

Closed-Loop Feedback Control in Skilled Overarm Throwers

by

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Abstract

Purpose: This investigation sought to determine whether skilled throwers can control the trajectory of overarm throws online following stride-foot contact. If online control is possible, the secondary purpose was to identify the sources of adjustment within the movement pattern.

Method: Eight healthy, college-aged males with previous high school pitching experience and able to throw in excess of 31.3 m/s participated. Pretesting and testing took place in a motion capture laboratory. During the pretest, subjects performed 10 maximal-effort overarm throws with a tennis ball to a target 8.84 m away and 1.22 m above ground. Motion capture, EMG, ball speed, and ball landing location data were collected. Subjects returned within 48 hours for testing and performed 10 maximal-effort overarm throws in each of three experimental conditions where the target remained at its starting location (test-center) or translated 152.4 cm to the left (test-left) or right (test-right) upon stride-foot contact. Motion capture, EMG, ball speed, and ball landing location data were collected.

Results: No significant differences ($p > .05$) were found between conditions in positional, velocity, or temporal kinematic parameters, as well as EMG parameters. Significant differences were found in ball trajectory parameters. The ball's global landing location within the horizontal dimension in the test-left and test-right conditions was more negative and positive, respectively, than in the pretest and test-center condition. Radial error was higher in the test-left and test-right conditions than in the pretest; radial error in the test-right condition was also higher than in the test-center condition. Similarly, bivariate variable error was higher in the test-left and test-right

conditions than in the pretest; bivariate variable error in the test-right condition was also higher than in the test-center condition. Ball speed was faster in the pretest than in all test conditions.

Conclusion: Overall, these findings suggest that skilled throwers are able to control the trajectory of overarm throws online following stride-foot contact. The lack of differences in kinematic and EMG parameters was attributed to a combination of factors including task novelty, as well as intra-subject and inter-subject variations in the strategy adopted to make online adjustments.

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Chapter 1

Introduction

Extensive research has documented the impact of biomechanical parameters on overarm throwing performance (e.g., Fleisig, Chu, Weber, & Andrews, 2009; Matsuo, Escamilla, Fleisig, Barrentine, & Andrews, 2001; Stodden, Fleisig, McLean, & Andrews, 2005; Stodden, Fleisig, McLean, Lyman, & Andrews, 2001). However, there is limited information concerning the sensorimotor control processes (i.e., open-loop, closed-loop) driving them. Some models of limb control indicate the characteristics of the movement trajectory depend almost exclusively on pre-programmed motor commands (Plamondon, 1995a, b; Plamondon & Alimi, 1997). Other research suggests that the sensorimotor system uses visual and proprioceptive feedback to regulate goal-directed limb control online (for a review, see Elliott et al., 2010). In some goal-directed, upper extremity movements, the objective is toprehend an object requiring physical contact with it. Inherently, the limb will negatively accelerate following peak velocity, providing additional time to use sensory feedback. However, the overarm throw involves sequential segment rotations that promote the transfer of angular momentum to the more distal segments, causing the most distal segment to accelerate through ball release. Ultimately, this reduces the time available for detecting and correcting error in the movement trajectory.

A limited number of studies have directly examined sensorimotor control in the context of overarm throwing (Hore, Ritchie, & Watts, 1999; Hore & Watts, 2005). The purpose of these investigations was to identify the control mechanism provoking extension of the proximal interphalangeal joint (PIJ). This joint rotation triggers ball release and occurs with a temporal

consistency of approximately 7-10 msec in skilled throwers (Hore, Watts, Martin, & Miller, 1995). Because the timing of ball release directly influences the projectile's trajectory (Hore, Watts, & Tweed, 1996), this event is intimately tied to performance quality. The findings of Hore et al. (1999) and Hore and Watts (2005) indicate that a central command based on an internal model of hand trajectory controls ball release.

A limitation of these studies relates to the generalizability of the throwing task to the movement pattern exhibited by skilled throwers. The skilled thrower maximizes the involvement of the lower extremities and trunk, promoting the transfer of momentum to the distal segment (Stodden, Langendorfer, Fleisig, & Andrews, 2006a). In doing so, the inertia of more distal segments causes them to lag behind the proximally adjacent segment (Southard, 2009). The throwing tasks (i.e., strapped down, seated and static, standing preparatory positions) of Hore et al. (1999) and Hore and Watts (2005) restricted proximal segment rotations and, in turn, minimized the production of segmental lag (Toyoshima, Hoshikawa, Miyashita, & Oguri, 1974).

Variability in motor output is inherent within all biological systems (Newell & Corcos, 1993). Therefore, a fundamental control-related issue then is the strategy the sensorimotor system uses to correct for deviations in the intended movement trajectory. This strategy is influenced by temporal constraints imposed by movement duration. In other words, the sensorimotor system's ability to modify the movement trajectory is impeded when phase lag in neural transmission is long relative to movement duration. Hore et al. (1999) and Hore and Watts (2005) developed their research question based on the notion that some movements are too rapid for sensory feedback to be used. The overarm throw is, indeed, a very rapid movement; the humeral internal rotation angular velocity of elite throwers has been measured at over 7000°/s (Dun, Fleisig, Loftice, Kingsley, & Andrews, 2007) making it the most rapid human movement

ever measured. However, higher-derivative kinematic characteristics (i.e., velocity, acceleration) are distinct from the duration over which a movement is performed. In maximal-effort throws, the sequence of joint rotations that begins at stride-foot contact and ends at projectile release lasts approximately 150 msec (Fleisig et al., 2009).

Research in the psychophysics domain of motor control has demonstrated that the sensorimotor system can use sensory feedback to amend the trajectory of goal-directed upper extremity movements (e.g., reaching, grasping, aiming) in very short intervals of time. Such movements are markedly different from the overarm throw on a number of features, but both are similar in that they are goal-directed to a target. Therefore, the temporal estimates yielded by previous research on goal-directed upper-extremity movements provide some indication of the speed with which sensory feedback can be used to control ongoing movement.

Researchers have determined the temporal onset and kinematic characteristics of online control by altering characteristics of the target prior to or upon movement initiation. By altering these characteristics after movement initiation, the pre-programmed motor commands are effectively dissociated from those commands issued and implemented as the movement is in progress. For example, Elliott and Allard (1985) used prism spectacles to laterally displace vision by 15°. On some attempts, accurate visual information was provided after movement initiation. Results indicated that errors were detected and corrected if the movement duration was at least 140 msec. Similar experiments have reported that adjustments are observed as early as 150-160 ms into the movement trajectory (Cressman, Franks, Enns, & Chua, 2006; Saunders & Knill, 2003). In rapid punching movements, corrections have been observed in approximately 110 ms (Bard, Hay, & Fleury, 1985).

Another perceptual perturbation paradigm that has been used extensively in the psychophysics domain is the double-step paradigm. This paradigm requires the subject to fixate visual attention on a light until a target appears, at which time the subject reaches for the target (i.e., step 1). During the eye saccade to the target, it will translate 2° to 4° to the left or right (i.e., step 2). Kinematic analyses indicate limb trajectory is adjusted toward the target's terminal location in approximately 100 ms (Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991; Pelisson, Prablanc, Goodale, & Jeannerod, 1986). In these and other investigations, subjects report not being consciously aware of any change in target location (Day & Brown, 2001; Day & Lyon, 2000; Desmurget, Prablanc, Jordan, & Jeannerod, 1999; Prablanc & Martin, 1992). This finding suggests that the cortical pathways integrating visual and proprioceptive input operate faster than other regions facilitating conscious awareness.

In experiments examining the temporal disparity between online control and perceptual awareness, subjects produced three distinct responses to target translation corresponding to separate conditions (Castiello, Paulignan, & Jeannerod, 1991). The first response is similar to the double-step procedure previously described. That is, subjects respond to target translation by orienting to its terminal location. The second response requires a verbal appraisal of target translation. The third response is a combination of both responses. The verbal appraisal required by the second and third condition indicates that the subject is consciously aware of a change in the target's location. Though adjustments to the limb trajectory occurred within 107 ms of the target changing location, over 300 ms passed before a verbal appraisal. These differences were noted between the first and second condition, as well as within the third condition. These findings indicate that the sensorimotor system is capable of controlling limb trajectory online even when the visual stimulus warranting correction has not reached conscious awareness.

The structural and functional characteristics of the visual system accounts for the immediacy with which the sensorimotor system is able to control limb trajectory. The existence of two distinct visual streams, the dorsal and ventral streams, is well established (Held, 1970; Ingle, 1973; Leibowitz & Post, 1982; Milner & Goodale, 1995; Schneider, 1967; 1969; Ungerleider & Mishkin, 1982). Though initial research efforts were focused on determining the specific perceptual functions attributable to each visual stream, contemporary evidence indicates these functions are not exclusive to either. Rather, the time-scales with which each visual stream operates, as well as the regions to which they project, are the principal determinant of the perceptual role each assumes (Cohen, Cross, Tunik, Grafton, & Culham, 2009; Desmurget et al., 1999; Milner & Goodale, 2008; Reichenback, Bresciani, Peer, Bulthoff, & Thielscher, 2011; Rice, Tunik, Cross, & Grafton, 2007; Tunik, Johnson-Frey, & Grafton, 2005). In particular, the primary corticoretinal input projecting to the dorsal stream processes visual stimuli at higher temporal frequencies (Logothetis, 1994; Snowden, 1994) and exhibits shorter response latencies (Bullier & Nowak, 1995; Maunsell et al., 1999) relative to other corticoretinal pathways. The dorsal stream also projects from the striate cortex to the posterior-parietal cortex where visual and proprioceptive information is combined for later use in motor-related cortical regions. These features underlie the immediacy with which the dorsal stream operates and implicates it as a mediator of online limb control.

In summary, the behavioral and neural evidence on goal-directed movement demonstrates that the sensorimotor system uses sensory feedback to control movement, even when there is minimal time available to do so. These findings run counter to the notion that such movements are exclusively under pre-programmed control (Henry & Rogers, 1960; Plamondon 1995a, 1995b; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). As previously indicated,

approximately 150 msec elapses from the beginning (i.e., stride-foot contact) to the end (i.e., ball release) of the kinetic chain of events within the throw (Fleisig et al., 2009). In any movement, there is likely a point late in the overall trajectory where error can be detected but not corrected. This is especially likely in the overarm throw, given the momentum that accumulates at the upper extremity. Aside from the demand to overcome these inertial aspects at the upper extremity to effectively alter the movement trajectory, the humerus begins to rotate very late in the pitch cycle, lagging behind the upper torso after 80% of the kinetic chain of events is complete (Werner, Gill, Murray, Cook, & Hawkins, 2001). Therefore, the adjustments that hypothetically occur late in the pitch cycle are likely due to errors detected early in the overall movement trajectory. Nevertheless, based on previous reports of the movement times in which closed-loop control processes occur, it seems likely that visual and proprioceptive feedback is used to guide the throwing motion following stride-foot contact.

Appropriately timing the sequence of body segment rotations is fundamental to producing effective throwing mechanics. Slight fluctuations in timing can lead to considerable differences in performance outcomes (Hore, Watts, & Tweed, 1996; Jegede, Watts, Stitt, & Hore, 2005; Matsuo et al., 2001). Proper timing is also associated with the efficiency of the throwing motion (Aguinaldo, Buttermore, & Chambers, 2007; Aguinaldo & Chambers, 2009). In addition to timing, positional orientations of body segments are also associated with performance quality and efficiency (Werner et al., 2001; Werner, Suri, Guido, Meister, & Jones, 2008). Even elite level throwers exhibit inter-trial variability in their mechanics (Stodden et al., 2001; Stodden et al., 2005). Therefore, it would appear that online corrections are necessary to preserve the quality and efficiency of performance. Visual feedback about the target combined with proprioceptive feedback about limb position provides a basis for error detection and correction.

Based on the previously presented evidence, this sensory information is readily accessible to motor-related regions of the cortex and may be used in sufficient time for online adjustments to be implemented.

Similar to the perceptual perturbations simulated in previous research on upper-extremity limb control, the current investigation will systematically alter target location upon stride-foot contact. This perturbation will take place in two test conditions where the target translates from its initial location to the left or right. In another test condition, the target will remain in its initial location. By comparing differences in ball trajectory, kinematics, and muscle activity on attempts with the perturbation (i.e., test-left and test-right) and without the perturbation (test-center), it will be possible to determine whether the sensorimotor system is using sensory feedback to control the movement trajectory. Attempts during a pre-test condition will also be compared to identify anticipatory strategies that may be used during test conditions.

Statement of the Purpose

The primary purpose of this investigation was to determine whether skilled throwers can control the trajectory of overarm throws online following stride-foot contact. If online control is possible, the secondary purpose was to identify the sources of adjustment within the movement pattern.

Hypotheses

The primary hypothesis was that there would be significant differences in the ball's landing location between the test-center condition relative to the test-left and test-right conditions. It was further hypothesized that there would not be a significant difference in the ball's landing location between the pre-test and test-center condition.

The hypothesized sources of adjustment within the movement pattern were as follows:

Positional Kinematic & EMG Parameters

Lateral trunk tilt at ball release would be significantly greater in the test-left condition relative to the other test conditions.

Humeral horizontal adduction angle at ball release would be greater in the test-left condition relative to the other test conditions. The peak activity of the pectoralis major and anterior deltoid would be greater in the test-left condition relative to other test conditions.

Elbow angle at ball release would be lesser in the test-left condition relative to the other test conditions. The peak activity of the biceps would be greater in the test left-condition relative to other test conditions.

Temporal Kinematic Parameters

The latency of peak pelvis angular velocity following stride-foot contact would be significantly longer in the test conditions relative to the pre-test condition.

The overall time from stride-foot contact to ball release would be significantly longer in the test conditions relative to the pre-test condition.

Chapter 2

Review of Literature

The primary purpose of this investigation was to determine whether skilled throwers can control the trajectory of overarm throws online following stride-foot contact. If online control is possible, the secondary purpose was to identify the sources of adjustment within the movement pattern. Extensive research on the biomechanics of overarm throwing has provided insight into the influence of various kinetic, kinematic, and temporal parameters on performance and injury. Despite the considerable amount of data available on these mechanics, little is known about the sensorimotor control processes driving them (Hore, Ritchie, & Watts, 1999; Hore & Watts, 2005). Moreover, the generalizability of the existing research is questionable. There are two primary objectives for the current chapter. The first objective is to draw from previous research at various levels of analysis concerning the neural and behavioral basis of goal-directed limb control. The second objective is to evaluate the existing research relating to sensorimotor control in overarm throwing, speculate on the possibility of a closed-loop mode of control in the throwing motion, and discuss the hypothetical nature of online adjustment(s) within the movement pattern. This chapter is divided into four sections followed by a brief summary: (a) neurophysiological evidence, (b) neuropsychological evidence, (c) psychophysical evidence, and (d) sensorimotor control in overarm throwing performance.

