. 1999). However, the arm acceleration phase has been found to be significantly faster during maximum speed throwing compared with 80% of maximum in elite baseball players (Freeston et al. 2015). Additionally a decrease in time during the arm-cocking phase, results in greater BV (Werner et al. 2008) potentially due to a greater stretch at the shoulder at MER. Time taken is an important variable to measure as any changes in the time taken can effect the timing of muscle activations, potentially effecting the sequential pattern of throwing, resulting in a decrease in BV (Fleisig et al. 2009a).

6.2 Timing of maximum angular velocities

A critical component to enhancing BV is optimizing the timing of rotations between a proximal and a distal joint, to maximize the contribution of each segment. If there is too much lag, or not enough time between the movements, the contributions of the segments will be diminished (Fleisig et al. 1998). Inconsistent timing of maximum pelvis rotation can affect the timing of all other rotations, and increase the risk of injury at upper extremity joints (Urbin et al. 2012). As a result, lumbopelvic control is critical (Chaudhari et al. 2011), therefore highlighting the need for gluteal and core development (Oliver & Keeley, 2010a; Oliver & Keeley, 2010b), that can enhance the ability to time pelvis and trunk segments (Urbin et al. 2012). Professional baseball pitchers begin their trunk rotation significantly later than collegiate, high school and youth pitchers (Aguinaldo et al. 2007, Table 10), optimizing the contribution of trunk and core muscles (Stodden et al. 2001), which results in the internal rotators being eccentrically loaded, from the trunk, for a shorter duration of time, resulting in a more rapid and efficient contraction (Urbin et al. 2013). The left external oblique must activate earlier than the one on the right to prevent the trunk rotating with the pelvis, which also aids putting the trunk musculature on stretch (Hirashima et al. 2002). The instant of peak pelvis rotation AV has been found to be between 25-39%, and the instant of peak trunk rotation AV has been recorded between 47-53%, when time is normalized so that 0% represents FFC, and 100% represents BR (Dun et al. 2008; Fleisig et al. 2006 Escamilla et al. 2002; Matsuo et al. 2001; Sisto et al. 1987). Increased time between peak pelvis and trunk rotations results in decreased BV, as less energy is transferred to the throwing arm (Urbin et al. 2012).

TABLE 10. Summary of literature of temporal variables. All variables are timing of maximum joint AV (%total movement time).

Study	Max pelvis rotation AV	Max trunk rotation AV	Max trunk flexion AV	Max knee extension AV
Matsuo et al. 2001	27	51	96	
	35	52	103	
Stodden et al. 2005	39	52	93	
Escamilla et al. 2001		44		
		46		
		52		
		45		
		52		
		43		
		36		
		45		
Escamilla et al. 2002	34	52		
	34	49		
Fleisig et al. 1999	34	51		
	34	52		
Dun et al. 2008	34	47		
Fleisig et al. 2006	30	50		
Kageyama et al. 2014	39	69	92	71
	38	67	93	56
Fleisig et al. 1996a	35*	50*	99*	
	56*	62*	76*	

Additionally, high-BV baseball pitchers reach maximum shoulder internal rotation AV closer to BR than those in a low-BV group, and achieved maximum elbow extension AV sooner than the low-BV group (Matsuo et al. 2001; Urbin et al. 2012, Table 11), thus optimizing the timing of arm acceleration and BR (Matsuo et al. 2001; Escamilla et al. 1998; Sisto et al. 1987). No significant differences were found between high- and low-BV groups in maximum shoulder external rotation AV (Matsuo et al. 2001) and maximum trunk flexion AV (Matsuo et al. 2001; Stodden et al. 2005; Sisto et al. 1987).

TABLE 11. Summary of literature of temporal variables. All variables are timing of movement (%total movement time). **significantly different within subject.

Study	Max shoulder ER	Max Shoulder IR AV	Max elbow extension AV
Matsuo et al. 2001	81	102	91
	81	103	93
Stodden et al. 2005	81	104**	95
Escamilla et al. 2001	78	96	85
	75	99	84
	81	102	87
	76	89	83
	85	105	86
	84	107	87
	84	99	89
	77	108	70
Escamilla et al. 2002	80	100	90
	84	103	93
Fleisig et al. 1999	81	103	91
	81	102	91
Dun et al. 2008		104	92
Fleisig et al. 2006		104	93
Fleisig et al. 1996a	81*	103*	92*
	71*	106*	95*

7 THROWING FOR ACCURACY

7.1 Movement variability

Variability is inherent within and between all biological systems (Newell & Corcos, 1993), as noise exists at all levels of the nervous system (Faisal et al. 2008). Movement variability has been suggested as the cause of decreased accuracy in throwing through variability in: the timing or the velocity of the onset of finger extension (which determines the moment of BR), and/or maximum AV of rotations, and/or timing of onset of rotation at distal joints, which determine the path of the hand through space (Hore et al. 1996; Van den Tillaar & Ettema, 2009). Among baseball pitchers of differing ability, movement variability was shown to significantly decrease in: knee flexion at FFC, maximum trunk AV, maximum elbow flexion, maximum shoulder external rotation, and trunk flexion at BR, as ability increased (Fleisig et al. 2009a). Decreased lower body movement variability reduces load upon the upper body, therefore reduces injury (Fleisig et al. 2009a). Low movement variability of the upper extremity was suggested to be due to neuromuscular development from repetition of pitching, and results in a consistent BV and spatial position of the throwing arm (Fleisig et al. 2009a).

7.1.1 Impulse variability theory

The impulse-variability theory suggests that, variability in static and dynamic force production peaks at approximately 65% of maximum force, and decreases as force increases to maximum, creating an inverted-U function between force magnitude and force variability (Sherwood & Schmidt, 1980; Schmidt & Sherwood, 1982 Sherwood et al. 1988). As a result, greater force should reduce movement variability, increasing accuracy, and directly contradict the VATO (Schmidt & Sherwood, 1982). In overarm throwing, any variation in the timing of muscle contractions may result in inadequate energy transfer between joints, and affect the positioning of the distal segments, and affect performance outcomes (Hirashima et al. 2008; Stodden et al. 2005). Therefore, a change in force, reflected by a change in duration over which the force can act, will influence the timing of segmental interactions, and approaching maximum force, variability in this timing decreases (Urbin et al. 2012). Urbin et al. (2012) investigated impulse-variability theory in overarm throwing. Sixteen skilled and 14 unskilled participants threw at a 0.01 x 0.01 centroid within an octagonal target with 0.20m sides. Throws were performed at 40%, 50%, 60%, 70%, 80% 90% and 100% of maximum throwing BV. The authors discovered a significant quadratic fit for all subjects with variability in throwing BV increasing from 40-60% of maximum, and then decreasing at each subsequent percentage to maximum. Movement variability was greater in skilled than unskilled participants at every data point except from at 100%, as the degrees of freedom are constrained by the complexity of the task (Bernstein, 1967), and/or because greater experience reduces movement variability. At approximately 60% of maximum BV, movement variability is greater because of the multi-joint nature of the overarm throw, which permits a number of different coordination strategies to achieve the goal (Barrett & Burton, 2002; Langendorfer & Roberton, 2002), which may increase accuracy, potentially through the ability to use compensatory movements. The results of this study agree with the findings of Sherwood & Schmidt (1980) that there is an inverted-U relationship between percentage maximum force, reflected in BV, and variability. Despite the increase in BV, and decrease in movement variability, no accuracy improvements were observed, which counters the impulse-variability theory, which would suggest that accuracy is greatest in maximum BV throws. Consequently, accuracy in ballistic, multijoint skills is too complex to be explained as a function of overall force magnitude, as the variability of positional configurations, modulating force with different segments, and the timing of BR, can affect accuracy (Urbin et al. 2012).

7.1.2 Launch window hypothesis

Throwing at such small targets as used in baseball requires precise timing accuracy, beyond the known accuracy of a single neuron (the neural machinery for rapid manual-brachial movements). Incredible natural selection pressure in human evolution, through hunting with rocks and spears, resulted in those with bigger and more organized brains surviving due to greater numbers of neurons working in parallel (Calvin, 1983). This hypothesis suggests that there is a finite time in which BR must occur to result in an accurate throw (Calvin, 1983). The size of the launch window is influenced by three factors: the target size, the distance to the target, and the speed of the throw. Calvin

(1983) suggested that there is an 8-fold decrease in total launch window when a distance doubles, and a 27-fold decrease when a distance triples. In a study of elite baseball players throwing at maximum BV and 80% of maximum BV, the launch window was significantly smaller when throwing at maximum BV (0.08 v 0.12msec), and maximum throwing BV is negatively related to the size of the launch window (Freeston et al. 2015). Therefore, the greater the BV of the throw, the smaller the window of BR is available to hit the target. Only the vertical component of the launch window is affected by the increase in BV (Freeston et al. 2015).