Neurophysiological Evidence

The existence of two separate pathways facilitating visual perception, the dorsal and ventral visual streams, is well established (e.g., Held, 1970; Ingle, 1973; Leibowitz & Post, 1982;

Milner & Goodale, 1995; Schneider, 1967, 1969; Ungerleider & Mishkin, 1982). In early investigations concerning visual perception, Schneider (1967, 1969) observed that hamsters with ablations to visual areas 17 and 18 were unable to discriminate patterns but could orient to objects in the environment. In another group of hamsters, the tectum was ablated, effectively disconnecting the superior colliculus. These hamsters were capable of discriminating patterns but could not orient to an object's location. Schneider (1969) interpreted these findings as an indication that there was a cortical visual pathway associated with identifying what an object is and a separate, subcortical pathway that provided information about an object's location in space. The findings of subsequent investigations (Held, 1970; Ingle, 1973) were consistent with this interpretation. This was the consensus until Ungerleider and Mishkin (1982) published their experiments on monkeys. Though they reported on two pathways, they suggested that both were cortical. They labeled these two cortical pathways emerging from the visual cortex the dorsal and ventral streams. Lesions to the ventral stream rendered monkeys incapable of discriminating between objects of different shapes; lesions to the dorsal stream compromised the monkeys' ability to perform landmark discrimination tasks. Thus, Ungerleider and Mishkin (1982) proposed that the ventral stream mediates object recognition, whereas, the dorsal stream provides information about an object's location in the environment.

This perceptual dichotomy was revised slightly by Milner and Goodale (1995) to account for the dorsal stream's involvement with limb control during goal-directed movement. This model asserts that the ventral stream facilitates vision-for-perception and the dorsal stream mediates vision-for-action. According to Milner and Goodale (1995), both visual streams operate on different time scales placing constraints on the perceptual functions each can assume (Cohen, Cross, Tunik, Grafton, & Culham, 2009; Desmurget, Prablanc, Jordan, & Jeannerod, 1999;

Milner & Goodale, 2008; Reichenbach, Bresciani, Peer, Bulthoff, & Thielscher, 2011; Rice, Tunik, Cross, & Grafton, 2007; Tunik, Johnson-Frey, & Grafton, 2005).

The corticoretinal projections (i.e., parvocellular and magnocellular cells) each visual stream receives partially account for these time scale differences. The axons of midget and parasol ganglion cells form the respective origin of the parvocellular and magnocellular pathways. A fundamental difference between these pathways exists in the temporal and spatial sensitivities associated with each (Schiller, 1996). For example, the parvocellular pathway processes visual stimuli at higher spatial frequencies making it better suited for perceptual awareness of fine detail. Conversely, the magnocellular pathway processes visual stimuli at higher temporal frequencies making it optimal for perceiving motion (Logothetis, 1994; Snowden, 1994). Additionally, the magnocellular pathway exhibits response latencies that are 10-20 ms shorter than that of the parvocellular pathway (Bullier & Nowak, 1995; Maunsell et al., 1999). Though both corticoretinal pathways project to the ventral stream, the dorsal stream receives its input almost entirely from the magnocellular pathway (Merigan & Maunsell, 1993). The short response latency and high temporal resolution of this corticoretinal input appear advantageous in the context of limb control, especially in rapid movements.

Another fundamental difference between the visual streams is the distinct brain regions to which each projects. The ventral stream projects to the infero-temporal cortex, and the dorsal stream projects to the posterior parietal cortex (Ungerleider & Mishkin, 1982). The posterior parietal cortex integrates visual and somatosensory input for subsequent use in motor-related regions of the cortex (Reichenbach et al., 2011; Rizzolatti, Luppino, & Matelli, 1998). The inferior temporal cortex participates in both visual perception and memory (Miyashita, 1993). Collectively, the functional characteristics of the corticoretinal input each visual stream receives

and the brain regions to which each visual stream projects underlie their respective perceptual functions. Specifically, the dorsal stream's role in mediating online limb control appears to be linked to the short transmission latency and high temporal resolution characteristic of its primary corticoretinal input, as well as the cortical regions to which it projects.

Neuropsychological Evidence

The dorsal stream's contribution to online control of goal-directed action (e.g., aiming, grasping, pointing, reaching, etc.) has also garnered support from research involving human subjects who have damage to regions within one of the visual streams. By contrasting behavioral deficits observed in either case, inferences can be made with regard to the specific functions attributed to each stream. A behavioral impairment associated with visual form agnosia, a condition resulting from damage to the ventral stream, exists in the inability to recognize objects. One subject with visual form agnosia has been studied extensively. Though this individual struggles with object recognition, the ability to control goal-directed limb movement remains relatively intact (Goodale, Meenan, et al., 1994; Rice, et al., 2006). A subject afflicted with optic ataxia, a condition stemming from damage to the dorsal stream, does not struggle with object recognition but cannot orient limb movements to an object's location in space (Goodale, Meenan, et al., 1994; Milner, Paulignan, Dijkerman, Michel, & Jeannerod, 1999).

Researchers have directly examined the dorsal stream's role in controlling limb trajectory by disrupting the functioning of associated brain regions in otherwise healthy human subjects. In one experiment, subjects performed aiming movements to a target that either remained stationary or changed position upon movement initiation (Desmurget et al, 1999). After the movement was initiated, a perturbation was applied via transcranial magnetic stimulation (TMS) to the posterior parietal cortex of the cerebral hemisphere contralateral to the moving limb. This perturbation was

intended to induce a temporary lesion to the dorsal stream. Given the cross-circuited nature of descending, corticospinal pathways, it was hypothesized that online adjustments to the limb's trajectory would be inhibited. Indeed, online corrections did not occur during attempts when TMS was applied and the target changed position. These findings are consistent with those of other experiments where TMS is applied to the anterior intraparietal sulcus, an area within the dorsal stream that is active when online corrections in the limb's trajectory are necessary to acquire the target (Rice et al., 2006; Rice et al., 2007; Tunik et al., 2005).

Though the ventral stream does not contribute to controlling limb trajectory online, it is involved in movement planning, as it reconstructs coordinates of the target/object from memory for use in both the short and long term (Glover, 2004). Accordingly, if a delay is required before reaching or grasping, errors in the visual form agnostic patient's limb trajectory will increase (Goodale, Jakobson, & Keillor, 1994; Milner, Dijkerman, & Carey, 1999). In contrast, the optic ataxic patient's ability to orient limb movements is enhanced when there is a delay before initiating the movement (Milner, Dijkerman, McIntosh, Rossetti, & Pisella, 2003; Milner et al., 2001; Revol et al., 2003; Rice et al., 2008). These findings suggest that under delayed conditions, the ventral stream is recruited because it provides a means for acquiring perceptual information from memory. Such is the case because visual information processed in the dorsal stream is available only on an immediate, faster time scale.

Other experiments involving healthy subjects have yielded findings consistent with those previously mentioned. For example, TMS applied to the anterior intraparietal sulcus (i.e., dorsal stream) is detrimental in both delayed and immediate conditions, whereas, TMS to the lateral occipital cortex (i.e., ventral stream) adversely impacts performance in delayed conditions (Cohen et al., 2009). These findings suggest that the ventral stream is essential for controlling

limb trajectory when visual information provided by the dorsal stream deteriorates. Recent research has also indicated that healthy subjects store representations of the target in memory and combines this information with visual feedback of limb trajectory for controlling reaching movements online (Heath, 2005).

Collectively, these findings highlight the different time scales with which each visual stream operates. Specific to the purpose of this chapter, the dorsal stream conveys visual feedback to motor-related regions of the cortex with negligible delays, implicating it as a mediator of online limb control during goal-directed action. Notwithstanding this evidence, extensive research from the psychophysics domain of motor control has demonstrated that the visual input conveyed by the dorsal stream enables the sensorimotor system to amend the trajectory of limb movements in exceptionally short intervals of time.

Psychophysical Evidence

Similar to neuropsychological investigations, research from the psychophysics domain of motor control provides insight into the sensorimotor system's limitations at the behavioral level of analysis. Over the past century, various theoretical models of limb control have been developed to account for the speed-accuracy relations observed during goal-directed behavior (e.g., aiming, reaching, grasping). While it is beyond the scope of this chapter to document the evolution of these theoretical models (for a thorough review on this topic, see Elliott et al., 2010), the original two-component model proposed by Woodworth (1899) has remained at the foundation of current theoretical positions on goal-directed limb control.

Woodworth (1899) reported that goal-directed limb movements are composed of two distinct phases. During the initial phase, limb trajectory is rapid and consistent relative to the second phase in which it becomes increasingly variable. Accordingly, two components constitute

the overall movement trajectory. Fundamentally, the presence of separate components is thought to reflect the delays in processing visual stimuli. In essence, the primary movement brings the limb in the vicinity of the target. By the time the primary movement is executed, visual feedback is available enabling a secondary sub-movement to acquire the target. In his experiments, Woodworth (1899) specified that 450 ms was necessary for visual feedback to be used to control limb trajectory. Though subsequent investigations have determined certain factors can reduce this time (Beggs & Howarth, 1972; Carlton, 1981; Keele & Posner, 1968; Zelaznik, Hawkins, & Kisselburgh, 1983), the two-component model remains central to contemporary theoretical explanations of limb control in the context of goal-directed movement. In the recent past, researchers have attempted to account for the sensorimotor system's strategy in implementing this two-component model (e.g., Elliott, Hansen, Mendoza, & Tremblay, 2004; Lyons, Hansen, Hurding, & Elliott, 2006).

In multijoint aiming movements the limb is propelled from its resting position to a peak velocity and then negatively accelerates until the target is acquired. Data from experiments on these movements have indicated that the primary movement typically undershoots the target, with overshoots occurring on only a fraction of the overall number of attempts (Chua & Elliott, 1993; Elliott et al., 2004; Engelbrecht, Berthier, & O'Sullivan, 2003). Elliott et al. (2004) examined the effects of practice on the frequency of undershooting the target. On each of the four practice days, only 10% of attempts fell short of the target, potentially indicating a preference to maximize efficiency. In short, overshooting the target requires that the limb be negatively accelerated to a zero-velocity, and then re-accelerated in the reverse direction to the target. Inherently, muscular forces must be graded to slow and speed the limb, thus, requiring additional work. A follow-up investigation examined whether the sensorimotor system

undershoots the target in an attempt to optimize energy expenditure (Lyons et al., 2006). The data from this and other investigations have provided compelling evidence for the efficiency hypothesis (Elliott, Hansen, & Grierson, 2009; Todorov, 2004; Trommershauser, Gepshtein, Maloney, Landy, & Banks, 2005).

Maximizing efficiency is particularly relevant to overarm throwing athletes. These athletes are susceptible to overuse injuries that result from repeated application of high-magnitude joint torques and forces acting at the upper extremity (Fleisig, Andrews, Dillman, & Escamilla, 1995). The concept of efficiency in the context of overarm throwing and multijoint aiming highlights a fundamental difference between these movements. In multijoint aiming, the target is acquired when the limb makes physical contact with it. Inherently, the limb will negatively accelerate until the target is acquired. The goal-directed component of the overarm throw requires that the projectile, not the limb, makes contact with the target. In addition to maximizing the accuracy of the projectile's spatial trajectory, there is also a performance demand to maximize its speed. In order to maximize speed the limb must accelerate through projectile release. This feature explains recent research examining the parallels between overarm throwing performance (Urbin, Stodden, Boros, & Shannon, 2012; Urbin, Stodden, Fischman, & Weimar, 2011) and theoretical models of goal-directed limb control that entail ballistic force production (Schmidt & Sherwood, 1982).

Despite this fundamental difference, the research on multijoint aiming movements provides insight into the speed with which the sensorimotor system can use visual feedback to implement online adjustments. Though there is some debate regarding the importance of central planning processes (Henry & Rogers, 1960; Plamondon 1995a, 1995b; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979), there is ample empirical evidence indicating online control

processes occur, even when the overall duration of the movement is short. As explained in the first section of this chapter, visual information is conveyed to motor-related regions of the cortex by the dorsal stream with negligible delay. Therefore, the time scaling of the dorsal stream presumably accounts for the sensorimotor system's capacity to control rapid limb movements online.

Perceptual perturbation paradigms have enabled researchers to dissociate pre-programmed motor commands from those issued and implemented while the movement is in progress. One way these perceptual perturbations have been simulated is through use of prism spectacles that laterally displace vision. In one study, these spectacles displaced vision by 15° during aiming movements (Elliott & Allard, 1985). On some attempts, accurate visual information was provided after the movement was initiated. Results indicated that errors were detected and corrected if the overall movement duration was at least 140 ms.

Similar studies have manipulated the size of the target after movement initiation to assess how limb trajectory is altered in response to new accuracy demands (Langolf, Chaffin, & Foulke, 1976; MacKenzie, Marteniuk, Dugas, Liske & Eickmeier, 1987; Soechting, 1984). When the target size is altered, a disproportionate increase in the duration of time is spent following peak velocity. In another investigation, both target size and location were manipulated to determine whether the movement trajectory was associated with the accuracy constraints imposed by the size and location of the target before or after movement onset (Heath, Hodges, Chua, & Elliott, 1998). Kinematic analyses indicated that peak velocity, as well as the time-course to this velocity, was associated with initial target size and location; the duration of time spent after peak velocity was associated with terminal target characteristics. These findings imply that the sensorimotor system is able to use visual information about the target while the movement is in

progress. Similar experiments have reported that these adjustments are observed as early as 150-160 ms into the movement trajectory (Cressman, Franks, Enns, & Chua, 2006; Saunders & Knill, 2003). In rapid punching movements, corrections have been observed in approximately 110 ms (Bard, Hay, & Fleury, 1985).

Another perceptual perturbation paradigm that has been used extensively in the psychophysics domain is the double-step paradigm. This paradigm requires the subject to fixate visual attention on a light until a target appears, at which time the subject projects the limb to the target (i.e., step 1). During the eye saccade required to locate the target in space, the target will translate 2° to 4° to the left or right while the subject reaches for it (i.e., step 2). Kinematic analyses of the wrist indicate limb trajectory is adjusted toward the target's terminal location in approximately 100 ms (Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991; Pelisson, Prablanc, Goodale, & Jeannerod, 1986). In these and other investigations, subjects report not being consciously aware of any change in target location (Day & Brown, 2001; Day & Lyon, 2000; Desmurget et al., 1999; Prablanc & Martin, 1992). This finding seems to suggest that the cortical pathways integrating visual and proprioceptive input operate faster than those regions facilitating conscious awareness. Presumably, this is due to the speed of processing visual stimuli within the dorsal stream.

In experiments examining the temporal disparity between online control and perceptual awareness, subjects produced three distinct responses to target translation corresponding to separate conditions (Castiello, Paulignan, & Jeannerod, 1991). The first response is similar to the double-step procedure previously described. That is, subjects respond to target translation by visually fixating and reaching for it. The second response requires a verbal appraisal of target translation. The third response is a combination of both responses. The verbal appraisal required

by the second and third condition indicates that the subject is consciously aware of a change in the target's location. Though adjustments to the limb trajectory occurred within 107 ms of the target changing location, over 300 ms passed before a verbal appraisal. These differences were noted between the first and second condition, as well as within the third condition. The findings indicate that the sensorimotor system is capable of controlling limb trajectory online even when the visual feedback warranting corrections to the movement has not reached consciousness.

The purpose for this section of the chapter is to demonstrate that visual information is used by the sensorimotor system to control limb trajectory in very short intervals of time. As such, it is important to note that some researchers have contended that the response times reported in the double-step paradigm experiments are overestimated. In essence, when the limb is projected toward the target, the muscular torques required to alter its path in the direction of the terminal target must overcome its momentum toward the original target. Kinematic analyses alone cannot account for this dynamic. The Lambda (λ) model (i.e., equilibrium-point hypothesis) asserts that descending motor commands use local spinal cord circuitry as a basis for changing muscle activity and, in turn, regulating limb control. This model was used to simulate the control of multijoint limb movement and address the overestimation of response times associated with double-step targeting (Feldman, Adamovich, Ostry, & Flanagan, 1990; Flanagan, Ostry, & Feldman, 1990; 1993). In all simulations, the virtual trajectory produced by the model responded to perturbations within 65 ms.

In summary, the trajectory of goal-directed limb movements is not exclusively associated with features of the muscular impulse preprogrammed by the central nervous system (Elliott, et al., 1999). The immediacy with which the dorsal stream processes visual stimuli for integration with somatosensory input plays a central role in the sensorimotor system's ability to control the

movement trajectory online. Therefore, it can be concluded that visual information is not used solely for the purpose of orienting the position of body segments prior to limb propulsion. Rather, this sensory input provides an external reference for detecting and correcting errors in the spatiotemporal trajectory of segments while the movement is in progress. However, the gain associated with such closed-loop processes may not be adequate if transmission times along the loop are lengthy. Delays in synaptic transmission and sensory receptor dynamics increase transmission time. Additionally, the gradual rise in force generation within a muscle (i.e., electromechanical delay) in response to descending commands from the motor cortex augments the delay associated with using sensory information to modify movement trajectory. These delays are potentially detrimental in the performance context of extremely rapid movements, such as the overarm throw.

Sensorimotor Control in Overarm Throwing Performance

The rapid nature of the overarm throw is best exemplified by the peak angular velocities of the individual joint actions constituting the overall movement pattern in elite level throwers. For example, the upper torso rotates in the direction of projectile release at a peak angular velocity of approximately 1200 °/s (Escamilla, Fleisig, Barrentine, Zheng, & Andrews, 1998). The humerus internally rotates to a peak angular velocity of approximately 7000 °/s, making it the fastest joint action ever measured (Fleisig et al., 1995; Dun, Fleisig, Loftice, Kingsley, & Andrews, 2007). Additionally, the elbow extends at an angular velocity of approximately 3000 °/s (Werner, Fleisig, Dillman, & Andrews, 1993; Wisleder, Fleisig, Dillman, Schob, & Andrews, 1989). These extreme distal segment velocities result from sequential accelerations of body segments (i.e., proximal-to-distal sequencing) that allow passive interaction torques to be exploited (Hirashima, Kudo, & Ohtsuki, 2003). Slight variations in temporal onset of rotations

among segments can lead to differences in projectile speed (Alexander, 1991; Fleisig, Chu, Weber, & Andrews, 2009). Moreover, appropriately timing joint rotations is critical for the projectile to assume an accurate spatial trajectory (Hore, Watts, & Tweed, 1996). While these performance-related features exemplify the complexity associated with coordinating an effective overarm throw, skilled throwers have been reported to time projectile release with a temporal variability of 7-10 ms (Hore, Watts, Martin, & Miller, 1995; Jegede, Watts, Stitt, & Hore, 2005).

The precision with which this event occurs, coupled with the notion that some movements are too fast to be guided by peripheral feedback (Lashley, 1951), led researchers to examine whether a feedforward mechanism controls projectile release (Hore, Ritchie, & Watts, 1999). It was hypothesized that differences in the latency of ball release would be observed between unperturbed throws to a target and throws where elbow extension was slowed or blocked with a rope attached to the wrist, or wrist flexion was slowed by changing the mass of the ball. Ball release was defined as the instant when the distal phalanx reversed direction relative to the hand. The authors reasoned that blocking or slowing elbow and wrist rotations would dampen the discharge rate of Ia afferents, in turn, dampening the neural signal required to contract the distal phalanx. As such, differences in ball release latency between unperturbed and perturbed throws would provide evidence of a feedforward mechanism controlling projectile release. However, no differences were observed.

In a later investigation, Hore and Watts (2005) measured the amplitude of extension at the proximal interphalangeal joint (PIJ) while subjects performed throws of varying speeds with a ball of constant mass. Results indicated that there was no difference across subjects in the amplitude of extension at the PIJ when the hand reached a fixed angular position in space regardless of throwing speed. The researchers concluded that projectile release is based on an

internal positional representation that matches angular positions of finger opening to the intended path of the hand. Internal models are thought to predict the sensory consequences of actions and can be used to overcome the delays associated with biological feedback loops, particularly in the context of rapid arm movements (Davidson & Wolpert, 2005).

Proponents of forward internal models suggest that sensory estimates can provide the missing sensory feedback that is available only at the end of the movement. The cerebellum is thought to contain these internal models and, therefore, acts as a Smith Predictor (Miall, Weir, Wolpert, & Stein, 1993). Such a mechanism couples a forward model located within a high gain internal feedback loop with a model of the transport delays (Wolpert, Miall, & Kawato, 1998). Consistent with these interpretations, Hore and Watts (2005) suggest that precisely timed projectile release occurs by a spatial controller within the cerebellum. This controller hypothetically adjusts the strength and timing of muscle contraction based on internal predictions of the executed motor command's sensory outcome (Wolpert et al., 1998).

While the experimental procedures of Hore and Watts (2005) are sound, generalizing these findings to the overarm throw, as it is coordinated in the actual performance context, is questionable. This doubt is based on the throwing tasks from which data were derived. Subjects performed throws while seated and strapped to a chair, or from a static, standing position (i.e., the left foot approximately 45 cm in front of the right, both feet stationary). In short, maximal-effort throws performed without lower extremity involvement and restriction of proximal segment rotations does not parallel the movement profile associated with maximal-effort throws in a typical performance context.

The summation-of-speed principle (Bunn, 1972; Putnam, 1991) maintains that each body segment makes a contribution to the throwing motion that is not independent of other segments

(Neal, Snyder, & Kroonenberg, 1991). Following proximal segment rotations, angular momentum will be transferred through the skeletal linkage to the upper extremity summing at the final distal link. Consistent with this concept, it has been reported that 47% of ball speed is lost when proximal segments are immobilized (Toyoshima, Hoshikawa, Miyashita, & Oguri, 1974). The point here is that differences in the amount of energy generated and transferred from the lower extremities and trunk directly influences the extreme range of motion exhibited at the upper extremity and, in turn, the time the sensorimotor system has to detect and correct for error in the overall movement trajectory.

Unlike less-developed throwers, skill throwers have acquired the ability to maximize the involvement of the lower extremities and trunk (Stodden, Langendorfer, Fleisig, & Andrews, 2006a). The momentum from these proximal segment rotations is then transferred to the upper extremity, causing it to lag behind the upper torso while the humerus externally rotates to anatomical limits (i.e., $\geq 180^\circ$, Fleisig, Barrentine, Escamilla, & Andrews, 1996). Thus, maximum humeral external rotation is achieved after stride-foot contact and after the pelvis and upper torso begins rotating in the direction of projectile release. In doing so, the upper extremity must negatively accelerate to a zero velocity before re-accelerating in the direction of projectile release. Though these movement characteristics lead to very rapid individual joint actions, as indicated by the peak angular velocities previously specified, they may also provide sufficient time for the sensorimotor system to integrate visual and proprioceptive feedback for use in controlling the movement online.

Relating back to the findings of psychophysics research on goal-directed limb control, the time from movement initiation until target acquisition reflects the time available for the sensorimotor system to detect and correct errors in the limb's trajectory. In overarm throwing,

the analogous phase is the time from stride-foot contact to projectile release, as this phase is crux of the throwing motion. This phase lasts approximately 150 ms in skilled throwers (Fleisig et al., 2009). In the trajectory of any movement, there is a critical point where sensory feedback can no longer be used in a closed-loop mode of control. However, the time from stride-foot contact to maximum external rotation of the humerus is approximately 124 ms (Werner, Gill, Murray, Cook, & Hawkins, 2001). Previous findings from the psychophysical domain indicate that visual feedback is used to make online corrections approximately 100 ms into the movement. Therefore, it is reasonable to suspect that visual feedback is combined with proprioceptive feedback to correct for errors in the movement trajectory following stride-foot contact. Though a closed-loop mode of control could not be expected to operate in the throwing task of Hore and Watts (2005), it cannot be ruled out in the usual performance context and in a skilled thrower.

The notion that variability in intersegmental coordination of whole-body movements, such as the basketball free throw (Button, MacLeod, Sanders, & Coleman, 2003; Mullineaux & Uhl, 2010) and jump shot (de Oliveira, Huys, Oudejans, van de Langenberg, & Beek, 2007), may be indicative of adjusting for error to improve end-point accuracy is well documented. Recently published data may indicate that skilled team-handball players exhibit this functional form of variability (Wagner, Pfusterschmied, Klous, Serge, & Müller, 2011). However, there is no evidence that directly indicates sensory feedback can be used in a closed-loop mode of control following stride-foot contact during throwing performance.

The remainder of this chapter considers the hypothetical nature of adjustment within the throwing motion. As previously specified, performance outcomes result from the extent to which interactions between individual body segments are optimized (Alexander, 1991; Hirashima et al., 2003; Putnam, 1991). Additionally, elite level throwers have been shown to exhibit considerable

inter-trial variability in key performance parameters during the time from stride-foot contact to ball release (Stodden, Fleisig, McLean, & Andrews, 2005; Stodden, Fleisig, McLean, Lyman, & Andrews, 2001). Therefore, this phase will be considered. During this discussion, references will be made to the arm-cocking and arm-acceleration phases of the throw. Arm cocking begins at stride-foot contact (SFC) and ends at maximal external rotation of the humerus (MER); the arm-acceleration phase begins at MER and ends at projectile release (PR) (Fleisig et al., 1995).

Approximately 30 to 50 ms after SFC, the pelvis begins to rotate in the direction of projectile release; approximately 50 to 70 ms after SFC, the upper torso begins to rotate in this direction (Escamilla et al., 1998). The delay of upper torso rotation after stride-foot contact occurs at a greater latency in professional pitchers relative to pitchers at lower competition levels (Aguinaldo, Buttermore, & Chambers, 2007). While this delay is indicative of greater elastic potential energy that is favorable for maximizing projectile speed, it should be noted that professional pitchers also exhibit less normalized internal rotation torque at the shoulder. Repeated exposure to high rotational torque places substantial tensile stress on the soft tissues of upper extremity joints (Werner, Murray, Hawkins, & Gill, 2002). The repeated microtrauma that results is thought to increase a thrower's susceptibility to overuse injury (Fleisig et al., 1995). Similarly, throwers who exhibit a greater delay between maximum pelvis and upper torso angular velocities produce higher projectile speeds relative to those who exhibit less time between these two events (Matsuo, Escamilla, Fleisig, Barrentine, & Andrews, 2001; Takahashi, Fujii, & Michiyoshi, 2002). While maximizing proximal segment rotations increases projectile speed (Matsuo et al., 2001; Takahashi et al. 2002) and attenuates the need for excessive rotational torques at the shoulder (Fleisig et al., 1996), it may also increase the time for sensory feedback processing.

The possible kinematic sources where online corrections are implemented within the throwing motion are challenging to conceptualize because of the high velocity with which individual body segments are rotating. In other words, there is considerable angular momentum that must be overcome to alter the movement trajectory. As such, it would appear that lateral and forward trunk tilt may be a primary source of online adjustment. Even elite throwers tend to exhibit inter-trial variability in forward trunk tilt (Stodden et al., 2005). By modulating the concentric contractions of the abdomen musculature, as well as the hip musculature contralateral to the throwing arm, the sensorimotor system may be able to adjust the position of the trunk, effectively repositioning the upper extremity and altering its spatial trajectory.

The rotations that occur about the shoulder and elbow, as well as the pattern of muscle activity producing these rotations, are important determinants of the performance outcome. The complexity associated with coordinating the passive and active muscle contractions makes their role in facilitating these performance outcomes challenging to conceptualize. Though it seems likely that any online correction is contingent upon the specific contextual factors warranting it, the patterns of muscle activity underlying individual joint actions provides insight into the kinematic characteristics of the upper extremity and any online adjustment that may be implemented in the associated body segments late in the movement trajectory.

During the arm-cocking phase, the anterior deltoid is active to help maintain the humerus at 90° of abduction, thus, maximizing the mass moment of inertia of the humerus relative to the upper torso (Escamilla et al., 1998). As momentum is transferred, the pectoralis major and anterior deltoid are active to horizontally adduct the humerus (Figure 3) at an angular rate of approximately 600 °/s from a position of 20° of horizontal abduction at SFC to 20° of horizontal adduction at MER (Escamilla et al., 1998). Because the trunk is rotating very rapidly, the

supraspinatus, infraspinatus, teres minor, and subscapularis become highly active to produce a centripetal acceleration required to keep the humeral head in the glenoid (Fleisig et al., 1995). Subsequently, the pectoralis major, latissimus dorsi, and subscapularis contract eccentrically to produce an internal rotation torque that reduces the rate of change in the humeral external rotation angle to zero at MER (Figure 9) (DiGiovine, Jobe, Pink, & Perry, 1992; Fleisig et al., 1995). Additionally, the serratus anterior is highly active throughout the arm-cocking phase to properly move and position the scapula relative to the humerus (Escamilla & Andrews, 2009). During the initial portion of this phase, the triceps contracts eccentrically to control the rate of elbow flexion (Figure 4) (Werner et al., 1993); at the end of this phase, it contracts concentrically to initiate elbow extension (Escamilla & Andrews, 2009). In the arm-acceleration phase, the subscapularis, pectoralis major, and latissimus dorsi are highly active to internally rotate the humerus (DiGiovine et al., 1992). Some of the scapular muscles (i.e., teres minor, infraspinatus, and supraspinatus) also become active to maintain the position of the humeral head within the glenoid (DiGiovine et al., 1992). The concomitant demands associated with accelerating the upper extremity segments at the previously specified angular velocities, as well as maintaining the integrity of joint structures, necessitate this magnitude of muscle activity.

In addition to the magnitude of activation observed in the upper extremity musculature, there is also a temporal sequence with which it occurs. The temporal onset of muscle activation at the shoulder follows a proximal-to-distal sequence (Hirashima, Kadota, Hiroshi, Sakurai, Kudo, & Ohtsuki, 2002). The serratus anterior of the 6th rib is active prior to serratus anterior of the 8th rib. After these scapular protractors are activated, the anterior deltoid and pectoralis major fire almost simultaneously. Finally, the lateral head of the triceps brachii, pronator teres, and flexor carpi ulnaris become active.

As can be inferred, there is a complex pattern of muscle activity at the upper extremity serving to stabilize joint structures and propel individual segments at the appropriate time. Potential sources of online adjustment in the upper extremity seem obscure given the complexity of these activation patterns. However, the extreme degree of humeral external rotation causes the internal rotators (e.g., pectoralis major, subscapularis, and latissimus dorsi) to undergo a high rate of stretch. This dynamic may account for the subsequent trajectory of the upper extremity. In essence, movements that incorporate a counter-movement activate intrafusal fibers (i.e., muscle spindles) that lead to an exploitation of the stretch-shortening cycle (McCaulley et al., 2007). The λ -model (Feldman, 1986) describes limb control as a mass-spring dynamic and emphasizes this neural component. Specifically, the model suggests that muscle activation is increased in proportion to the difference between the current length of the muscle and the length (λ) at which it is initially activated. As such, principles of this model may be useful in accounting for the upper extremity trajectory from the point of MER to PR, which tends to be very brief (approximately 30 ms, Werner et al., 2001). The λ -model proposes that the peripheral organization of the muscle and its neural components represent complex units that can be modulated via descending motor commands. Consequently, this model may provide insight into online adjustments at the upper extremity late in the throwing motion.