As a result of the incredibly small launch window in which to throw accurately, athletes in throwing sports must display extremely small movement variability at BR to be successful. Theoretical calculations suggest that a timing precision of <1ms is needed for "very great" accuracy (Calvin, 1983; Chowdhary & Challis, 1999), with a 1-2ms window for baseball pitchers to hit the strike zone (Fleisig et al. 2009a), to ensure correct joint motions and optimal handpath in space (Hore et al. 2002). Timing errors in BR of elite baseball pitchers was 0.51ms when throwing at 80%, while 0.78ms at 100% BV. However, for every millisecond that elapsed between optimal release and actual release during the 80% speed condition, an accuracy error of 0.61m was measured, while at 100% it was 0.84m (Freeston et al. 2015). In constrained throws, variability in timing of BR ranged from 1-10ms for skilled athletes (Hore et al. 1995; Hore et al. 2002; Timmann et al. 2001; Jegede et al. 2005) and between 27-28ms for unskilled participants (Jegede et al. 2005; Timmann et al. 2001).

7.1.3 Timing of onset of finger extension

All timings of onset of joint rotations in the throwing arm are important to accuracy, but onset of finger extension has twice as great an effect on accuracy as any other, due to the greater AV of distal segments (Hore et al. 1996). There are two phases of finger opening. The first is where finger flexor torque is progressively increased throughout the throw in anticipation of the progressively increasing backforce from the projectile, which produces initial finger opening (Hore et al. 2001; Hore & Watts, 2011). The second phase is characterized by the ball rolling down the fingers, and determines accuracy. This occurs when the backforce from the ball overcomes the finger stiffness of the proximal interphalangeal joint (PIJ) (Hore & Watts, 2011). Onset of BR from the hand is strongly correlated with extension at the PIJ (Hore & Watts, 2005), which is based on state estimates of hand acceleration in space, and the finger flexor muscle torque that opposes initial backforce from the ball (finger stiffness) (Braitenberg, 1967; Ivry, 1996; Ivry, 1997; Jueptner et al. 1996; Keele & Ivry, 1990; Raymond et al. 1996; Thompson et al. 1997; Jueptner et al. 1997; Timmann et al. 2000; Hore & Watts, 2011). These estimates are based on prior experiences of throwing a projectile of similar size and weight (Johansson & Westling, 1988; Lacquaniti et al. 1992), and occur via a spatial controller within the cerebellum (Wolpert et al. 1998). The time interval from elbow extension to onset of finger opening is ~20ms, which does not leave time for proprioceptive or visual feedback to trigger the finger extensors (Hore et al. 1999a). Therefore, finger stiffness is based on an internal forward model of hand trajectory (Hore et al. 1999b; Haruno, et al. 2001; Miall & Reckess, 2002; Wolpert & Kawato, 1998), which provides the missing sensory information that only becomes apparent at the end of the movement (Wolpert et al. 1998). When this computation of strength and timing of muscle contraction is incorrect, it results in inaccuracies (Hore & Watts, 2011), where if finger stiffness is too high, the ball will be released late and miss the target low, while if finger stiffness is too low, the ball will be released early and miss the target high (Timmann et al. 2000; Hore et al; 1999; Freeston et al. 2015).

7.1.4 Compensation for movement errors

When performing goal orientated tasks, individuals express greater movement variability at the more distal wrist joint than the shoulder or the wrist, suggesting a compensatory mechanism is present (Button et al, 2003; Robins et al. 2006; Müller & Sternad, 2004; Muller & Loosch, 1999; Nasu et al. 2014), assisted by the freeing of biomechanical degrees of freedom, which occurs with motor learning (Vereijken et al. 1992). It has been suggested however, that the overarm throwing movement is too fast to process any sensory feedback (Schmidt et al. 1978), and therefore impossible to create any sensory feedback-based corrections (Hore & Watts, 2005; Henry & Rogers, 1960; Lashley, 1917; Schmidt & Russell, 1972; Klapp, 1977), resulting in total reliance on an internal model. Therefore, it was believed that all inaccuracies of throwing were a result of the variability in the initial muscular impulses applied to produce the movement (Schmidt et al. 1978). Nonetheless, recent research suggests that visual and proprioceptive information, which can be used to orient the position of the body segments and as an external reference for detecting and correcting errors in the trajectory of limbs, is rapidly conveyed to motor-related regions of the cortex by the dorsal stream during the throwing movement (Urbin, 2012; Ghez et al. 1995). Accurate visual information can be provided after movement is initiated, to compensate for any errors in proximal movement pattern or inaccurate finger stiffness, through compensatory coordination of distal limbs (Bernstein, 1967; Bootsma & Van Wieringen, 1990), but only if the duration of the movement is greater than 100ms (Paulignan et al. 1991; Pelisson et al. 1986; Bard et al. 1985; Elliot et al. 1998; Urbin, 2013). These adjustments happen unconsciously, suggesting the cortical pathways integrating visual and proprioceptive input operate faster than those facilitating conscious awareness (Paulignan et al. 1991; Day & Lyon, 2000; Day & Brown, 2001), and therefore the sensorimotor system is capable of controlling limb trajectory online, and potentially modifying the timing of the onset of finger opening (Urbin, 2012). The total time of FFC to BR is 150ms (Fleisig et al. 2009b), with maximum external rotation occurring at 124ms (Werner et al. 2001), suggesting that any adjustments must occur at the distal segments. However there is a critical point (~30ms to BR) where sensory feedback can no longer be used (Urbin, 2012), as the transmission times to and from the CNS are too long, (which may be delayed by increased synaptic transmission, sensory receptor dynamics, gradual rise in force generation, in response to descending motor commands), to predict the sensory consequences of actions and overcome these delays (Urbin, 2012; Davidson & Wolpert, 2005). Elite overarm throwers have the ability to maximize the energy from the lower body and trunk compared with recreational throwers (Stodden et al. 2006). This delays distal joint rotations in relation to the trunk (Fleisig et al. 1996b), and may provide adequate time for the sensorimotor system to integrate visual and proprioceptive feedback for use in controlling the movement online (Urbin et al. 2012), which could be a mechanism for the greater accuracy in elite players. However, any adjustments to the movement pattern must overcome the great AVs produced, making online corrections difficult to implement (Urbin, 2012). Potentially, any of the muscles used from arm cocking to the critical point can be adjusted to compensate for any errors (Urbin, 2012). An example of this is through concentric contractions of the abdominals and hip contralateral to the throwing arm, the sensorimotor system may be able to adjust the position of the trunk, repositioning the upper extremity and altering its spatial trajectory (Urbin, 2012). This ability to compensate for proximal errors in an internal model may explain the significantly greater movement variability observed at the shoulder and the forearm when performing maximum throws (Wagner et al. 2012a) or in table tennis forehand drives (Bootsma & Van Wieringen, 1990). This suggests that movement variability, and therefore online control is critical to accuracy, and can explain the inverted U of velocity and accuracy. It should be noted that this could be simply due to the greater experience, resulting in a greater functional movement variability to achieve successful movement execution (Bootsma & Wieringen 1990; Kudo et al. 2000).

7.2 Kinematics associated with accuracy

The combination of shoulder abduction and lateral trunk flexion at BR creates the "arm slot," which is usually approximately 90 degrees of shoulder abduction at BR. This position maximizes functional stability while maintaining greater BV. (Poppen & Walker, 1978; Matsuo et al. 2002). Any change in position of the "arm slot" could affect accuracy, through affecting a change in the handpath.

8 LIMITATIONS TO PREVIOUS RESEARCH

Research into throwing at different targets and understanding the kinematics of accurate throwing is restricted to simple 2-3 segmental movements such as dart throwing (Gross & Gill, 1982; Müller & Loosch, 1999; Mckay & Wuif, 2012; Juras & Slomka, 2013; Nasu et al. 2014), robotic models (Chowdhary & Challis, 1999) or throwing with a fixed trunk (Hore et al. 1996). It is impossible to compare overarm throwing to dart throwing, as dart throwing is not a ballistic skill, using a very different technique, and lacking three of the major components of the kinetic chain mechanism used in throwing. Firstly, throwing a dart requires little or no movement from proximal segments, and throwing without the use of the trunk results in a reduction in projectile velocity by 47% (Toyomshima et al. 1974). Secondly, dart throwing lacks the explosive acceleration of segments and pronounced follow through observed in overarm throwing, and range of motion of joints involved in throwing (Urbin et al. 2011). Finally, the interaction of the segments used in dart throwing do not produce the sequential pattern of proximal to distal energy generation and transfer which result in maximum distal segment velocities at BR (Urbin et al. 2011). Many of the studies of the VATO use a one-dimensional method of determining accuracy of the throw (Freeston et al. 2007; Indermill & Husak, 1984; Etnyre, 1998), which is not as comprehensive or as accurate as measurement as in two-dimensions (Hancock et al. 1995). Further, studies are limited by only comparing two points of reference, instead of manipulating the trials over a greater range of BV (Etnyre, 1998; Freeston & Rooney, 2014; Freeston et al. 2015; Garcia et al. 2013).