Summary and Conclusion

Based on the research presented in this chapter, there is reason for future research to examine online control processes in skilled overarm throwers. Attempts made to elucidate the origins of adjustment within the movement pattern that preserve performance quality may have practical utility. Examining online control from a learning perspective is also warranted. Though early accounts of motor learning assert that highly skilled performers are less reliant on sensory

information (Pew, 1966; Schmidt & McCabe, 1976), this view is not consistent with the findings of subsequent research (Elliott, Ricker, & Lyons, 1998; Proteau, Marteniuk, & Lévesque, 1992; Proteau, Tremblay, & DeJaeger, 1998).

Drawing from various levels of analysis relating to limb control, this chapter has attempted to demonstrate the relevance of online sensorimotor control processes to overarm throwing performance, specifically after stride-foot contact. Based on the neurophysiological and neuropsychological research presented, it is apparent that the dorsal stream conveys visual feedback to the sensorimotor system with negligible delay. Research from the psychophysics domain indicates that visual and somatosensory input is integrated and used to amend the trajectory of goal-directed upper extremity movement in very short intervals of time. These findings, taken together with the complex interactions that occur between body segments during the throwing motion, suggests that a closed-loop mode of control contribute in some way to successful throwing performance.

Chapter 3

Method

The primary purpose of this investigation was to determine whether skilled throwers can control the trajectory of overarm throws online following stride-foot contact. If online control is possible, the secondary purpose was to identify the sources of adjustment within the movement pattern. A controlled laboratory study with a completely within-subjects design was used to satisfy these objectives. This chapter describes how the experiment was conducted and consists of the following six sections: (a) Subjects, (b) Apparatus, (c) Instrumentation, including electromyography and motion capture, (d) Procedure, (e) Data Reduction, and (f) Statistical Analyses, including ball trajectory, electromyography, and motion capture.

Subjects

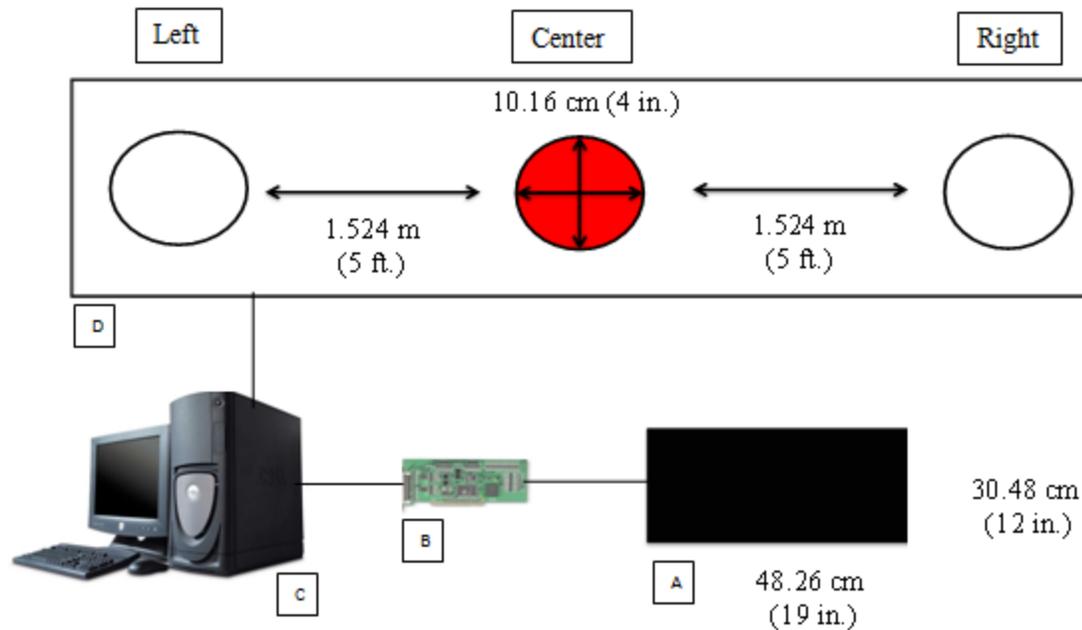
Eight male, undergraduate students who pitched competitively at the high school level participated in the study. Two subjects competed at the junior college level. The mean age, height, and mass of subjects were 21.38 ± 1.3 years, 183.52 ± 4.0 cm, and 77.7 ± 7.3 kg, respectively. All subjects were right-hand dominant and lacked any musculoskeletal condition that would be adversely impacted by participation. Subjects were recruited based on their ability to produce ball speeds of 31.3 m/s (70 mph) or greater. Subjects were retained for testing if the average ball speed across 10 pre-test trials was ≥ 31.3 m/s. This inclusion criterion was intended to ensure that subjects exhibited segmental lag characteristics indicative of advanced throwing skill development (Stodden, Langendorfer, Fleisig, & Andrews, 2006a; 2006b). Each subject

provided informed consent by signing a form approved by the Auburn University Institutional Review Board (Appendix A).

Apparatus

The change in target location was simulated with three lights (Figure 1), each consisting of a soldered array of light-emitting diodes. Each light was 10.16 cm in diameter and mounted to a wall at a height of 1.22 m above the ground. The lights were positioned 152.4 cm apart in the horizontal dimension. This arrangement provided the subject with three potential targets requiring a decisive online adjustment. The substantial distance between targets also minimized the risk of misinterpreting the intended throwing target.

The center target was mounted 8.84 m from a pressure-sensitive mat (.61 x .33 m) that subjects contacted with their stride-foot. The 152.4 cm offset between the center light and the right and left lights formed subtended angles of approximately 10 degrees from these outside targets with the vertex at the pressure-sensitive mat. Stride-foot contact with this mat actuated a signal transmitted to a data acquisition device. The illumination of each light was controlled according to commands specified by the experimenter in a custom-written Labview program. The center light was illuminated prior to every test trial and remained illuminated in the test-center condition. In the test-left/test-right condition, stride-foot contact caused the center light to extinguish and the left/right light to illuminate, thus, simulating a translation of target location. The delay between stride-foot contact and illumination of the appropriate target was negligible (≤ 100 microseconds).



- A: Force-sensitive mat
- B: Data acquisition device
- C: Computer containing Labview Program
- D: Lights (Center, Left, Right)

(Force-sensitive mat was centered relative to center light and positioned 8.84 meters (29 feet) from wall containing lights. Lights were positioned 1.22 meters (4 feet) above ground.)

Figure 1. Illustration of apparatus with dimensions.

Instrumentation

Electromyography

Bipolar Ag/AgCl active surface EMG electrodes were placed over the area of greatest bulk on the anterior deltoid, pectoralis major, biceps brachii, and long head of the triceps with a 1 cm inter-electrode distance. A reference electrode was placed over the acromion process.

Electrodes were anchored over the muscle with pre-wrap and athletic tape. Electromyographic signals were sampled at 3000 Hz over a bandwidth of 20–450 Hz using a telemetry EMG system

(DelSys Bagnoli 8, DelSys Inc., Boston, MA: differential amplification, input impedance > 1015/0.2 ohm/pF, CMRR = 92 dB @ 60 Hz, SNR = 65 dB, overall noise (RMS, RTI) <1.2 IV). After A/D conversion, EMG signals were corrected for DC bias, bandpass filtered at 20–350 Hz and notch filtered at 59.5–60.5 Hz (2nd order Butterworth). In addition, EMG signals were smoothed using a 100 ms time constant RMS sliding window function.

Motion Capture

Six cameras, backlit with spotlights, tracked the location of reflective markers. The cameras captured data synchronously at 180 Hz with a 1/1000-shutter speed. A digital image processing system (Motion Reality Incorporated, Marietta, GA) recorded the three-dimensional location of each reflective marker visible in two or more of the cameras. Thirty-eight permanent markers and six temporary markers were affixed to spandex clothing overlying the approximate location of anatomical landmarks (Figure 2a and 2b).

Three markers were attached to a baseball hat each subject wore (not shown in Figures 2a and 2b). Three markers were attached to each of the hands at the radial styloid and the second and fifth carpophalangeal joints. Three markers were attached to each of the arms at the lateral epicondyle of the elbow, the lateral portion of the mid-humeral shaft, and the acromion process. One marker was placed on the anterior upper torso at the mid-sternum. Five markers were placed on the posterior upper torso at the lower angle of each scapula and on the scapular spine and on the thoracic vertebra directly between the markers on the scapular spines. Subjects wore a belt around the waist with five total markers located above each anterior superior iliac spine and on the lumbar vertebra; a marker was placed midway between these two locations on both sides. Four markers were placed on each knee at the lateral condyle of the tibia and tibial tuberosity. Four markers were placed on each foot at the approximate location of the dorsal surface of the

first and fifth distal phalanges, the lateral aspect of the fifth metatarsal, and the calcaneus. Temporary markers were placed on the mediolateral shoulder rotational axis, the medial portion of the elbow near the antecubital space, and on the greater trochanter of the femur. These temporary markers were necessary to scale and appropriately locate each body segment in a hierarchical model. The subject stood in the capture volume with the shoulders abducted to approximately 70° for the scaling procedure that allowed the segments to be scaled and appropriately defined. Temporary markers were removed prior to pre-test and test trials. However, the subject assumed this same position before each pre-test and test trial.



Figure 2a. Anterior view of marker set-up.



Figure 2b. Posterior view of marker set-up

A model configuration was generated that was as consistent as possible with the marker locations for each motion capture frame. System variable values corresponding to these marker locations were derived through an optimization process enabled by a number of preliminary measures that established the model characteristics. The optimal model configuration was that which was most consistent with the measured global marker coordinates. Consistency was defined as the sum of squared error terms over each marker. The error for any marker was the difference between its model-based location and its actual global location. Therefore, the system

variables were those values that minimized the sum of the squared distances between the global location of the marker and its model-based or predicted location.

Procedure

Subjects came to the motion capture laboratory on two separate days with no more than 48 hours between the pre-test and test. Before the pre-test, subjects were guided through a warm-up protocol consisting of 10 minutes of cycling followed by a combination of static and dynamic stretches. Then, the subject performed warm-up throws until he felt prepared to throw at maximal effort. Once prepared, the subject performed 10 maximal-effort throws with a tennis ball to the center target. All subjects threw on flat ground from a stride. After each attempt, two observers identified and recorded two-dimensional accuracy (i.e., radial error) of the ball's landing location relative to the target by extending a measuring tape from the center of the target to the center of the ball's landing location. Additionally, the observers identified and recorded the global x- (horizontal) and y- (vertical) coordinates of the ball's terminal location with 0 reflecting the center of the center target. Ball speed was obtained from a Stalker II radar gun (Stalker Radar, Plano, TX) positioned behind the subject. Motion capture and EMG data were also collected on these trials. After the final throw, the subject was introduced to the three experimental conditions in which he would perform on the test day (i.e., test-center, test-left, and test-right). The subject performed 10 additional throws where these conditions were presented randomly. These practice trials were meant to familiarize the subject with the test conditions. Following each throw, the approximate distance of the stance leg to the pressure-sensitive mat was measured with a measuring tape. These distances were used to establish a location for the subject to position his stance-foot on the test day. No other data were collected on these throws.

On the test day, the subject was guided through the same warm-up protocol. Once prepared, the subject performed 30 maximal-effort throws to the target. Tape was placed on the ground for the subject to position his stance-foot to ensure the stride-foot made contact with the pressure-sensitive mat. Motion capture and EMG data, ball speed, global x- and y- coordinates of the ball's landing location, as well as the radial error of the ball's landing location relative to the target were collected on these trials. The three experimental conditions (i.e., test-center, test-left, and test-right) were presented equally over the 30 trials in a pre-specified, quasi-random order with the stipulation that the same condition would not appear on more than two consecutive trials. This order was determined via a random number generator. The subject was not informed of the total number of trials presented in each experimental condition and was instructed to throw the ball to the illuminated target while maintaining maximal ball speed. Prior to testing, there was a stipulation that trials where ball speed was below 80% of the average ball speed from pre-test trials would be repeated. However, ball speed never dropped below this lower limit.

Data Reduction

Ball Trajectory

The global x- and y- coordinates of the ball's terminal location were used to calculate bivariate variable error (BVE) for each condition, providing an index of variability in two-dimensional space (Hancock, Butler, & Fischman, 1995). The radial error (RE) derived by measuring the distance between the ball's landing location and the target was averaged across the 10 trials in each condition. Ball speed and the global x- coordinate (i.e., in the horizontal dimension) of the ball's landing location were averaged across the 10 trials in each condition.

Motion Capture

Motion capture data on the three trials with the most accurate global x- coordinate relative to final target location were analyzed. The three most accurate trials were analyzed to increase the likelihood of detecting differences in the adjustments made between conditions. The selection of three trials is also consistent with previous throwing research that used a within-subjects design to analyze kinematic data (e.g., Escamilla, Fleisig, Barrentine, Zheng, & Andrews, 1998; Shouchen, Kingsley, Fleisig, Loftice, & Andrews, 2008). Positional kinematic parameters were calculated at the instant of ball release. These parameters included humeral horizontal ab/adduction, elbow flexion/extension, lateral trunk tilt, forward trunk tilt, pelvis orientation, and upper-torso orientation. Ball release was defined as the first frame where the wrist origin overtook the elbow origin in the throwing direction (i.e., capture negative-x direction). The capture x-direction was defined as the throwing direction, the capture y-direction was defined as the vertical direction, and the capture z- direction was defined as the cross-product of the capture x- and y- directions.

Angular displacements associated with the glenohumeral and elbow joints, as well as those about the pelvis and upper torso, were calculated according to a procedure in Fleisig, Escamilla et al. (1996). Humeral horizontal ab/adduction (Figure 3) was defined as the angle formed by unit vectors projecting along the longitudinal axis of the upper arm and a line projecting between the shoulders. Elbow flexion/extension (Figure 4) was defined as the angle formed by unit vectors projecting along the longitudinal axis of the upper arm and forearm in the frontal plane. Lateral trunk tilt (Figure 5) was defined as the angle formed by a unit vector projecting from the mid-pelvis and mid-upper torso in the global z (i.e., mediolateral) direction in the global yz plane. Forward trunk tilt (Figure 6) was defined as the angle formed by a unit

vector projecting from the mid-pelvis and mid-upper torso in the frontal plane and the global y (i.e., vertical) direction in the global xy plane. The mid-pelvis was defined as the midpoint of a line projecting between the hips, and the mid-upper torso was defined as the midpoint of a line projecting between the shoulders. Pelvis and upper-torso orientation (Figures 7 and 8, respectively) were defined as the angle formed by a line projecting between the hips/shoulders and the x-axis in the global xz plane. Maximum humeral external rotation was also calculated (Figure 9). This parameter was defined as the angle formed by a unit vector projecting from the mid-pelvis and mid-upper torso and the unit vector projecting along the longitudinal axis of the forearm in the plane perpendicular to the upper arm.

Peak velocity kinematic parameters were calculated between the instant of stride-foot contact and ball release. These parameters included peak linear and angular velocities of the pelvis and upper torso, as well as the peak angular velocity of elbow extension. Two independent raters visually inspected the frame-by-frame animations of each throw to determine stride-foot contact. Inter-rater objectivity for stride-foot contact was calculated using the proportion of agreement adjusted for chance, or *kappa* coefficient (Safrit & Wood, 1995). The resulting kappa coefficient was .91. The pelvis and upper torso angular velocities were calculated with a method reported by Feltner & Dapena (1986). Angular velocity of the pelvis was obtained from successive orientation of the pelvis vector and its derivative. Angular velocity of the upper torso was obtained from successive orientation of the upper torso vector and its derivative. Angular velocity of elbow extension was calculated as the rate of change in elbow angle.

Temporal kinematic parameters were calculated based on the frames in which stride-foot contact, ball release, and peak angular velocities of the pelvis, upper torso, and elbow extension, occurred. These events were used to quantify five parameters consisting of the time between: 1)

stride-foot contact and maximum pelvis angular velocity, 2) maximum pelvis and upper torso angular velocities, 3) maximum upper torso and elbow extension angular velocities, 4) maximum elbow extension angular velocity and ball release, 5) stride-foot contact and ball release.

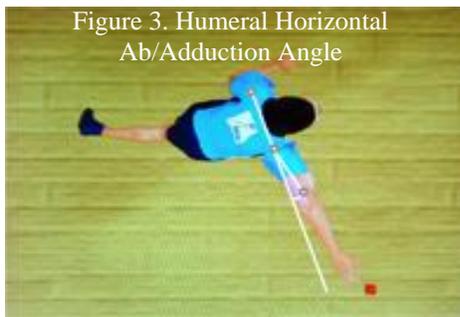


Figure 3. Humeral Horizontal Ab/Adduction Angle



Figure 4. Elbow Angle



Figure 5. Lateral Trunk Tilt Angle



Figure 6. Forward Trunk Tilt Angle



Figure 7. Pelvis Orientation Angle



Figure 8. Upper Torso Orientation Angle



Figure 9. Humeral Maximum External Rotation Angle

Electromyography

EMG data were analyzed on the same three trials as motion capture data. The peak activation of the anterior deltoid, pectoralis major, biceps brachii, and long-head of the triceps was identified between stride-foot contact and ball release. This peak was normalized to the peak activation prior to stride-foot contact. The magnitude of activation over the time from stride-foot contact to ball release was summed and divided by the number of data points between these two events. This value was then normalized to the peak activity prior to stride-foot contact. Thus, two EMG parameters were calculated for each muscle: normalized peak activity and normalized average activity.

Statistical Analysis

Ball trajectory parameters were averaged across subjects and then entered into separate repeated-measures ANOVAs to test for differences between conditions: 1) pre-test, 2) test-center, 3) test-left, and 4) test-right. EMG and kinematic parameters were averaged for each subject and entered into statistical analyses. Both EMG parameters were entered into a 4 (condition) x 4 (muscle) repeated-measures MANOVA. Positional, velocity, and temporal kinematic parameters were entered into separate repeated-measures MANOVAs. All statistical procedures were performed in SPSS (PASW Statistics 18). Alpha level was set at .05 for all analyses. If significant, Bonferroni post-hoc analyses were used to identify specific differences. Power and effect size (i.e., partial eta squared) were also calculated. In cases where the sphericity assumption was violated, Greenhouse-Geisser estimates were used.

Chapter 4

Results

The primary purpose of this investigation was to determine whether skilled throwers can control the trajectory of overarm throws online following stride-foot contact. If online control is possible, the secondary purpose was to identify the sources of adjustment within the movement pattern. This chapter presents the results of the study and is divided into the following sections: (a) ball trajectory parameters, (b) kinematic parameters, and (c) electromyography parameters. Complete ANOVA summary tables for all analyses appear in Appendix G.

A total of ten subjects volunteered to participate. However, two subjects did not produce an average ball speed of ≥ 31.3 m/s over pre-test trials, and were not retained for testing. The remaining eight subjects completed all pre-test and test trials.

Ball Trajectory Parameters

x-Component of Global Ball Landing Location

The global x-component of the ball's landing location by condition is presented in Figure 10. The repeated-measures ANOVA indicated that the main effect for condition was significant, $F(1.385, 9.697) = 45.99, p < .001$. The means (cm) for each condition were: pre-test = -9.84; test-center = -7.82; test-left = -90.94; test-right = 71.79. The effect size was .868 and power was 1.0. Bonferroni post-hoc tests indicated that the x-component in the pre-test was closer to zero than in the test-left ($p = .001$) and test-right ($p = .009$) conditions. The x-component in the test-center condition was also closer to zero in the test-left ($p = .001$) and test-right ($p = .002$) conditions. Additionally, the x-component in the test-left condition was different from the test-

right condition ($p = .001$). The x-component was negative in the test-left condition and positive in the test-right condition. There was no difference between the pre-test and test-center condition ($p = 1.0$).

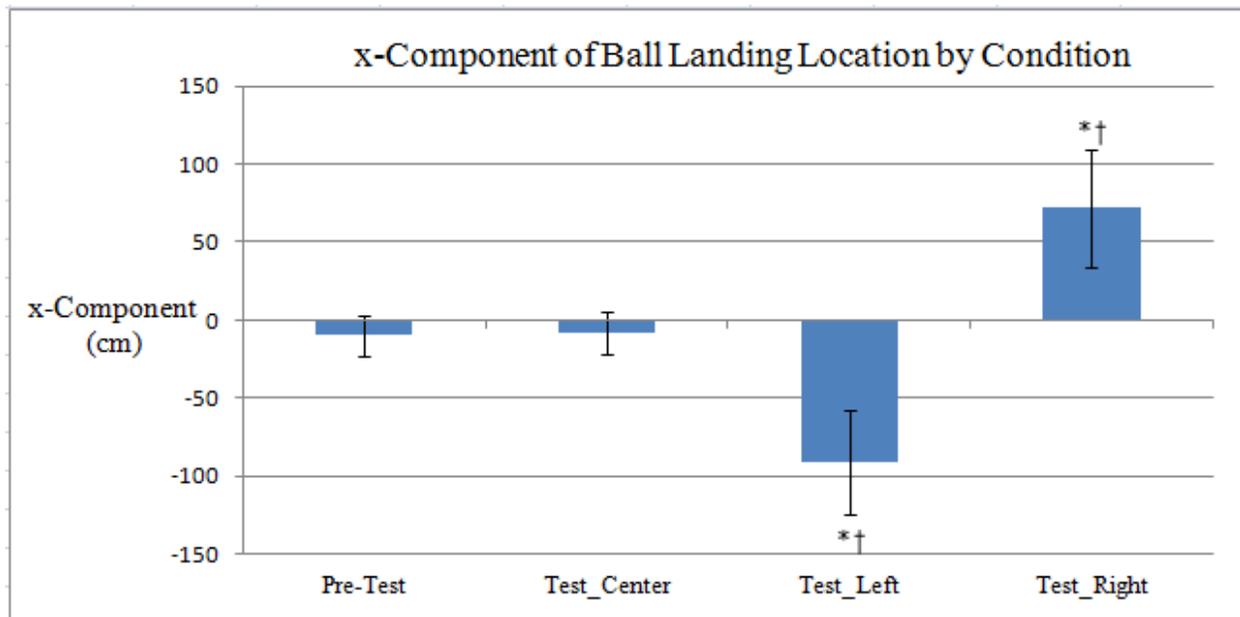


Figure 10. Mean global x-component by condition. (*) indicates a significant difference relative to the pre-test and the test-center condition, and (†) indicates a significant difference between the test-left and test-right conditions. Error bars represent the standard deviation.

Radial Error of Ball Landing Location

The radial error of the ball's landing location by condition is presented in Figure 11. The repeated-measures ANOVA indicated that the main effect for condition was significant, $F(1.838, 12.865) = 12.805, p = .001$. The means (cm) for each condition were: pre-test = 39.37; test-center = 43.29; test-left = 70.46; test-right = 87.69. The effect size was .647 and power was .980.

Bonferroni post-hoc tests indicated that the radial error in the pre-test was lower than in the test-left ($p = .012$) and test-right ($p = .025$) conditions. The radial error in the test-center condition was also lower than in the test-right condition ($p = .021$).

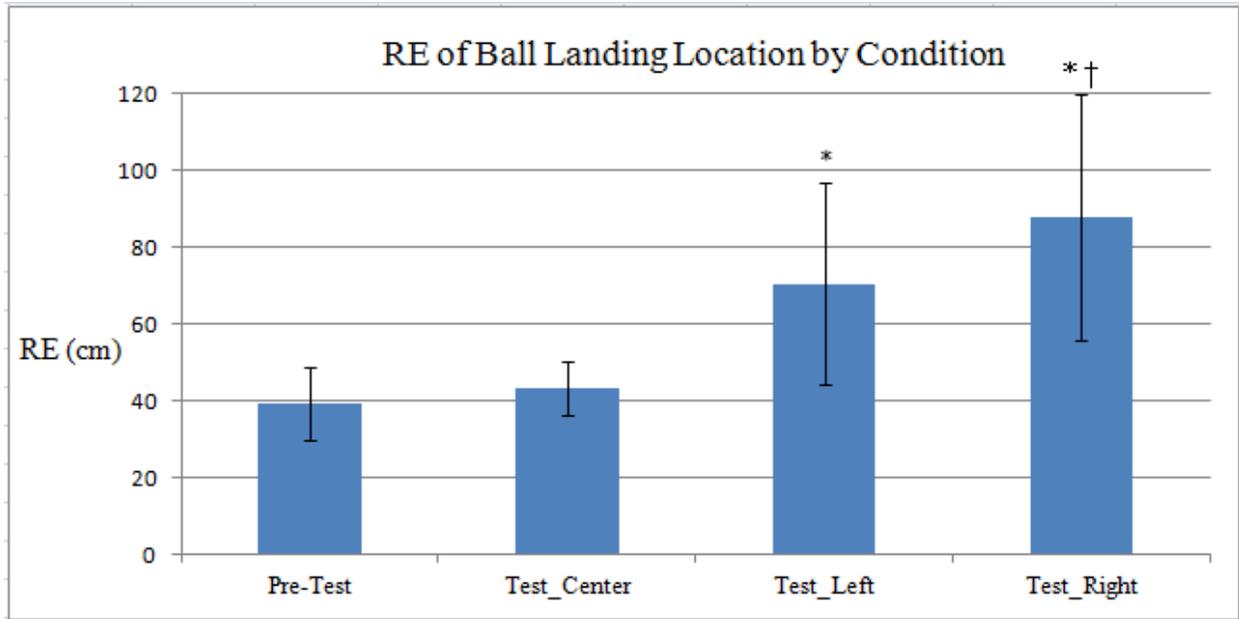


Figure 11. Mean radial error by condition. (*) indicates a significant difference relative to the pre-test and (†) indicates a significant difference relative to the test-center condition. Error bars represent the standard deviation.

Bivariate Variable Error of Ball Landing Location

The bivariate variable error of the ball's landing location by condition is presented in Figure 12. The repeated-measures ANOVA indicated that the main effect for condition was significant, $F(1.664, 11.649) = 11.913, p = .002$. The means (cm) for each condition were: pre-test = 37.49; test-center = 45.88; test-left = 58.3; test-right = 58.49. The effect size was .630 and power was .959. Bonferroni post-hoc tests indicated that bivariate variable error in the pre-test was lower than in the test-left ($p = .045$) and test-right ($p = .001$) conditions. The bivariate variable error in the test-center condition was also lower than in the test-right condition ($p = .006$).

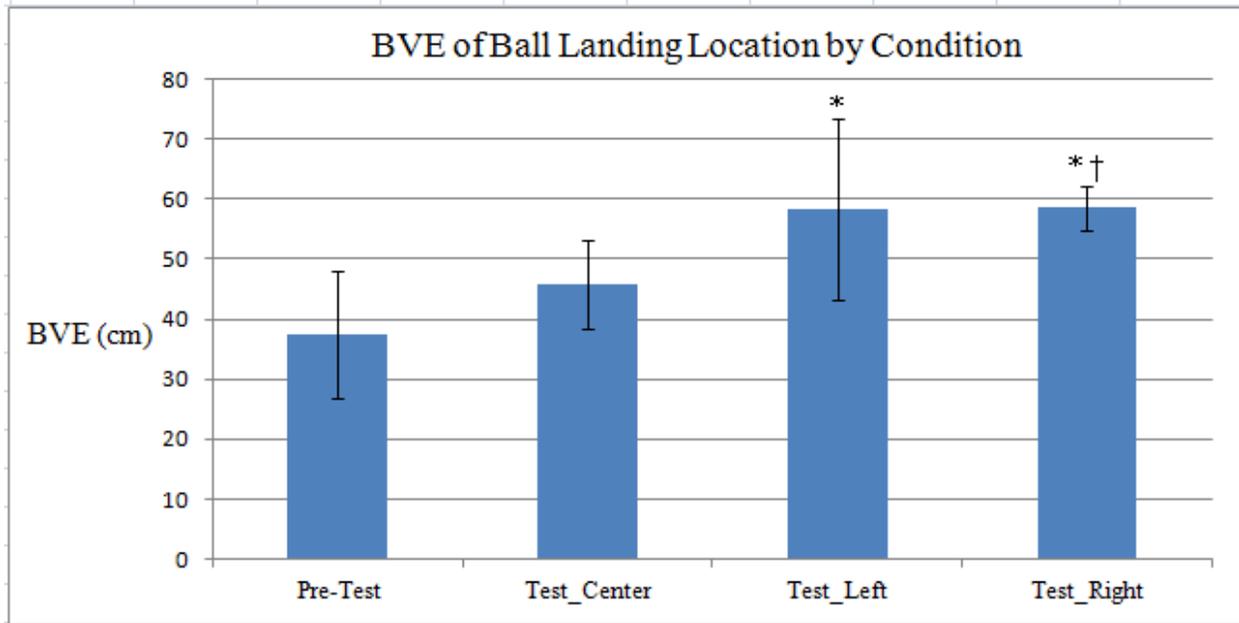


Figure 12. Mean bivariate variable error by condition. (*) indicates a significant difference relative to the pre-test and (†) indicates a significant difference relative to the test-center condition. Error bars represent the standard deviation.

Ball Speed

Ball speed by condition is presented in Figure 13. The repeated-measures ANOVA indicated that the main effect for condition was significant, $F(2.054, 14.381) = 18.931, p < .001$. The means (m/s) for each condition were: pre-test = 35.28; test-center = 33.33; test-left = 33.37; test-right = 33.46. The effect size was .730 and power was .999. Bonferroni post-hoc tests indicated that ball speed in the pre-test was significantly faster than in the test-center ($p = .002$), test-left ($p = .009$) and test-right ($p = .008$) conditions.