9 PURPOSE OF THE STUDY

Due to the conflicting research into the VATO and overarm throwing, it is important to determine if there is a VATO in elite Finnish baseball players, a population group which has not been measured in this context before. Similar to research that have studied self – selected throwing speeds in the VATO context (Van den Tillaar & Ettema, 2003a, Van den Tillaar & Ettema, 2006; Garcia et al. 2013), it is hypothesized that there will be no VATO in Finnish baseball players.

As a result of the severe lack of research into understanding the timing of movements and kinematics that effect throwing accuracy; it is of great importance to quantify this to highlight any movement errors that may affect accuracy. Further, this will be the first study to compare kinematic and temporal variables with participants throwing at different velocity, and it is important to understand if a change in movement pattern is observed, as this could effect training protocols. It is hypothesized that a significant change in the kinematics, or in the timing of movements, between instructions will result in a significant change in accuracy or BV.

Understanding of the movement variability in kinematic and temporal variables that contribute to BV and accuracy will help determine if the impulse-variability theory is applicable to overarm throwing. Further, it will determine if it is possible for the sensorimotor system to make compensatory adjustments to distal limbs in response to proximal movement errors, which could provide explanation for the VATO. It is hypothesized that movement variability will be significantly greater in the accuracy instruction.

10 METHODOLOGY

10.1 Participants

Eight elite, right-handed, male Finnish Baseball players, all currently playing in the Superpesis and Ykköspesis (the top two leagues in Finnish Baseball) took part in the study (mean age = 25.00 yr., SD = 1.77, mean height = 1.82m, SD = 2.92, mean body mass = 86.65kg, SD = 7.41). The participants were required to be injury free, and currently active on the playing roster. At the beginning of the study, all participants were made aware of the experimental procedure, before giving written consent to participate in the study. The study was performed in accordance with the Declaration of Helsinki.

10.2 Procedure

Measurements were conducted in an indoor sports hall. After a thorough, self-administered warm-up, participants were permitted a familiarisation period with the target, to minimize the learning effect within the study (Hopkins, 2000). Using a regulation size (diameter = 0.22m) and weight (0.16kg) Finnish baseball, maximum throwing speed was determined through five 20.00m, maximum intensity throws, towards a net with no specific target. Following this, participants performed three series of ten throws, towards a target (Freeston & Rooney, 2014). The target consisted of an orange circle, 0.07m in diameter, the centre of which was located 0.70m above the ground, corresponding with the average approximate center of the strike-zone in American baseball (Figure 3). The distance between the target and the participants' back-foot was set at 20m for all throwing trials. To avoid fatigue effects on BV and accuracy, the participants rested 2 minutes between each series (including after maximum intensity throws) (Freeston et al. 2007), and 8 seconds between each throws (Escamilla et al. 2007).

The number of throws performed should permit assessment of velocity and accuracy characteristics, due to the stability of the throwing pattern in elite players (Van den Tillaar & Ettema, 2003a). The participants were required to throw with an overarm technique, and were permitted one stride forward. This position was utilised to minimize the influence of outside factors on throwing performance, such as approach speed and angle (Cook & Strike, 2000). The instruction given to the participants during these throws were: to throw with the greatest accuracy possible (accuracy instruction), to throw with the greatest velocity possible (velocity instruction), and to throw with a combination of accuracy and velocity (combination instruction). The instruction imposed upon each throw was randomised equally for all participants.

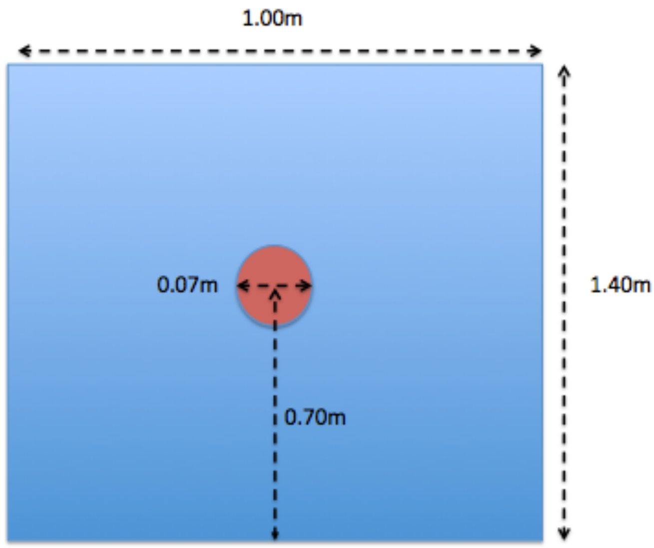

FIGURE 3: Dimensions of the target

10.3 Kinematic analysis and joint angle calculations

Biomechanical measurements were conducted using an eight-camera motion analysis system (Vicon T40, Oxford, UK), operating at 300Hz. Anthropometric measurements (height, weight, leg length, shoulder offset, hand thickness, and ankle, knee, elbow and wrist diameters) and placement of 45 retro-reflective markers were performed according to the Upper Limb Model with Plug in Gait full-body model (Murray, 1999; Davis et al. 1991; Vicon, Oxford, UK; Figure 4). Joint centres were calculated using centering algorithms (Murray, 1999; Davis et al. 1991). Markers on the upper arm, forearm, thigh and shank were positioned asymmetrically. Additionally, reflective tape was added to the ball to determine BR and BV. The Upper Limb Model increases the accuracy of motion analysis compared with the Plug In Gait Model, through a reduction in soft tissue artifact at upper-arm and forearm segments. This is achieved through using the wrist joint centre to define the upper-arm anatomical reference frame (Cutti et al. 2005), as well as the addition of a cluster of markers on the upper arm, and an additional marker on the forearm, allowing for greater accuracy of describing movements, and tracking, of these segments (Cappozzo et al. 1995; Murray, 1999).

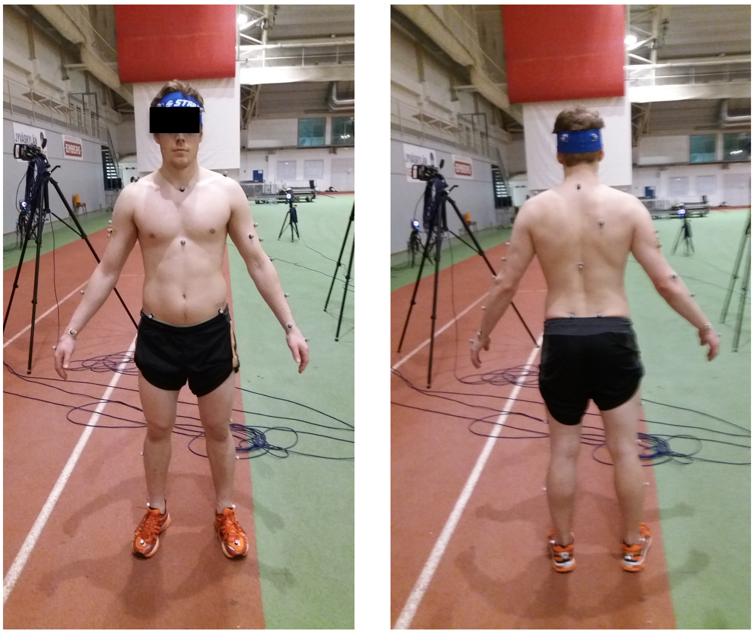

FIGURE 4: Placement of retro-reflective markers including bilateral placement on the: 2^{nd} metatarsal head, posterior calcaneus, lateral malleolus, lateral shank, knee lateral epicondyle, lateral thigh, anterior-superior iliac spine, posterior-superior iliac spine, acromion process, humerus lateral epicondyle, humerus medial epicondyle (calibration only), lateral forearm, radial styloid, ulnar styloid, dorsum of the 2^{nd} metacarpal, front of head, rear of head, and 3 markers positioned on the upper arm. Additionally, retro-reflective markers were positioned on the: jugular notch, xiphoid process, 7^{th} cervical vertebra, 10^{th} thoracic vertebra and the right scapula.

Three-dimensional trajectories of the markers were analysed utilizing Nexus software (Nexus 1.6, Vicon, Oxford, UK). Raw 3D marker trajectories were filtered through a Butterworth 4^{th} order low-pass filter (25Hz) to maximize the signal to noise ratio (Winter, 2009), and marker gaps up to 25 frames were interpolated using the same Nexus software. Euler angles were used to calculate joint angles for shoulder internal/external rotation using rotation order YZ’Y’’, which reduces the effect of gimbal lock (Murray, 1999), and rotation order XZ'Y'' was used to calculate shoulder adduction/abduction. Euler angles were also used to define joint angles of the elbow and wrist using rotation order X'ZY'' (Murray, 1999), and Cardan angles were used to calculate joint angles for the trunk, pelvis and knee using rotation order YX'Z''(Davis et al. 1991). Throwing accuracy data were collected using one high-speed, two-dimensional camera (Sony NXCAM, HXR-NX5R, Japan), positioned 10.00m away from the target, with a sample frequency of 200Hz and a shutter speed of 1/500. Accuracy data were analysed using Quintic software (Quintic Biomechanics v26, UK).

10.4 Data analysis

Ball release was determined as the frame in which the centre of the ball abruptly increased in distance from the dorsum of the metacarpal (Van den Tillaar & Ettema, 2007). Linear BV and AVs were calculated using a five-point central differential method (Van den Tillaar & Ettema, 2003a). Ball release during accuracy, combination and velocity trials, was calculated as the percentage of peak BV from the maximum throwing test (Table 12). Maximum joint angles were determined as the greatest angle within the throw from FFC to BR. Front foot contact was determined as the time the velocity of the leading ankle joint centre decreased to less than 1.5m/s (Fleisig et al. 2009a).

TABLE 12. Maximum peak and mean BV (m/s) from the maximum throwing test

	Max (Peak)	**Max (Mean)**
BV (Absolute)	32.44	30.99

The 'time taken' parameter was measured in seconds, while other temporal parameters were scaled as percent time. For scaling the time for each throw, 0% was determined as FFC, and 100% was determined as BR. Stride length was determined as the distance from the left ankle joint centre to the right ankle joint centre at FFC. In accordance with Hancock et al. (1995) methods for analysing error in two-dimensional performance tasks, total error was defined as the distance between the centre of the ball and the centre of the target. Total error was decomposed into horizontal (x) and vertical (y) components, defined as the average distance in the x and y directions, respectively, between each throw and the target. Absolute constant error, a measure of bias, was defined as the distance between the centroid and the target. The centroid was calculated by averaging the x and y coordinates of each throw in an instruction. Variable error, a measure of consistency, was calculated as the average distance between each throw and the centroid (Schmidt & Wrisberg, 2008). The combination of total error, ACE and variable error is suggested to provide a more comprehensive understanding of accuracy in two-dimensions (Hancock et al. 1995). Mean intra-subject standard deviations of variables in each instruction were calculated to determine movement variability (Fleisig et al. 2009a).

10.5 Statistical analysis

Normal distribution was assessed through a Shapiro-Wilks test with Lilliefors correction, and the Levenes test for non-matching samples (SPSS, 18.0, SPSS, Chicago, USA). Data that violated the assumption of normality was transformed, and the normal distribution tests performed again. Repeated-measures ANOVA were performed for testing the mean differences of variables between each instruction. If spherecity was violated, and epsilon was less than 0.75, the Greenhouse-Geisser (1959) correction was used, and if epsilon was greater than 0.75, the Huynh-Feldt (1976) correction was used. If significant, a post-hoc Bonferroni correction pairwise analysis was used to determine the specific significant difference between instructions, and adjust the alpha level for each instruction to control type I error inflation (Field, 2013). If transformed data still violated the assumption of normality, a non-parametric Friedman's test was performed for testing mean differences of variables between instructions. If significant, a post-hoc Wilcoxon rank-sum test was performed. Level of significance was set at $P \leq 0.05$. Effect size was calculated using partial effect size (η^2_p) (or Pearson's correlation (r) for non parametric data) and Cohen's d for post-hoc analysis. Effect size (d) was defined as small ≤ 0.2, medium = 0.2 – 0.5, and large ≥ 0.8 (Cohen, 1988).

11 RESULTS

11.1 Ball velocity and accuracy

There was a significant main effect of instruction on relative BV ($F_{2, 14} = 21.29$, $p < 0.01$, $\eta_p^2 = 0.75$, Table 13). Post-hoc analysis revealed significant differences between: accuracy and velocity ($p < 0.01$, $d = 1.51$), accuracy and combination ($p < 0.01$, $d = 0.95$) and combination and velocity ($p < 0.05$, $d = 1.10$). Among accuracy variables, there was a significant main effect of instruction on horizontal error ($F_{2,14} = 3.851$, $p < 0.05$, $\eta_p^2 = 0.36$) and variable error ($F_{2, 14} = 4.428$, $p = 0.03$, $\eta_p^2 = 0.39$). However, post-hoc analysis revealed no significant differences between instructions. Additionally, no significant main effects were observed in total error, vertical error, or ACE (Table 13).

TABLE 13. Means, standard deviations and statistics of BV (% max) and accuracy (cm) data * indicates significant main effect of instruction (significant differences between groups indicated by: $_a$ = accuracy and velocity, $_b$ = accuracy and combination, $_c$ = combination and velocity)

Variable	Accuracy	Combination	Velocity	Effect size η_p^2	*p*
Relative BV	84.15 ± 7.23	91.01 ± 5.65	96.69 ± 2.57	0.75	<0.001*$_{a\ b\ c}$
Total error	52.18 ± 5.20	54.54 ± 12.54	60.18 ± 14.10	0.21	0.196
Horizontal error	31.10 ± 9.63	31.26 ± 8.99	38.21 ± 7.75	0.36	0.046*
Vertical error	34.53 ± 9.28	36.41 ± 10.32	40.66 ± 12.15	0.15	0.328
Variable error	46.42 ± 8.65	54.57 ± 11.53	61.03 ± 10.95	0.39	0.032*
ACE	26.16 ± 14.04	26.13 ± 8.55	25.56 ± 11.94	<0.01	0.993

11.2 Kinematic and temporal variables

Among temporal variables, a significant effect was observed between instruction and time taken ($F_{2, 14} = 7.135$, $p < 0.01$, $\eta_p^2 = 0.51$). Post-hoc analysis displayed significant differences between accuracy and velocity instructions ($p = 0.03$, $d = 0.52$). No significant effect of instruction was present upon any temporal variables (Table 14).

TABLE 14. Means, standard deviations and statistics of time taken (s) and timing of maximum velocities (% movement). * indicates significant main effect of instruction (significant differences between groups indicated by: $_a$ = accuracy and velocity, $_b$ = accuracy and combination, $_c$ = combination and velocity)

Variable	Accuracy	Combination	Velocity	Effect size η_p^2	*p*
Time taken	0.22 ± 0.04	0.20 ± 0.04	0.20 ± 0.03	0.51	0.007*$_a$
Max pelvis rotation AV	51.68 ±10.08	52.84 ± 11.15	55.78 ±10.99	0.34	0.052
Max trunk rotation AV	59.40 ± 10.06	59.93 ± 9.86	60.10 ± 9.27	0.08	0.544
Max shoulder external rotation	78.16 ± 6.24	78.49 ± 5.92	78.76 ± 5.99	0.19	0.231
Max shoulder external rotation AV	56.46 ± 10.94	56.02 ± 10.90	56.15 ± 11.97	0.03	0.785
Max internal rotation AV	101.29 ± 2.89	100.83 ± 2.66	100.82 ± 3.18	0.15	0.322
Max elbow extension AV	94.95 ± 2.32	94.65 ± 1.49	94.02 ± 1.49	r=0.35	0.072

There were significant main effects of instruction on SL ($F_{2, 14}$ = 9.748, p < 0.01, η_p^2 = 0.58) and knee flexion at FFC ($F_{2, 14}$ = 6.482, p = 0.01, η_p^2 = 0.48, Table 15). Post-hoc analysis revealed: significantly greater SL in the combination (p < 0.01, d = 0.36) and velocity (p = 0.02, d = 0.55) instructions than the accuracy instruction, and no significant differences between instructions for knee flexion at FFC. No significant main effect of instruction on knee flexion at BR was present.