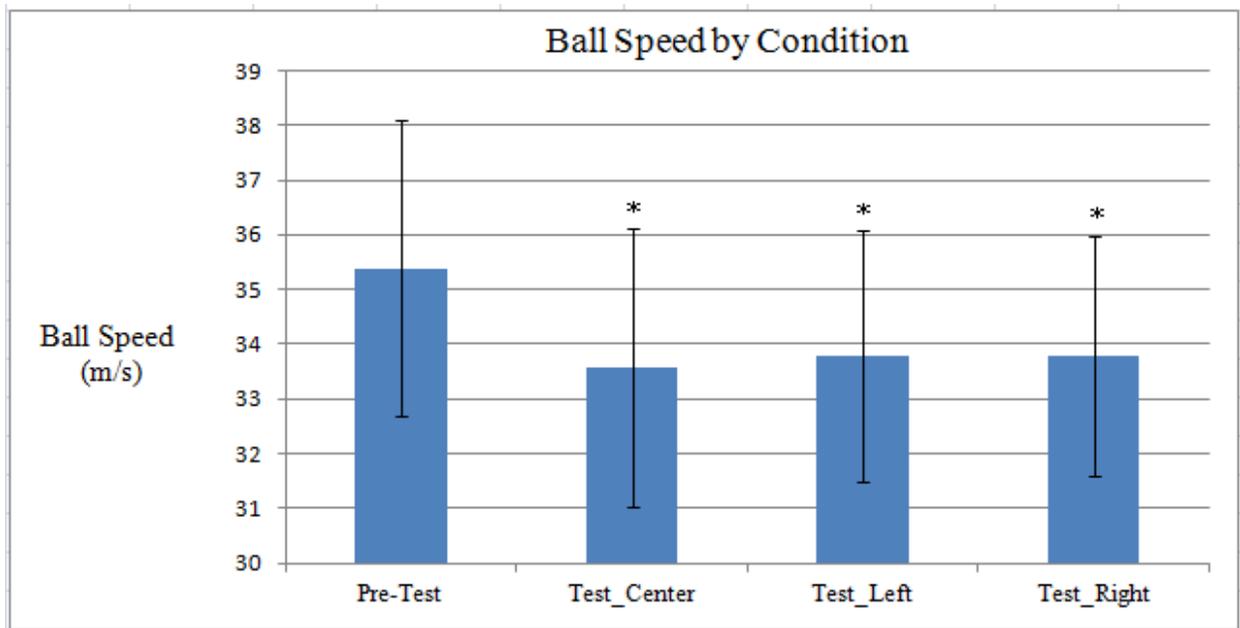


Figure 13. Mean ball speed by condition. (*) indicates a significant difference relative to the pre-test. Error bars represent the standard deviation.

Kinematic Parameters

Positional Parameters

Means and standard deviations for positional kinematic parameters by condition are presented in Table 1. The repeated-measures MANOVA was not significant, $F(21, 43.622) = .896, p = .596$. The effect size was .291 and power was .520.

Table 1. Means and standard deviations for positional kinematic parameters at ball release.

Kinematic Positional Parameter (°)	Pre-Test	Test-Center	Test-Left	Test-Right
Humeral Horizontal Ab/Adduction	-6.0 ±9.1	-6.4 ±7.3	-1.1 ±13.9	-5.0 ±9.9
Elbow Angle	162.2 ±9.3	162.3 ±9.5	160.5 ±4.2	158.1 ±13.8
Lateral Trunk Tilt	13.4 ±7.4	7.8 ±6.8	14.4 ±24.0	15.2 ±26.0
Forward Trunk Tilt	24.2 ±6.6	23.9 ±8.7	21.8 ±8.5	22.6 ±8.5
Pelvis Orientation	102.7 ±6.8	100.6 ±4.7	103.6 ±3.5	99.0 ±5.7
Upper Torso Orientation	107.2 ±4.8	104.4 ±5.0	105.9 ±7.8	100.1 ±9.2
Maximum Humeral External Rotation	146.1 ±2.0	145.1 ±3.3	145.6 ±2.1	144.3 ±3.9

Velocity Parameters

Means and standard deviations for velocity kinematic parameters by condition are presented in Table 2. The repeated-measures MANOVA was not significant, $F(15, 47.331) = 1.249, p = .271$. The effect size was .264 and power was .613.

Table 2. Means and standard deviations for peak velocity kinematic parameters.

Kinematic Velocity Parameter (°/s)	Pre-Test	Test-Center	Test-Left	Test-Right
Pelvis Linear	1.8 ±0.4	2.0 ±0.5	2.1 ±0.3	2.1 ±0.4
Upper Torso Linear	3.1 ±0.5	3.2 ±0.4	2.9 ±0.4	3.1 ±0.4
Pelvis Angular	818.4 ±77.2	785.2 ±87.1	791.9 ±87.9	820.2 ±164.6
Upper Torso Angular	1080.9 ±141.0	1089.5 ±217.4	1122.4 ±94.5	1053.3 ±119.3
Elbow Extension Angular	3046.9 ±418.8	2954.2 ±532.7	3155.6 ±430.5	2930.4 ±424.4

Temporal Parameters

Means and standard deviations for temporal kinematic parameters by condition are presented in Table 3. The repeated-measures MANOVA was not significant, $F(15, 47.331) = 1.373, p = .200$. The effect size was .283 and power was .665.

Table 3. Means and standard deviations for temporal kinematic parameters.

Kinematic Temporal Parameter (ms)	Pre-Test	Test-Center	Test-Left	Test-Right
Stride-Foot Contact to Peak Pelvis Angular Velocity	108.8 ±40.5	165.7 ±64.3	174.7 ±61.1	171.9 ±61.5
Peak Pelvis to Upper Torso Angular Velocity	35.7 ±21.7	41.4 ±22.1	40.9 ±36.5	26.4 ±13.2
Peak Upper Torso to Elbow Extension Angular Velocity	35.2 ±18.8	27.7 ±26.1	28.4 ±25.8	39.2 ±14.4
Peak Elbow Extension Angular Velocity to Ball Release	10.4 ±5.5	14.5 ±6.1	11.9 ±5.3	10.1 ±6.9
Stride-Foot Contact to Ball Release	190.1 ±33.8	238.9 ±48.8	255.3 ±59.2	247.6 ±47.5

EMG Parameters

Peak and Average Activity

Means and standard deviations for normalized peak and normalized average activity by muscle and condition are presented in Table 4. The 4 (Condition) x 4 (Muscle) MANOVA for peak and average activity indicated that the main effect for condition was not significant, $F(6, 40) = 1.338, p = .263$. The effect size was .167 and power was .462. The interaction was also not significant, $F(18, 124) = .787, p = .712$. The effect size was .103 and power was .542.

Table 4. Means and standard deviations for peak and average activity by muscle and condition.

EMG Parameters	Pre-Test	Test-Center	Test-Left	Test-Right
<i>Normalized Peak Activity (stride-foot – ball release)</i>				
Anterior Deltoid	1.3 ±0.4	3.2 ±3.3	2.6 ±1.4	3.1 ±2.4
Pectoralis Major	2.5 ±2.5	3.8 ±1.9	3.5 ±1.9	4.3 ±3.4
Bicep	1.2 ±1.9	1.6 ±1.1	1.9 ±1.9	1.5 ±1.2
<u>Tricep</u>	6.0 ±5.0	14.4 ±16.8	13.7 ±18.1	12.1 ±14.7
<i>Normalized Average Activity (stride-foot – ball release)</i>				
Anterior Deltoid	0.8 ±0.3	1.5 ±0.9	1.5 ±0.7	1.7 ±1.3
Pectoralis Major	1.3 ±1.2	2.0 ±1.1	1.9 ±1.0	1.8 ±1.2
Bicep	0.7 ±0.5	0.7 ±0.3	0.8 ±0.5	0.8 ±0.5
<u>Tricep</u>	2.6 ±1.3	5.0 ±4.3	5.0 ±5.3	5.2 ±5.3

Chapter 5

Discussion

The primary purpose of this investigation was to determine whether skilled throwers can control the trajectory of overarm throws online following stride-foot contact. If online control is possible, the secondary purpose was to identify the sources of adjustment within the movement pattern. This chapter provides an interpretation and discussion of the results from this study. The discussion of results progresses according to parameter category and consists of ball trajectory findings followed by kinematic and electromyography findings. After these findings are discussed, conclusions and recommendations for future research are provided.

Ball Trajectory

The difference between conditions in the global x-component of the ball's landing location provides evidence that skilled throwers are able to control the movement trajectory online following stride-foot contact. This parameter was calculated because the change in target location was constrained to the horizontal dimension. As such, the x-component of the ball's landing location in global space provides the most direct index of the subjects' ability to adjust to target translation. Results indicate that subjects were adjusting in the direction of target translation following stride-foot contact.

Two other spatial measures of the ball's landing location were calculated and analyzed providing an index of the accuracy and variability in each condition. Radial error was used to quantify the ball's two-dimensional landing distance from the target location. Bivariate variable error was used to quantify the ball's two-dimensional landing distance from its mean landing

location. For radial error, subjects were less accurate in the test-left and test-right conditions relative to the pre-test. Subjects were also less accurate in the test-right condition relative to the test-center condition. The same trends were observed in bivariate variable error. That is, subjects were more variable in the test-left and test-right conditions relative to the pre-test. Additionally, subjects were more variable in the test-right condition relative to the test-center condition.

An inherent limitation of the current study was the artificial task required in the test-left and test-right conditions. That is, adjusting a maximal-effort throw to a target translating 152.4 cm to the right or left of its initial location is unrealistic and not typical of an actual throwing performance context. However, a substantial distance between target locations was necessary to differentiate between performance outcomes associated with motor commands implemented prior to stride-foot contact and those implemented online during the kinetic chain of events leading to ball release. Moreover, the large distance between targets was also necessary to rule out the possibility that the ball's landing location was attributable to noise in the sensorimotor system. Results indicate that the global x-component, radial error, and bivariate variable error of the ball's landing location were not different between the pre-test and test-center conditions. However, there were differences in these parameters between the test-left and test-right conditions. This indicates that the performance outcomes reflected by ball trajectory parameters were not due to noise in the sensorimotor system. Rather, findings of the current study reflect the sensorimotor system's ability to detect and correct for error following stride-foot contact (i.e., closed-loop control) supporting the primary hypothesis.

The mean global x-component of the ball's landing location in the test-left and test-right conditions was short of the 152.4 cm distance between the target's initial and terminal location in the horizontal dimension. This indicates that subjects, as a group, struggled to consistently

regulate ball trajectory under these conditions. The differences in accuracy and variability of the ball's landing location between the pre-test and test-left/test-right conditions may be accounted for by the subjects' lack of experience performing maximal-effort throws with the requirement to make such a considerable adjustment. This is likely due to the subjects' unfamiliarity with how to effectively manipulate their mechanics to project the ball in the appropriate direction.

Consistent with theoretical accounts of motor learning (e.g., Fitts & Posner, 1967), individuals exhibit similar trends in error (i.e., high variability, low accuracy) when faced with a novel task. If practice trials following the pre-test are included, subjects performed approximately 12 throws under the test-left and test-right conditions. Consequently, the relatively poor accuracy and high variability of the ball's landing location may be due to the novelty of the task.

The decreased accuracy and increased variability of the ball's landing location between the test-center and test-right conditions are likely due to a combination of factors. These factors include the right-hand dominance of each subject, the extreme velocities at which the trunk and upper extremity segments are rotating, and the latency with which online adjustments occur in the course of any movement. In terms of right-hand dominance, the center and left target locations are more accessible given the spatial trajectory of segmental rotations exhibited by a right-handed thrower. That is, the sequential rotation of the pelvis, upper torso, and humerus occur in a plane that is more aligned with center and left target locations rather than the right target location. This likely promotes an enhanced ability to regulate ball release in the direction of the center and left targets. Projecting the ball to the right target location is a relatively more complicated task because online adjustments occur late in the overall movement trajectory since error must be detected before it can be corrected. Moreover, body segments rotate away from the right target location in the right-handed thrower. Therefore, projecting the ball in this direction

would require the thrower to overcome the momentum of these high-velocity rotations to re-orient to the right target location. These factors, combined with the novelty of the task, may explain the trend for decreased accuracy and increased variability in test-right condition relative to the test-center condition. One would expect the opposite effect for left-handed throwers, but for similar reasons.

Ball speed was significantly lower in all test conditions relative to the pre-test. The reason for this finding is not straightforward. Though it may seem intuitive that subjects decreased the speed of the overall movement to gain a performance advantage in gauging the target's terminal location, this view is not supported by the kinematic analyses. Peak linear and angular velocities, as well as the timing of these velocities, were not different between the pre-test and test conditions. Additionally, the experimental protocol stipulated that any throw falling below 80% of the mean ball speed of pre-test trials would be repeated. This never occurred. In fact, the lowest mean ball speed under any test condition was approximately 92% of the mean ball speed from the pre-test. Another possibility is that the 30 test trials caused fatigue. However, this does not appear to be a viable explanation because 30-45 seconds elapsed between each trial to allow the motion capture system to process data from the previous trial. This delay likely provided adequate rest between trials. Additionally, every subject was monitored half way through the testing protocol, and none reported being excessively fatigued.

It is also possible that the drop in ball speed from the pre-test to test conditions may be attributable to the entire sample of subjects. Testing was scheduled within 48 hours of the pre-test to ensure that subjects maintained familiarity with the experimental protocol. None of the subjects reported being recreationally or competitively engaged in throwing activity at the time of testing. Therefore, it is possible that subjects were not in adequate physical condition to

produce maximal ball speeds over 30 trials required on the day of testing relative to the 10 trials performed in the pre-test. Some subjects reported muscle soreness from the pre-test; however, none indicated that this soreness was sufficient to keep them from participating on the test day. Consequently, the uniform decrease in ball speed from the pre-test to test conditions may be accounted for by a combination of these factors, further reflecting a limitation of the current study. Using a sample of subjects engaged in competitive and/or recreational throwing activity at the time of participation may have increased the probability of the subjects' ability to maintain ball speed on the day of testing. It is also acknowledged that the continuum of throwing skill extends beyond the classification used in the current study. However, the inclusion of subjects with high school and/or junior college pitching experience able to achieve the minimum ball speed criterion ensured the movement characteristics theorized to facilitate online control were exhibited.

Kinematics and Electromyography

The secondary purpose of this study was to examine the sources of adjustment within the movement pattern. As indicated by ball trajectory data, subjects were able to make online adjustments. However, the lack of significant differences in positional kinematic parameters at the time of ball release does not provide insight into the spatial adjustments subjects made in response to target translation. Accordingly, the hypothesized sources of adjustment (i.e., lateral trunk tilt, humeral horizontal ab/adduction, and elbow flexion/extension) were not supported. This is likely due to a combination of factors. First, the overarm throw entails the use of several body segments, some of which have multiple biomechanical degrees of freedom. When several segments are coordinated, the relation between the movement characteristics and the performance outcome is not always direct (Newell & Corcos, 1993). In other words, there are

numerous combinations of segmental trajectories subjects could have adopted to project the ball in the direction of the target. Consequently, inter-trial variations in the strategy subjects adopted possibly detracted from the ability to detect differences between conditions.

A second factor that may explain the lack of positional differences between conditions is associated with inter-subject variability. That is, the solutions adopted by one or more subjects may have been different from those used by other subjects. Though subjects were similar in terms of skill, this does not necessarily imply that they all used the same strategy to make online adjustments. Previous research supports this interpretation. Kinematic analyses of elite volleyball servers show a considerable amount of inter-subject variability that is not accounted for by group analyses (Temprado, Della-Grasta, Farrell, & Laurent, 1997). The volleyball serve is a movement that entails the same kinetic chain principles associated with overarm throwing. Consequently, inter-subject variability in the nature of online adjustment(s) may have also compromised the ability to detect differences between conditions.

A related issue further complicating the ability to detect differences in positional kinematic parameters by condition can be inferred from the individual subject means of the global x-component of the ball's landing location. These means indicate that some subjects were more adept at consistently making the full adjustment in ball trajectory in the test-left and test-right conditions. For example, subject JL was able to land the ball within 20 cm of the right target on 9 out of 10 attempts, whereas, subject JW was able to land the ball within this bandwidth on only 1 out of 10 attempts. Moreover, even with the intent to make the full adjustment, performance is still susceptible to error. As previously discussed, this propensity for error is theoretically exacerbated by the novelty of the task; hence, the rationale for analyzing the three most accurate attempts per condition. Nevertheless, the interplay between intra- and inter-

subject variability in the online strategies adopted, as well as the inability of some subjects to make the full adjustment, likely accounts for the lack of differences in positional kinematic parameters between conditions.