TABLE 15. Means, standard deviations and statistics of stride length (% height) and knee angle (°). * indicates significant main effect of instruction (significant differences between groups indicated by: $_a$ = accuracy and velocity, $_b$ = accuracy and combination, $_c$ = combination and velocity)

Variable	Accuracy	Combination	Velocity	Effect size η_p^2	*p*
Stride length	55.62 ± 4.59	57.28 ± 4.77	58.11 ± 4.40	0.58	0.002*$_{a\ b}$
Knee angle FFC	40.37 ± 9.15	43.54 ± 8.36	47.08 ± 5.85	0.48	0.010*
Knee angle BR	34.71 ± 17.55	31.66 ± 17.08	30.54 ± 15.68	0.31	0.077

There were significant main effects of instruction on: trunk flexion at BR ($F_{1.175, 8.227}$ = 5.136, $p < 0.05$, $\eta_p^2 = 0.42$), shoulder abduction at FFC ($F_{2, 14} = 9.091$, $p < 0.01$, η_p^2 = 0.57), and maximum shoulder external rotation ($F_{2, 14} = 4.771$, p = 0.03, $\eta_p^2 = 0.41$). Post-hoc analysis revealed: significantly greater trunk flexion at BR in the combination instruction than the accuracy instruction (p = 0.01, d = 0.22), significantly greater shoulder abduction at FFC in the accuracy instruction compared with the velocity instruction (p = 0.04, d = 0.78), and no significant differences were found between instructions in maximum shoulder external rotation. Furthermore, no significant main effects of instruction were found on: shoulder abduction at BR, shoulder rotation angle at FFC, or shoulder rotation at BR (Table 16).

TABLE 16. Means, standard deviations and statistics of trunk and shoulder angles (°). * indicates significant main effect of instruction (significant differences between groups indicated by: $_a$ = accuracy and velocity, $_b$ = accuracy and combination, $_c$ = combination and velocity)

Variable	**Accuracy**	**Combination**	**Velocity**	**Effect size η_p^2**	***p***
Trunk flexion BR	25.45 ± 7.13	27.04 ± 7.62	28.50 ± 8.16	0.42	0.048*$_b$
Shoulder abduction FFC	72.11 ± 7.57	69.62 ± 5.45	66.33 ± 6.42	0.57	0.003*$_a$
Shoulder rotation FFC	-73.89 ± 26.89	-70.90 ± 25.35	-68.73 ± 24.17	r=0.25	0.607
Max shoulder external rotation	-147.95 ± 7.58	-149.28 ± 8.68	-151.13 ± 9.99	0.41	0.026*
Shoulder abduction BR	77.38 ± 5.00	78.33 ± 5.52	78.19 ± 6.73	0.03	0.688
Shoulder rotation BR	-82.80 ± 12.93	-84.77 ± 17.75	-81.67 ± 18.91	0.12	0.421
Lateral trunk flexion	11.55 ± 11.56	11.80 ± 10.92	13.43 ± 11.99	0.32	0.105

There were significant main effects of instruction on: maximum elbow flexion ($F_{2, 14}$ = 8.938, $p < 0.01$, $\eta_p^2 = 0.66$), elbow flexion angle at BR ($F_{1.123, 7.864} = 6.658$. p = 0.03, η_p^2 = 0.49) and wrist angle at BR ($F_{2, 14} = 9.137$, $p < 0.01$, $\eta_p^2 = 0.57$). Post-hoc analysis demonstrated: significantly greater maximum elbow flexion in the velocity instruction than combination (p < 0.01, d = 0.33) or accuracy instructions (p = 0.04, d = 0.37), significantly greater wrist flexion at BR in the accuracy instruction compared with the velocity instruction (p = 0.03, d = 0.83), and no significant differences between instructions in elbow flexion angle at BR. Additionally, no significant main effect was found on elbow flexion at FFC (Table 17).

TABLE 17. Means, standard deviations and statistics of elbow and trunk angles (°). * indicates significant main effect of instruction (significant differences between groups indicated by: $_a$ = accuracy and velocity, $_b$ = accuracy and combination, $_c$ = combination and velocity)

Variable	Accuracy	Combination	Velocity	Effect size η_p^2	*p*
Elbow flexion FFC	115.37 ± 19.72	115.42 ± 17.99	116.28 ± 19.51	r=0.16	0.687
Max elbow flexion	122.85 ± 10.05	123.40 ± 8.92	126.30 ± 8.85	0.66	0.003*$_{a\ c}$
Elbow flexion BR	23.18 ± 16.30	20.22 ± 14.71	18.23 ± 12.86	0.49	0.031*
Wrist BR	20.21 ± 10.71	16.63 ± 10.12	12.15 ± 7.02	0.57	0.003*$_a$

There were significant main effects of instruction on: maximum knee extension AV ($F_{2, 14}$ = 7.410, p < 0.01, η_p^2 = 0.51), maximum pelvis AV ($F_{2, 14}$ = 10.493, p < 0.01, η_p^2 = 0.60), maximum trunk flexion AV ($F_{2, 14}$ = 14.830, p < 0.01, η_p^2 = 0.68), and maximum trunk rotation AV ($F_{2, 14}$ = 16.469, p < 0.01, η_p^2 = 0.70, Table 18).

TABLE 18. Means, standard deviations and statistics of knee, pelvis and trunk maximum AV (°/s). * indicates significant main effect of instruction (significant differences between groups indicated by: $_a$ = accuracy and velocity, $_b$ = accuracy and combination, $_c$ = combination and velocity)

Variable	Accuracy	Combination	Velocity	Effect size η_p^2	*p*
Max knee extension AV	-241.72 ± 141.81	-286.96 ± 165.12	-343.11 ± 145.14	0.51	0.006*
Max pelvis AV	596.68 ± 115.31	660.80 ± 101.52	713.05 ± 95.19	0.60	0.002*$_a$
Max trunk flexion AV	166.78 ± 44.72	191.36 ± 40.38	221.12 ± 34.71	0.68	<0.001*$_{a\ b\ c}$
Max trunk rotation AV	861.26 ± 145.30	918.08 ± 110.00	994.19 ± 70.15	0.70	<0.001*$_{a\ c}$

Further, post-hoc analysis determined: significantly greater maximum pelvis AV in the velocity instruction than the accuracy instruction ($p = 0.02$, $d = 0.98$), significantly greater maximum trunk flexion AV in the velocity instruction than the combination ($p < 0.05$, $d = 0.75$) and accuracy ($p < 0.01$, $d = 1.14$) instructions (the combination instruction was also significantly greater than the accuracy instruction, $p < 0.05$, $d = 0.57$), significantly greater trunk rotation AV in the velocity instruction than the combination ($p = 0.01$, $d = 0.78$) or accuracy instructions ($p = 0.01$, $d = 1.03$), and no significant differences between instruction in maximum knee extension AV.

There were significant main effects of instruction on maximum shoulder internal rotation AV ($F_{1.110, 7.769} = 12.125$, $p < 0.01$, $\eta_p^2 = 0.063$), maximum shoulder external rotation AV ($F_{2, 14} = 9.048$, $p < 0.01$, $\eta_p^2 = 0.56$) and maximum elbow extension AV ($F_{2, 14} = 14.102$, $p < 0.01$, $\eta_p^2 = 0.67$). No significant main effect of instruction on maximum wrist flexion AV was found (Table 19).

TABLE 19. Means, standard deviations and statistics of shoulder, elbow and wrist maximum AV (°/s). * indicates significant main effect of instruction (significant differences between groups indicated by: $_a$ = accuracy and velocity, $_b$ = accuracy and combination, $_c$ = combination and velocity)

Variable	**Accuracy**	**Combination**	**Velocity**	**Effect size η_p^2**	***p***
Max shoulder IR AV	4350.95 ± 1282.68	4576.62 ± 1283.78	4877.45 ± 1285.42	0.63	0.008*$_{a\ b}$
Max shoulder ER AV	-739.12 ± 207.31	-836.50 ± 173.98	-911.84 ± 189.98	0.56	0.003*$_a$
Max elbow extension AV	-2664.20 ± 670.87	-2860.27 ± 603.10	-3028.31 ± 570.55	0.67	<0.001*$_{a\ c}$
Max wrist flexion AV	-1946.50 ± 379.04	-2033.55 ± 363.38	-2026.74 ± 285.67	0.07	0.534

Post-hoc analysis revealed: significantly less maximum shoulder internal rotation AV in the accuracy instruction than the combination ($p = 0.01$, $d = 0.18$) and velocity instructions ($p = 0.02$, $d = 0.41$), significantly greater maximum shoulder external rotation AV in the velocity instruction than the accuracy instruction ($p = 0.03$, $d = 0.82$), and significantly greater maximum elbow extension AV in the velocity instruction than combination (p = 0.04, d = 0.31) and accuracy instructions (p = 0.01, d = 0.58).

11.3 Movement variability

No significant main effects of instruction were found on any movement variability variables (Table 20, Table 21).

TABLE 20. Mean and standard deviation of intra-subject movement variability in each instruction for relative BV and temporal variables

Variable	**Accuracy**	**Combination**	**Velocity**	**Effect size η_p^2**	***p***
Relative BV (% Maximum)	2.86 ± 1.11	2.33 ± 1.25	2.64 ± 1.31	0.18	0.412
Temporal					
Total time taken (s)	0.02 ± 0.01	0.02 ± 0.01	0.01 ± 0.00	0.27	0.116
Time of max PRAV (%movement)	6.44 ± 2.47	6.62 ± 2.52	6.15 ± 2.71	0.03	0.793
Time of max TRAV (%movement)	3.66 ± 1.77	3.61 ± 1.23	3.55 ± 1.25	0.01	0.965
Time of max ER (%movement)	2.05 ± 1.22	2.17 ± 0.74	1.72 ± 0.65	0.19	0.235
Time of max ERAV (%movement)	4.99 ± 3.49	4.94 ± 2.61	4.69 ± 3.89	0.10	0.607
Time of max IRAV (%movement)	1.08 ± 0.24	1.20 ± 0.34	1.06 ± 0.16	0.16	0.303
Time of max EEAV (%movement)	1.17 ± 0.38	1.18 ± 0.27	0.98 ± 0.29	0.15	0.322

TABLE 21. Mean and standard deviation of intra-subject movement variability in each instruction for all kinematic variables

Variable	Accuracy	Combination	Velocity	Effect Size η_p^2	*p*
Shoulder rotation angle FFC (°)	7.52 ± 4.31	5.39 ± 3.20	5.94 ± 4.36	0.17	0.270
Shoulder abduction FFC (°)	3.97 ± 2.44	3.67 ± 1.31	3.37 ± 0.81	0.04	0.636
Max shoulder external rotation (°)	2.03 ± 1.26	1.86 ± 1.10	1.73 ± 0.41	0.00	0.975
Max shoulder internal rotation AV (°/s)	288.46 ± 160.26	267.30 ± 162.28	247.51 ± 175.89	0.15	0.417
Max shoulder external rotation AV (°/s)	63.29 ± 36.31	62.54 ± 33.73	81.08 ± 37.70	0.04	0.743
Shoulder abduction BR (°)	3.80 ± 2.08	3.21 ± 1.48	3.34 ± 2.04	0.03	0.662
Shoulder rotation angle BR (°)	10.82 ± 6.14	10.52 ± 4.82	14.20 ± 13.23	0.02	0.895
Elbow angle FFC (°)	4.08 ± 2.59	5.28 ± 4.30	4.07 ± 1.26	0.04	0.747
Max elbow extension AV (°/s)	132.86 ± 47.09	110.81 ± 46.47	117.60 ± 46.27	0.15	0.315
Max elbow flexion (°)	2.57 ± 1.32	3.83 ± 2.67	2.53 ± 1.30	0.18	0.247
Elbow angle BR (°)	3.61 ± 2.08	3.61 ± 2.22	2.44 ± 1.58	0.36	0.078
Wrist angle BR (°)	4.84 ± 3.43	5.89 ± 4.45	9.43 ± 6.67	0.20	0.207
Max wrist flexion AV (°/s)	133.74 ± 78.13	135.34 ± 50.95	134.50 ± 44.73	0.11	0.447
Lateral trunk flexion (°)	2.62 ± 2.38	2.27 ± 2.01	2.95 ± 2.56	0.04	0.643
Stride length (%height)	3.07 ± 1.32	2.81 ± 1.51	2.87 ± 1.09	0.04	0.773
Knee angle FFC (°)	6.43 ± 5.29	4.10 ± 1.67	4.80 ± 1.36	0.07	0.531
Knee angle BR (°)	4.43 ± 2.09	4.28 ± 1.71	4.66 ± 2.35	0.03	0.803
Max Knee extension AV (°/s)	53.53 ± 28.97	47.82 ± 18.92	53.03 ± 18.92	0.04	0.645
Max pelvis AV (°/s)	47.29 ± 27.86	37.32 ± 16.05	43.13 ± 17.51	0.10	0.420
Trunk flexion BR (°)	1.66 ± 0.77	1.34 ± 0.84	1.70 ± 0.92	0.06	0.575
Max trunk flexion AV (°/s)	24.90 ± 10.65	15.12 ± 7.34	24.11 ± 12.12	0.31	0.111
Max trunk rotation AV (°/s)	42.52 ± 18.44	36.34 ± 18.21	35.70 ± 16.45	0.25	0.137

12 DISCUSSION

Ball velocity was significantly different between each instruction, and was greatest in the velocity instruction (96.69%), followed by combination, (91.01%) and then accuracy (84.15%). No significant differences were observed between instructions for any measure of accuracy, with total error in accuracy, combination and velocity being 52.18cm, 60.18cm and 54.54cm in accuracy, velocity and combination instructions respectively. Multiple significant differences between instructions were present in many of the kinematic variables including: stride length, trunk flexion at BR, maximum elbow flexion, wrist flexion at BR, shoulder abduction at FFC, maximum pelvis rotation AV, maximum trunk rotation AV, maximum trunk flexion AV, maximum shoulder internal rotation AV, maximum shoulder external rotation AV and maximum elbow extension AV. A significant difference was observed in time taken to complete the movement between instructions. No significant differences between instructions were discovered between any other temporal variable or in any of the movement variability variables.

12.1 Velocity-accuracy trade-off

As expected, BV was significantly affected by each instruction. Ball velocity in the accuracy instruction was 7.54% and 12.97% less than in the combination or velocity instructions respectively, and BV in the combination instruction was 5.87% less than in the velocity instruction. Interestingly, in the accuracy instruction, the self-selected BV was 84% of maximum, similar to the findings of previous research, which found that when emphasizing accuracy, cricket and handball players throw between 75-85% of their maximum BV (Van den Tillaar & Ettema, 2003a; Freeston et al. 2007; Van den Tillaar & Ettema, 2006; Garcia et al. 2013). This finding suggests that skilled overarm throwers rarely throw at less than 75-85% of their maximum BV, and can explain why, when throwing at 50% of maximum BV, accuracy is significantly reduced (Indermill & Husak, 1984, Freeston et al. 2007), as players are less experienced at throwing at this BV. The significant reduction of BV in the combination and accuracy instructions agrees with the findings of Van den Tillaar & Ettema (2006) and Van den Tillaar & Ulvik (2014), who suggested that there is a trade-off between BV and task priortisation of accuracy, as a result of limited information processing capacity of humans, which prevents simultaneous attentional focus on both maximum velocity and maximum accuracy (Fitts, 1954).