Similar to positional parameters, there were no significant differences in velocity kinematic parameters. The lack of differences in these variables may also be accounted for by a combination of the previously mentioned factors. However, the lack of differences between pre-test to test conditions indicates that some subjects were able to maintain peak linear and angular segmental velocities while making online adjustments. A clear performance advantage in this experimental task would be to slow the overall movement trajectory allowing more time to process visual information about the terminal target location. In goal-directed aiming movements, subjects typically respond to target perturbations by increasing the absolute and proportional amount of time following peak velocity (e.g., Heath, Hodges, Chua, & Elliott, 1998). However, this strategy is not viable in maximal-effort overarm throws. In the overarm throw and other kinetic chain movements, performance demands typically entail maximal projectile speeds. This requires that the most distal segment accelerates through release. Therefore, any reduction in segmental velocities would compromise performance. Despite the possibility of intra- and inter-subject variability in this regard, the lack of significance suggests that it is possible to maintain segmental velocities even with the demand to make online adjustments.

Consistent with the results of positional and velocity kinematics, the temporal kinematic and EMG parameters were also not significant. Without a change in segmental velocities between conditions, it seems logical that the timing between peak angular velocities would also not be different. Similarly, it also seems reasonable to suspect that there would not be differences

in the patterns of muscle activity underlying observable movement characteristics. However, a limitation of the current study is associated with measurement of both parameter categories. This limitation is due to the extremely short duration from stride-foot contact to ball release. The precise measurement of EMG and temporal parameters is related to accurate identification of the instant of stride-foot contact. A previous criterion used to identify this event was not consistent with visual inspection of the motion capture animations. Consequently, two independent raters determined the frame at which stride-foot contact occurred. The temporal resolution of the motion capture system yielded data every 6 msec. Therefore, any error associated with identifying this event with respect to overall movement duration possibly compromised the precision of measuring temporal kinematic and EMG parameters.

According to traditional perspectives of motor control, rapid movements are driven by central, feedforward sensorimotor control processes that are not responsive to afferent, sensory input (Henry & Rogers, 1960; Plamondon 1995a, 1995b; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). By these same accounts, motor skill acquisition is predicated on a diminished reliance on the use of sensory information to guide the movement trajectory (Keele, 1968; Schmidt & McCabe, 1976). However, the accumulation of research on goal-directed upper extremity movements suggests otherwise (for a review, see Elliott et al., 2010). Moreover, the findings of the current study indicate that sensory feedback is used to control the overarm throw following stride-foot contact (i.e., closed-loop control). Detecting the nature of the online adjustments generalizable to the entire sample of subjects was not possible due to the inherent complexity of coordination. Nevertheless, this study provides baseline evidence of online control in the maximal-effort overarm throws of skilled subjects.

Conclusion

Based on the findings of the current study, the following conclusion is made:

Skilled overarm throwers are able to use sensory feedback to control movement trajectory following stride-foot contact.

Recommendations for Future Research

The findings of the current study form the basis for the following recommendations for future research:

1. As previously discussed, to address the research question in the current study, subjects performed a throwing task under experimental conditions that exaggerated the demands of a typical performance context. The tradeoff associated with the novelty of these demands possibly compromised the subjects' ability to produce accurate and consistent ball trajectories. However, it is also possible that using sensory feedback to control a high-velocity movement online, especially under the demands imposed by this experiment, requires learning. Therefore, future research should explore the effects of practice on the ability to control maximal-effort throws online. It may also be possible that practicing under these demands may enhance a thrower's ability to use sensory feedback under normal performance conditions.
2. The simulation used in the current study may have practical utility. The high-magnitude joint kinetics associated with maximal-effort throwing are linked to multiple forms of shoulder and elbow overuse injury (Fleisig, Andrews, Dillman, & Escamilla, 1995). A pitcher's ability to appropriately time the latency of upper torso rotation is correlated with the magnitude of these kinetics (Aguinaldo, Buttermore, & Chambers, 2007; Aguinaldo & Chambers, 2009). Therefore, performance optimization practitioners should find ways

to promote the appropriate latency of upper torso rotation. Research from motor learning indicates that modeling techniques can promote acquisition of the appropriate temporal structure of movement (Blandin & Proteau, 2000). The current study demonstrated that subjects were able to use visual information to adjust the overall movement trajectory. Therefore, it may be useful for future research to examine whether simulations used in the current study can be tailored to effect change in the movement pattern of individual throwers.

References

- Alexander, R.M. (1991). Optimum timing of muscle activation for simple models of throwing. *Journal of Theoretical Biology*, *150*, 349-372.
- Aguinaldo, A.L., Buttermore, J., & Chambers, H.G. (2007). Effects of upper trunk rotation on shoulder joint torque between baseball pitchers of various levels. *Journal of Applied Biomechanics*, *23*, 42-51.
- Aguinaldo, A.L., & Chambers, H.G. (2009). Correlation of throwing mechanics with elbow valgus load in adult baseball pitchers. *American Journal of Sports Medicine*, *37*, 2043-2048.
- Bard, C., Hay, L., & Fleury, M. (1985). Role of peripheral vision in the directional control of rapid aiming movements. *Canadian Journal of Experimental Psychology*, *39*, 151–161.
- Blandin, Y., & Proteau, L. (2000). On the cognitive basis of observational learning: Development of mechanisms for the detection and correction of errors. *Quarterly Journal of Experimental Psychology*, *53*, 846-867.
- Beggs, W.D.A., & Howarth, C.I. (1972). The accuracy of aiming at a target: Some further evidence for a theory of intermittent control. *Acta Psychologica*, *36*, 171–177.
- Bullier, J., & Nowak, L.G. (1995). Parallel versus serial processing: New vistas on the distributed organization of the visual system. *Current Opinion in Neurobiology*, *5*, 497–503.
- Bunn, J.W. (1972). *Scientific principles of coaching (2nd Ed.)*. Englewood Cliffs, NJ: Prentice-Hall.

- Button, C., MacLeod, M., Sanders, R., & Coleman, S. (2003). Examining movement variability in the basketball free-throw action at different skill levels. *Research Quarterly for Exercise and Sport*, *74*, 257-269.
- Carlton, L.G. (1981). Processing visual feedback information for movement control. *Journal of Experimental Psychology: Human Perception and Performance* *7*, 1019–1030.
- Castiello, U., Paulignan, Y., & Jeannerod, M. (1991). Temporal dissociation of motor responses and subjective awareness: A study in normal subjects. *Brain*, *114*, 2639-2655.
- Chua, R., & Elliott, D. (1993). Visual regulation of manual aiming. *Human Movement Science*, *12*, 365–401.
- Cohen, N.R., Cross, E.S., Tunik, E., Grafton, S.T., & Culham, J.C. (2009). Ventral and dorsal stream contributions to the online control of immediate and delayed grasping: A TMS approach. *Neuropsychologia*, *47*, 1553-1562.
- Cressman, E. K., Franks, I. M., Enns, J. T., & Chua, R. (2006). No automatic pilot for visually guided aiming based on colour. *Experimental Brain Research*, *171*, 174–183.
- Davidson, P.R., & Wolpert, D.M. (2005). Widespread access to predictive models in the motor system: A short review. *Journal of Neural Engineering*, *2*, 313-319.
- Day, B.L., & Brown, P. (2001). Evidence for subcortical involvement in the visual control of human reaching. *Brain*, *124*, 1832-1840.
- Day, B.L., & Lyon, I.N. (2000). Voluntary modification of automatic arm movements evoked by motion of a visual target. *Experimental Brain Research*, *130*, 159-168.

- de Oliveira, R.F., Huys, R., Oudejans, R.R.D., van de Langenberg, R., & Beek, P.J. (2007). Basketball jump shooting is controlled online by vision. *Experimental Psychology*, *54*, 180-186.
- Desmurget, M., Epstein, C.M., Turner, R.S., Prablanc, C., Alexander, G.E., & Grafton, S.T. (1999). Role of the posterior parietal cortex in updating reaching movements to a visual target. *Nature Neuroscience*, *2*, 563-567.
- Desmurget, M., Prablanc, C., Jordan, M., & Jeannerod, M. (1999). Are reaching movements planned to be straight and invariant in the extrinsic space? Kinematic comparison between compliant and unconstrained motions. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *52*, 981-1020.
- DiGiovine, N.M., Jobe, F.W., Pink, M., & Perry, J. (1992). Electromyography of upper extremity in pitching. *Journal of Shoulder and Elbow Surgery*, *1*, 15-25.
- Dun, S., Fleisig, G.S., Loftice, J., Kingsley, D., & Andrews, J.R. (2007). The relationship between age and baseball pitching kinematics in professional baseball pitchers. *Journal of Biomechanics*, *40*, 265-270.
- Elliott, D., & Allard, F. (1985). The utilization of visual feedback information during rapid pointing movements. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *37(A)*, 407-425.
- Elliott, D., Hansen, S., & Grierson, L.E.M. (2009). Optimizing speed and energy expenditure in accurate visually directed upper limb movements. *Ergonomics*, *52*, 438-447.
- Elliott, D., Hansen, S., Grierson, L.E.M., Lyons, J., Bennett, S.J., & Hayes, S.J. (2010). Goal-directed aiming: Two components but multiple processes. *Psychological Bulletin*, *136*, 1023-1044.

- Elliott, D., Hansen, S., Mendoza, J., & Tremblay, L. (2004). Learning to optimize speed, accuracy, and energy expenditure: A framework for understanding speed–accuracy relations in goal-directed aiming. *Journal of Motor Behavior*, *36*, 339–351.
- Elliott, D., Heath, M., Binsted., G., Ricker, K.L., Roy, E.A., & Chua, R. (1999). Goal-directed aiming: Correcting a force specification error with the right and left hand. *Journal of Motor Behavior*, *31*, 309-324.
- Elliott, D., Ricker, K., & Lyons, J. (1998). The control of sequential goal-directed movement: Learning to use feedback or central planning? *Motor Control*, *2*, 61-80.
- Engelbrecht, S. E., Berthier, N. E., & O’Sullivan, L. P. (2003). The undershoot bias: Learning to act optimally under uncertainty. *Psychological Science*, *14*, 257–261.
- Escamilla, R.F., & Andrews, J.R. (2009). Shoulder muscle recruitment patterns and related biomechanics during upper extremity sports. *Sports Medicine*, *39*, 569-590.
- Escamilla, R.F., Fleisig, G.S., Barrentine, S.W., Zheng, N., & Andrews, J.R. (1998). Kinematic comparisons of throwing different types of baseball pitches. *Journal of Applied Biomechanics*, *14*, 1-23.
- Feldman, A.G. (1986). Once more on the equilibrium-point hypothesis (lambda model) for motor control. *Journal of Motor Behavior*, *18*, 17-54.
- Feldman, A.G., Adamovich, S.V., Ostry, D.J., & Flanagan, J.R. (1990). The origin of electromyograms: Explanations based on the equilibrium point hypothesis. In J.M. Winters & S.L. Woo (Eds.), *Multiple muscle systems: Biomechanics and movement organization* (pp. 195-213). New York: Springer-Verlag.
- Feltner, M.E., & Dapena, J. (1986). Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. *International Journal of Sports Biomechanics*, *2*, 235-259.

- Fitts, P.M., & Posner, M.I. (1967). *Human performance*. Belmont, CA: Brooks/Cole.
- Flanagan, J.R., Ostry, D.J., & Feldman, A.G. (1990). Cerebral control of speech and limb movements. In G.E. Hamman (Ed.), *Control of human jaw and multi-joint arm movements* (pp. 29-58). Amsterdam: North-Holland.
- Flanagan, J.R., Ostry, D.J., & Feldman, A.G. (1993). Control of trajectory modifications in target-directed reaching. *Journal of Motor Behavior*, 25, 140-152.
- Fleisig, G.S., Andrews, J.R., Dillman, C.J., & Escamilla, R.F. (1995). Kinetics of baseball pitching with implications about injury mechanisms. *American Journal of Sports Medicine*, 23, 233-239.
- Fleisig, G.S., Barrentine, S.W., Escamilla, R.F., & Andrews, J.R. (1996). Biomechanics of overhand throwing with implications for injuries. *Sports Medicine*, 21, 421-437.
- Fleisig, G.S., Chu, Y., Weber, A., & Andrews, J.R. (2009). Variability in baseball pitching biomechanics among various levels of competition. *Sports Biomechanics*, 8, 10-21.
- Fleisig, G.S., Escamilla, R.F., Andrews, J.R., Matsuo, T.M., Satterwhite, Y., & Barrentine, S.W. (1996). Kinematic and kinetic comparison between baseball pitching and football passing. *Journal of Applied Biomechanics*, 12, 207-224.
- Glover, S. (2004). Separate visual representations in the planning and control of action. *Behavioral and Brain Sciences*, 27, 3-24.
- Goodale, M.A., Jakobson, L.S., & Keillor, J.M. (1994). Differences in the visual control of pantomimed and natural grasping movements. *Neuropsychologia*, 32, 1159-1178.
- Goodale, M.A., Meenan, J.P., Bulthoff, H.H., Nicolle, D.A., Murphy, K.J., & Racicot, C.I. (1994). Separate neural pathways for the visual analysis of object shape in perception and prehension. *Current Biology*, 4, 604-610.

- Hancock, G.R., Butler, M.S., & Fischman, M.G. (1995). On the problem of two-dimensional error scores: Measures and analyses of accuracy, bias, and consistency. *Journal of Motor Behavior*, 27, 241-250.
- Heath, M. (2005). Role of limb and target vision in the online control of memory-guided reaches. *Motor Control*, 9, 281-311.
- Heath, M., Hodges, N.J., Chua, R., & Elliott, D. (1998). Online control of rapid aiming movements: Effects of target characteristics on movement kinematics. *Canadian Journal of Experimental Psychology*, 52, 163–173.
- Held, R. (1970). Two modes of processing spatially distributed visual stimulation. In F. O. Schmitt (Ed.), *The Neurosciences* (pp. 317-324). New York: Rockefeller University Press.
- Henry, F.M., & Rogers, D.E. (1960). Increased response latency for complicated movements and a “memory drum” theory of neuromotor reaction. *Research Quarterly*, 31, 448-458.
- Hirashima, M., Kadota, Hiroshi, K., Sakurai, S., Kudo, K., & Ohtsuki, T. (2002). Sequential muscle activity and its functional role in the upper extremity and trunk during overarm throwing. *Journal of Sports Sciences*, 20, 301-310.
- Hirashima, M., Kudo, K., & Ohtsuki, T. (2003). Utilization and compensation of interaction torques during ball-throwing movements. *Journal of Neurophysiology*, 89, 1784–1796.
- Hore, J., Ritchie, R., & Watts, S. (1999). Finger opening in an overarm throw is not triggered by proprioceptive feedback from elbow extension or wrist flexion. *Experimental Brain Research*, 125, 302-312.
- Hore, J., & Watts, S. (2005). Timing finger opening in overarm throwing based on a spatial representation of hand path. *Journal of Neurophysiology*, 93, 3189-3199.