Despite a significant reduction in BV, there was no subsequent improvement in accuracy in any of the accuracy instruction throws, thus demonstrating that a VATO is not present in elite Finnish baseball players. These results have also been observed in elite handball players (Van den Tillaar & Ettema, 2003a, Van den Tillaar & Ettema, 2006; Garcia et al. 2013), but conflict with studies involving elite baseball, cricket and darts players, and novice handball players (Freeston et al. 2015, Freeston & Rooney, 2014; Garcia et al. 2013; Freeston et al. 2007; Etnyre, 1998; Indermill & Husak, 1984). The lack of a VATO in Finnish baseball players could be attributed to the task in the study. Unlike baseball pitchers or cricket players who routinely aim at very small targets, the role of a Finnish baseball player is to throw the ball to the man on base, resulting in a comparatively lower emphasis on accuracy. Further, the lack of VATO mirrors that observed in elite handball players (Van den Tillaar & Ettema, 2003a, Van den Tillaar & Ettema, 2006; Garcia et al. 2013), another sport which has a lower emphasis on accuracy than baseball and cricket. Therefore, when faced with a task where very great accuracy was required, Finnish baseball players, and possibly handball players, are not as skilled, or as experienced as baseball players or cricket players, which is reflected in total error scores being up to 35% worse in maximum throws, when performing the same task (Freeston et al. 2015, Freeston & Rooney, 2014). Alternatively, the BV selected to emphasize accuracy could be too great to elicit any significant differences between the groups, as other studies, which discovered a VATO in elite athletes, selected lower relative BV (Freeston & Rooney, 2014, Freeston & Rooney, 2015, Freeston et al. 2007; Indermill & Husak, 1984). Throwing at a lower BV may see greater movement variability in joint rotations, AVs and timing of movements, due to an increased number of coordination strategies (Barrett & Burton, 2002; Langendorfer & Roberton, 2002). Another reason for the lack of VATO in the present study, is that the BV thrown in the accuracy instruction, may suggest that Finnish baseball players have overcome the VATO, and in light of similar findings in elite handball players, where self-selected ball velocity was also ~85% (Van den Tillaar & Ettema, 2003a; Van den Tillaar & Ettema, 2006; Garcia et al. 2013), questions the application of the VATO to elite players in overarm throwing sports. Elite players in throwing sports may have attained specific adaptations that lead to consistent performance at near-maximum and maximum BV, thus overcoming the VATO (Urbin et al. 2012, Chappell et al. *In Press*). The adaptive changes of repetitive overarm throwing occur as a result of an increase in shoulder external rotation, and a decrease in shoulder internal rotation, while maintaining the rotational range of motion seen in the contralateral shoulder (Burkhart et al. 2003; Chant et al. 2007; Crockett et al. 2002; Drakos et al. 2010; Myers et al. 2009; Reagan et al. 2002). The gain in shoulder external rotation with a loss of internal rotation, is an adaptive change resulting from alterations in bony (Crockett et al. 2002; Reagan et al. 2002; Meister et al. 2005), capsuloligamentous (Burkhart et al. 2003; Thomas et al. 2011) and muscular (Proske & Morgan, 1999; Whitehead et al. 2001) structures in and around the shoulder facilitates greater BV and accuracy (Kibler et al. 2013; Burkhart et al. 2003).

The significant main effect of instruction on horizontal error is curious, as horizontal error has previously been related to handpath errors (Timmann et al. 2001; Freeston et al. 2015), but no significant movement variability was measured between instructions to suggest this. Potentially, the greater maximum elbow flexion observed in the velocity instruction may have resulted in greater horizontal error, as it results in a more indirect handpath, less control over the movement, and therefore less accuracy for near-maximum movements (Knudson, 2007; Parrington et al. 2015). Alternatively, any movement errors may have occurred in a movement not measured in this study, such as forearm pronation or supination, or via the culminative effects of multiple small errors. Potentially, small errors in the timing of muscular contractions could affect the positioning of distal segments, whose effect may be magnified at greater BV due to the decreased time to release the ball successfully (Calvin, 1983). Further, this could have resulted in the significant effect of instruction on variable error, causing accuracy in overarm throws to be less consistent at greater BV. Online adjustments are unlikely to be implemented, if possible, due to the great AV produced in the distal segments (Urbin et al. 2012), so these errors cannot be compensated for.

The lack of significant difference between instructions in vertical error suggests that the timing of finger opening, which must occur in a finite time to maintain accuracy (Calvin, 1983; Freeston et al. 2015), is consistent across instructions. This is crucial to maintaining accuracy, as this has been determined the greatest detriment to throwing accuracy (Freeston et al. 2015). This could suggest that Finnish baseball players are highly skilled and experienced at throwing at maximum or near maximum BV. Additionally, this could suggest that it is possible for an online adjustment made by the sensorimotor system (Urbin, 2012), which can occur as soon as 0.11s after the initiation of the movement (Bard et al. 1985). Initially, the timing of finger opening is based on an internal forward model of hand trajectory (Hore et al. 1999b; Haruno et al. 2001; Miall & Reckess, 2002; Wolpert & Kawato, 1998), which sets finger stiffness to oppose the increasing backforce of the ball until it forces the fingers open, resulting in BR (Hore et al. 2001; Hore & Watts, 2011). If finger stiffness is too great, the ball will be released late and miss the target low, while if finger stiffness is too weak, the ball will be released early and miss the target high (Timmann et al. 2000; Hore et al. 1999b; Freeston et al. 2015). However, prior to 30ms before BR (after which transmission times to and from the central nervous system are too long), it may be possible to make adjustments to the stiffness of the PIJ, especially with the small muscle size, and likely small AV of this joint, and alter the timing of BR. This may compensate for any proximal errors (Bernstein, 1967; Bootsma & Van Wieringen, 1990), through the sensorimotor system integrating visual and proprioceptive information (Urbin, 2012). This could be a mechanism of greater accuracy in elite players.

12.2 Movement variability

In this study, no significant differences in any variable were observed in intra-subject movement variability between any instruction, which suggests that elite Finnish baseball players are highly skilled across a maximum and near maximum BV, with minimal movement variability observed (Fleisig et al. 2009a). Low movement variability of the movements in overarm throwing is suggested to be due to neuromuscular development from the repetition of overarm throwing, which results in a consistent BV and spatial position of the throwing arm, which enhances accuracy, and may lead to a violation of the VATO (Fleisig et al. 2009a; Chappell et al. in press; Urbin et al. 2012). Further, the players may have accumulated more experiences in throwing, which have allowed them to discover different strategies. These strategies include: modulating force with different segments, altering timing of movements and different preparatory positional configurations. From this experience, the most successful coordination strategy for maintaining accuracy at near maximum BV is learned (Urbin et al. 2012). Alternatively, the increase in difficulty of the task, by decreasing the margin of error, compared with a typical Finnish Baseball scenario, may have constrained their movement pattern (Bernstein, 1967; Newell & Vaillancourt, 2001). Lack of training throwing at very small targets may reduce the number of successful coordination strategies to achieve the goal (Barrett & Burton, 2002; Langendorfer & Roberton, 2002). Another reason for the lack of movement variability in the present study is that it is unlikely that a compensatory mechanism can occur, as seen in basketball and dart throwing (Button et al, 2003; Robins et al. 2006; Müller & Sternad, 2004; Muller & Loosch, 1999; Nasu et al. 2014). The movement time produced during overarm throws in Finnish baseball occur much faster than dart and basketball throws, potentially making it impossible to create any sensory feedback-based corrections (Hore & Watts, 2005), or if sensory feedback compensatory adjustments are possible, the great AV of the distal limbs are impossible to overcome (Urbin, 2012).

Lack of significant differences in movement variability between instructions conflicts with impulse-variability theory, which suggests that as force increases, movement variability decreases, resulting in increased consistency of movement, (Sherwood & Schmidt, 1980; Schmidt & Sherwood, 1982; Sherwood et al. 1988), which was suggested to be a mechanism of maintaining accuracy at maximum BV in elite handball players (Van den Tillar & Ettema; 2003b; Van den Tillaar & Ettema, 2006; Garcia et al. 2013; Van den Tillaar & Ettema, 2003a). The results in this present study may be too narrow to elicit such a response, with only a 12.54% difference in BV between accuracy and velocity instructions. The results of the present study agree with the finding of Urbin et al. (2012), who suggest that accuracy in ballistic, multijoint skills is too complex to be explained as a function of overall force magnitude, as BR and positioning of distal segments, as well as physiological, psychological, motor control and other biomechanical factors, are likely to act independently of force and affect accuracy. Further, these results suggest that the VATO and impulse-variability theory are mutually exclusive.

12.3 Kinematics

Maximum throwing BV was similar to sub-elite BV baseball pitchers (Matsuo et al. 2001; Kageyama et al. 2014), and less than elite and college baseball pitchers (Escamilla et al. 2001; Werner et al. 2008; Escamilla et al. 2002; Fleisig et al. 2011; Stodden et al. 2001; Stodden et al. 2005; Fleisig et al. 1999), which is not surprising due to the effect of the raised throwing mound on enhancing BV (Nissen et al. 2013). Similar to baseball and handball, significantly greater, SL, knee angle at FFC, maximum knee extension AV, maximum pelvis rotation AV, trunk flexion at BR, maximum trunk rotation AV, maximum shoulder external rotation, maximum elbow flexion, maximum shoulder internal rotation AV, maximum elbow extension AV and reduced elbow flexion at BR was apparent when BV was increased, suggesting that these movements are critical to attaining greater BV (Werner et al. 2008; Escamilla et al. 2002; Wagner et al. 2011; Matsuo et al. 2001; Kageyama et al. 2014; Stodden et al. 2001; Fleisig et al. 1999; Van den Tillaar & Ettema, 2007; Stodden et al. 2005; Montgomery & Knudson, 2002).

In the present study, significantly greater maximum AVs were observed in the velocity instruction in pelvis rotation, trunk rotation, trunk flexion, shoulder external rotation, shoulder internal rotation and elbow extension. Greater maximum pelvis rotation AV puts a greater stretch on the abdominal and oblique muscles (Fleisig, 2010), aiding greater maximum trunk rotation AV, through facilitating concentric contractions via SSC activity, and enhancing the efficiency of the kinetic chain. Greater trunk rotational AV and trunk flexion AV results in greater efficiency in the transference of kinetic energy from the trunk into the throwing arm, and significantly contributes to elastic energy storage in the shoulder (Matsuo et al. 2001; Roach & Lieberman, 2014). Pelvis and trunk rotations account for ~30% of the power and work generated for internal rotation of the shoulder, and 90% of the total work required to achieve high-BV throws (Roach & Lieberman, 2014). Further, the significantly decreased shoulder abduction at FFC in the velocity instruction suggests that the throwing arm is lagging behind the trunk, further facilitating storage of elastic energy. In addition, significantly greater maximum elbow flexion enables passive inertial forces to counter-rotate the arm, stretching the tendons, ligaments, and elastic components of the muscles, which cross the shoulder, storing elastic energy (Roach et al. 2013). This combination of movements results in greater shoulder external rotation, which results in an increased acceleration path for the arm (Matsuo et al. 2001; Escamilla et al. 2002; Werner et al. 2008; Park et al. 2002), and suggests that greater eccentric stretch of the internal rotators is present, storing greater elastic energy, and thus contributing to the increased BV in the velocity instruction (Bosco et al. 1982; Walshe et al. 1998). Finally, greater elbow extension AV contributes to BV by reducing the moment of inertia of the humerus, thus allowing the stretched structures of the shoulders to recoil, releasing their stored elastic energy, and facilitating shoulder internal rotation AV (Roach et al. 2013). The elastic energy stored within the shoulder accounts for approximately 54% of the external work of the shoulder (Roach et al. 2013). This is likely the cause of greater maximum shoulder internal rotation AV, and therefore greater BV observed in the present study, when velocity was emphasised.

Significantly greater trunk flexion and elbow extension at BR was observed in higher BV instructions. This increases the acceleration path of the ball, allowing more force to be applied to the ball, and therefore contributes to greater BV (Matsuo et al. 2001; Stodden et al. 2005). Greater trunk flexion at BR is suggested to occur due to a more extended knee, observed in the present study, as this aids acceleration of the trunk over the front leg due to the increased braking effect (Fleisig et al. 1995). Additionally, significantly greater SL increases the linear momentum of an overarm throw, thus increasing the acceleration path of the trunk, which increases the efficiency of the kinetic chain (Dillman et al. 1993; Ramsey et al. 2014; Crotin et al. 2015).

No significant differences were present in shoulder abduction at BR or in shoulder rotation angle at BR, which may have resulted in the consistent accuracy observed between the instructions. Additionally, significantly greater wrist flexion and elbow flexion was observed in the accuracy instruction. This suggests that the timing of BR is altered so the release angle changes in response to the reduction in BV, and subsequent change in ball flight trajectory, to maintain accuracy.

12.4 Temporal variables

Compared with baseball pitchers, maximum pelvis rotation AV occurred 12-28% later in Finnish baseball players. This is likely to be an effect of the mound, which results in greater linear momentum (Nissen et al. 2013), and the effect of the wind-phase, both of which make it difficult for lumbopelvic muscles to resist rotation. All other timing of maximum AVs occurred similar to those in baseball pitchers, which suggests there is one dominant movement pattern for maximum and near maximum throwing velocity. Despite the time taken to execute the movement being significantly faster in the velocity condition, no significant differences between relative timing of maximum AVs was present between instructions. This suggests that in overarm throws, that there is no change in the technique of the throw, despite the change in BV, similar to the findings in elite handball players (Van den Tillaar & Ettema, 2003b). Experienced players are unlikely to change a technique that they have mastered and control. Consistent timing of movements suggests the optimal transfer of kinetic energy occurs between segments in maximum and near maximum throwing BV (Urbin et al. 2012b), and the threat of injury is reduced by decreasing load on distal joints (Fleisig et al. 1996b; Aguinaldo et al. 2007; Urbin et al. 2012b). The decrease in time taken results in a greater AV required at all joints, to position the limbs correctly for future movement. A trend ($p = 0.052$) of later maximum pelvis AV in greater BV throws suggests an increase in efficiency of the kinetic chain, as the time between maximum pelvis rotation AV and maximum trunk rotation AV is reduced, increasing BV (Urbin et al. 2012). This suggests facilitation of the concentric contraction of abdominals and the obliques, through greater elastic energy obtained from a greater eccentric stretch (Stodden et al. 2001). The greater movement time of lower BV throws (Fleisig et al. 2009a), could give greater time for the sensorimotor system to unconsciously position distal limbs, or alter the timing of release, in response to proximal movement errors (Urbin, 2012), resulting in an increase in accuracy.

12.5 Practical applications

The present study suggests, that in elite overarm sports, athletes should throw at near maximum BV as this decreases flight time of the ball, and therefore increases the chance of attaining an out, without detriment to accuracy. This is especially important in motor skill development (Roberton, 1996), and should be promoted early in skill acquisition (Urbin et al. 2012). Further, repetition of throwing near maximum BV is likely to enhance neuromuscular development, so BV and spatial position of the throwing arm contribute to consistent throwing speed and accuracy (Fleisig et al. 2009a; Urbin et al. 2012).

12.6 Limitations

In the present study, there were limitations. Firstly, difficulty defining BR as a distance from the ball to the finger causes error, as for example, between frames the shoulder rotation could change up to 12 degrees. In future research, a sensor between the throwing hand and the ball should be used to determine BR. Another limitation is the effect of soft tissue artifact, where the soft tissue moves independently to the rigid skeleton underneath. It can translate as much as 30mm away from the skeleton, affecting joint rotations by up to 10 degrees (Cappozzo et al. 1996; Tsai et al. 2011), which affects the accuracy of the results. In future research, the use of rigid supports (Yack et al. 2000) and different calibration methods, such as CAST (Cappozzo et al. 1995) should be implemented to minimize the effect of soft tissue artifact. The low number of participants affects the reliability of the study, as it reduces the likelihood that a statistically significant result reflects a true effect, and/or decreases the probability of a true effect reaching a significant effect (Button et al. 2013). Further, there are accuracy concerns in the 3D measures of shoulder internal rotation and elbow extension, when the elbow is close to full extension, which could contribute to errors in these variables (Elliot & Alderson, 2007). The very small size of the target may also have had an effect, as it was novel to the Finnish baseball players, who are used to throwing to a man on base, which could have constrained the movement pattern (Newell & Vaillancourt, 2001). A more sport specific task, may have elicited different movement patterns as the difficulty of the task decreases, affecting the ecological validity of the study. A further limitation is that testing was performed in laboratory conditions as, in a game situation, the player is likely to be under match situation pressure, and be faced with a moving ball, and to have to think about which base to throw to, which reduces the ecological validity of this study. In this study, there was no such pressure, with the athlete permitted to take time to think about the throw ahead, which may affect accuracy scores, as skilled performers may recompute and compile new skill execution processes, creating opportunities for error which are not possible when under match pressures (Belilock et al. 2008).

12.7 Future research

More research is required into the VATO in elite athletes, across other sports, using a self-selected velocity to emphasize accuracy, and maximum BV. This will help determine if the VATO is applicable in elite players. Further, future research should measure continuous coordination variability for the joint couplings of the wrist, elbow and shoulder to determine if compensation mechanisms in distal joints occur in response to proximal movement errors. Additionally, the use of the BR sensors will help determine the exact timing of BR, which will increase the accuracy of throwing studies, and help to determine if compensation in the timing of ball release is possible. Future investigations should quantify the VATO in sidearm and underarm throws, both of which are utilized in many throwing-dominated sports.

12.8 Conclusion

No trade-off was present between velocity and accuracy in elite Finnish baseball players, instead; a trade-off was observed between velocity and task prioritisation of accuracy. In addition, the great BV at which elite Finnish baseball players throw when emphasizing accuracy, questions the application of the VATO in elite players. No reduction in movement variability between instructions, despite an increase in BV, disproves the impulse-variability theory for complex, multijoint movements, as accuracy did not improve. Similar movement variability and temporal variables between instructions suggests that the players use the same overarm throwing technique, regardless of instruction. Further, the lack of difference in movement variability between instructions suggests that online compensations are not possible in the distal limbs, but timing of finger opening is a possible source of compensation to proximal errors. Significant differences in kinematics between instructions were observed to increase the acceleration path of the ball, and to put a greater eccentric stretch on the elastic structures crossing the shoulder, facilitating concentric contractions through utilisation of the SSC, resulting in greater BV.

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