- Hore, J., Watts, S., Martin, J., & Miller, B. (1995). Timing of finger opening and ball release in fast and accurate overarm throws. *Experimental Brain Research*, 103, 277-286.
- Hore, J., Watts, S., & Tweed, D. (1996). Errors in the control of joint rotations associated with the inaccuracies in overarm throws. *Journal of Neurophysiology*, 75, 1013-1025.
- Ingle, D. (1973). Two visual systems in the frog. *Science*, 181, 1053-1055.
- Jegede, E., Watts, S., Stitt, L., & Hore, J. (2005). Timing of ball release in overarm throws affects ball speed in unskilled but not skilled individuals. *Journal of Sports Sciences*, 23, 805-816.
- Keele, S.W. (1968). Movement control in skilled motor performance. *Psychological Bulletin*, 70, 387-403
- Keele, S.W., & Posner, M.I. (1968). Processing of visual feedback in rapid movement. *Journal of Experimental Psychology*, 77, 155-158.
- Langolf, G.D., Chaffin, D.B., & Foulke, J. A. (1976). An investigation of Fitts' law using a wide range of movement amplitudes. *Journal of Motor Behavior*, 8, 113-128.
- Lashley, K.S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior* (pp. 112-146). New York: Wiley.
- Leibowitz, H.W., & Post, R.B. (1982). The two modes of processing concept and some implications. In J. Beck (Ed.), *Organization and representation in perception* (pp. 343-363). Hillsdale, NJ: Erlbaum.
- Logothetis, N.K. (1994). Physiological studies of motion inputs. In A. T. Smith & R. J. Snowden (Eds.), *Visual detection of motion* (pp. 177-216). London: Academic Press.
- Lyons, J., Hansen, S., Hurding, S., & Elliott, D. (2006). Optimizing rapid aiming behaviour:

- Movement kinematics depend on the cost of corrective modifications. *Experimental Brain Research*, 174, 95–100.
- MacKenzie, C.L., Marteniuk, R.G., Dugas, C., Liske, D., & Eickmeier, B. (1987). Three dimensional movement trajectory in a Fitts' task: Implications for control. *Quarterly Journal of Experimental Psychology*, 39, 629-647.
- Matsuo, T., Escamilla, R.F., Fleisig, G.S., Barrentine, S.W., & Andrews, J.R. (2001). Comparison of kinematic and temporal parameters between different pitch velocity groups. *Journal of Applied Biomechanics*, 17, 1-13.
- Maunsell, J.H., Ghose, G.M., Assad, J.A., McAdams, C.J., Bourdreau, C.E., & Noerager, B.D. (1999). Visual response latencies of magnocellular and parvocellular LGN neurons in macaque monkeys. *Visual Neuroscience*, 16, 1-14.
- McCaulley, G.O., Cormie, P., Cavill, M.J., Nuzzo, J.L., Urbiztondo, Z.G., & McBride, J.M. (2007). Mechanical efficiency during repetitive vertical jumping. *European Journal of Applied Physiology*, 101, 115-123.
- Merigan, W.H., & Maunsell, J.H. (1993). How parallel are the primate visual pathways? *Annual Review of Neuroscience*, 16, 369–402.
- Miall, R.C., Weir, D.J., Wolpert, D.M., & Stein, J.F. (1993). Is the cerebellum a smith predictor? *Journal of Motor Behavior*, 25, 203-216.
- Milner, A.D., Dijkerman, H.C., & Carey, D.P. (1999). Visuospatial processing in a pure case of visual-form agnosia. In N. Burgess, K.J. Jeffery, & J. O'Keefe, (Eds.), *The hippocampal and parietal foundations of spatial cognition* (pp. 443-466). Oxford, UK: Oxford University Press.

- Milner, A.D., Dijkerman, H.C., Pisella, L., McIntosh, R.D., Tilikete, C., Vighetto, A., & Rossetti, Y. (2001). Grasping the past: Delay can improve visuomotor performance. *Current Biology, 11*, 1896–1901.
- Milner, A.D., Dijkerman, H.C., McIntosh, R.D., Rossetti, Y., & Pisella, L. (2003). Delayed reaching and grasping in patients with optic ataxia. *Neural Control of Space Coding and Action Production, 142*, 223–240.
- Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action*. Oxford, UK: Oxford University Press.
- Milner, A.D., & Goodale, M.A. (2008). Two visual systems re-viewed. *Neuropsychologia, 46*, 774-785.
- Milner, A.D., Paulignan, Y., Dijkerman, H.C., Michel, F., & Jeannerod, M. (1999). A paradoxical improvement of misreaching in optic ataxia: New evidence for two separate neural systems for visual localization. *Proceedings of the Royal Society: Biological Science, 266*, 2225-2229.
- Miyashita, Y. (1993). Inferior temporal cortex: Where visual perception meets memory. *Annual Review of Neuroscience, 16*, 245-263.
- Mullineaux, D.R., & Uhl, T.L. (2010). Coordination-variability and kinematics of misses versus swishes of basketball free throws. *Journal of Sports Sciences, 28*, 1017-1024.
- Neal, R.J., Snyder, C.W., & Kroonenberg, P.M. (1991). Individual differences and segment interactions in throwing. *Human Movement Science, 10*, 653-676.
- Newell, K.M., & Corcos, D.M. (1993). Issues in variability and motor control. In K.M. Newell & D.M. Corcos (Eds.), *Variability and motor control* (pp. 1-12). Champaign, IL: Human Kinetics Publishers.

- Paulignan, Y., MacKenzie, C.L., Marteniuk, R.G., & Jeannerod, M. (1991). Selective perturbations of visual input during prehension movements: I. The effects of changing object position. *Experimental Brain Research*, 83, 502-512.
- Pelisson, D., Prablanc, C., Goodale, M.A., & Jeannerod, M. (1986). Visual control of reaching movements without vision of the limb: II. Evidence of fast unconscious processes correcting the trajectory of the hand to the final position of a double-step stimulus. *Experimental Brain Research*, 62, 303-313.
- Pew, R. W. (1966). Acquisition of hierarchical control over the temporal organization of a skill. *Journal of Experimental Psychology*, 71, 764-771.
- Plamondon, R. (1995a). A kinematic theory of rapid human movements: 1. Movement representation and generation. *Biological Cybernetics*, 72, 295-307.
- Plamondon, R. (1995b). A kinematic theory of rapid human movements: 2. Movement time and control. *Biological Cybernetics*, 72, 309-320.
- Plamondon, R., & Alimi, A.M. (1997). Speed/accuracy trade-offs in target-directed movements. *Behavioral and Brain Sciences*, 20, 279-349.
- Prablanc, C., & Martin, O. (1992). Automatic control during hand reaching at undetected two-dimensional target displacements. *Journal of Neurophysiology*, 67, 455-469.
- Proteau, L., Marteniuk, R.G., & Levesque, L. (1992). A sensorimotor basis for motor learning: Evidence indicating specificity of practice. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, 44A, 557-575.
- Proteau, L., Tremblay, L., & DeJaeger, D. (1998). Practice does not diminish the role of visual information in on-line control of a precision walking task: Support for the specificity of practice hypothesis. *Journal of Motor Behavior*, 30, 143-150.

- Putnam, C.A. (1991). A segment interaction analysis of proximal-to-distal sequential segment motion patterns. *Medicine and Science in Sports and Exercise*, 23, 130-144.
- Reichenbach, A., Bresciani, J.P., Peer, A., Bühlhoff, H.H., & Thielscher, A. (2011). Contributions of the PPC to online control of visually guided reaching movements assessed with fMRI-guided TMS. *Cerebral Cortex*, 21, 1602-1612.
- Revol, P., Rossetti, Y., Vighetto, A., Rode, G., Boisson, D., & Pisella, L. (2003). Pointing errors in immediate and delayed conditions in unilateral optic ataxia. *Spatial Vision*, 16, 347–364.
- Rice, N.J., Edwards, M.G., Schindler, I., Punt, T.D., McIntosh, R.D., Humphreys, G.W., & Milner, A.D. (2008). Delay abolishes the obstacle avoidance deficit in unilateral optic ataxia. *Neuropsychologia*, 46, 1549–1557.
- Rice, N.J., McIntosh, R.D., Schindler, I., Mon-Williams, M., Demonet, J.F., & Milner, A.D. (2006). Intact automatic avoidance of obstacles in patients with visual form agnosia. *Experimental Brain Research*, 174, 176–188.
- Rice, N.J., Tunik, E., Cross, E.S., & Grafton, S.T. (2007). Online grasp control is mediated by the contralateral hemisphere. *Brain Research*, 1175, 76-84.
- Rizzolatti, G., Luppino, G., & Matelli, M. (1998). The organization of the cortical motor system: New concepts. *Electroencephalography and Clinical Neurophysiology*, 106, 283-296.
- Safrit, M.J., & Wood, T.M. (1995). *Introduction to measurement in physical education and exercise science* (3rd ed.). St. Louis, MO: Mosby-Year Book.
- Saunders, J.A., & Knill, D. C. (2003). Humans use continuous visual feedback from the hand to control fast reaching movements. *Experimental Brain Research*, 152, 341–352.

- Schiller, P.H. (1996). On the specificity of neurons and visual areas. *Behavioural Brain Research*, 76, 21–35.
- Schmidt, R.A., & McCabe, J.F. (1976). Motor program utilization over extended practice. *Journal of Human Movement Studies*, 2, 239–247.
- Schmidt, R.A., & Sherwood, D.E. (1982). An inverted-U relation between spatial error and force requirements in rapid limb movements. Further evidence for the impulse-variability model. *Journal of Experimental Psychology: Human Perception and Performance*, 8, 158-170.
- Schmidt, R.A., Zelaznik, H.N., Hawkins, B., Frank, J.S., & Quinn, J.T., Jr. (1979). Motor-output variability: A theory for the accuracy of rapid motor acts. *Psychological Review*, 86, 415-451.
- Schneider, G.E. (1967). Contrasting visuomotor functions of tectum and cortex in the Golden Hamster. *Psychologische Forschung*, 31, 52–62.
- Schneider, G.E. (1969). Two visual systems. *Science*, 163, 895–902.
- Shouchen, D., Kingsley, D., Fleisig, G.S., Loftice, J., & Andrews, J.R. (2008). Biomechanical comparison of the fastball from wind-up and the fastball from stretch in professional baseball pitchers. *American Journal of Sports Medicine*, 36, 137-141.
- Snowden, R.J. (1994). Motion processing in the primate cerebral cortex. In R.J. Snowden (Ed.), *Visual detection of motion* (pp. 51–83). San Diego: Academic Press.
- Soechting, J.F. (1984). Effect of target size on spatial and temporal characteristics of a pointing movement. *Experimental Brain Research*, 54, 121-132.

- Stodden, D.F., Fleisig, G.S., McLean, S.P., & Andrews, J.R. (2005). Relations of biomechanical factors to baseball pitching velocity: Within pitcher variation. *Journal of Applied Biomechanics*, *21*, 44-56.
- Stodden, D.F., Fleisig, G.S., McLean, S.P., Lyman, S.L., & Andrews, J.R. (2001). Relationship of trunk kinematics to pitched ball velocity. *Journal of Applied Biomechanics*, *17*, 164-172.
- Stodden, D.F., Langendorfer, S.J., Fleisig, G.S., & Andrews, J.R. (2006a). Kinematic constraints associated with the acquisition of overarm throwing Part I: Step and trunk actions. *Research Quarterly for Exercise and Sport*, *77*, 417-427.
- Stodden, D.F., Langendorfer, S.J., Fleisig, G.S., & Andrews, J.R. (2006b). Kinematic constraints associated with the acquisition of overarm throwing Part II: Upper extremity actions. *Research Quarterly for Exercise and Sport*, *77*, 428-436.
- Southard, D. (2009). Throwing pattern: Changes in timing of joint lag according to age between and within skill level. *Research Quarterly for Exercise and Sport*, *80*, 213-222.
- Takahashi, K., Fujii, N., & Michiyoshi, A. (2002). Kinematic comparison of different pitch velocity groups in baseball using motion model method. In K. E. Gianikellis (Ed.), *Proceedings of the XXth International Symposium on Biomechanics in Sports* (pp. 203–206). Caceres, Spain.
- Temprado, J.J., Della-Grasta, M., Farrell, M., & Laurent, M. (1997). A novice-expert comparison of (intra-limb) coordination subserving the volleyball serve. *Human Movement Sciences*, *16*, 653-676.
- Todorov, E. (2004). Optimality principles in sensorimotor control. *Nature Neuroscience*, *7*, 907–915.

- Trommershauser, J., Gepshtein, S., Maloney, L.T., Landy, M.S., & Banks, M.S. (2005). Optimal compensation for changes in task-relevant movement variability. *Journal of Neuroscience*, *25*, 7169–7178.
- Toyoshima, S., Hoshikawa, T, Miyashita, M., & Oguri, T. (1974). Contribution of the body parts to throwing performance. In R.C. Nelson & C.A. Morehouse (Eds.), *Biomechanics IV* (pp. 169-174). Baltimore: University Park Press.
- Tunik, E., Johnson-Frey, S.H., & Grafton, S.T. (2005). Virtual lesions of the human anterior intraparietal area disrupts goal-dependent online adjustments of grasp. *Nature Neuroscience*, *8*, 505-511.
- Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Eds.), *Analysis of visual behavior* (pp. 549-586). Cambridge, MA: MIT Press.
- Urbin, M.A., Stodden, D.F., Boros, R.L., & Shannon, D.M. (2012). Examining impulse-variability theory in overarm throwing. *Motor Control*, *16*, 19-30.
- Urbin, M.A., Stodden, D.F., Fischman, M.G., & Weimar, W.H. (2011). Impulse-variability theory: Implications for ballistic, multijoint motor skills. *Journal of Motor Behavior*, *43*, 275-283.
- Wagner, H., Pfusterschmied, P., Klous, M., Serge, P., & Müller, E. (2011). Movement variability and skill level of various throwing techniques. *Human Movement Science*, *31*, 78-90.
- Werner, S.L., Fleisig, G.S., Dillman, C.J., & Andrews, J.R. (1993). Biomechanics of the elbow during baseball pitching. *Journal of Orthopaedic and Sports Physical Therapy*, *17*, 274-278.

- Werner, S.L., Gill, T.J., Murray, T.A., Cook, T.D., & Hawkins, R.J. (2001). Relationships between throwing mechanics and shoulder distractions in professional baseball pitchers. *American Journal of Sports Medicine*, 29, 354-358.
- Werner, S.L., Murray, T.A., Hawkins, R.J., & Gill, T.J. (2002). Relationship between throwing mechanics and elbow valgus in professional baseball pitchers. *Journal of Shoulder and Elbow Injuries*, 11, 151-155.
- Werner, S.L., Suri, M., Guido, J.A., Meister, K., & Jones, D.G. (2008). Relationships between ball velocity and throwing mechanics in collegiate baseball pitchers. *Journal of Shoulder and Elbow Surgery*, 17, 905-908.
- Wisleder, D., Fleisig, G.S., Dillman, C.J., Schob, C.J., & Andrews, J.R (1989). Biomechanics-development of a biomechanical analysis of throwing with clinical applications for pitchers. *Sports Medicine Update*, 4, 28-31.
- Wolpert, D.M., Miall, R.C., & Kawato, M. (1998) Internal models in the cerebellum. *Trends in Cognitive Science*, 2, 338-347.
- Woodworth, R.A. (1899). The accuracy of voluntary movement. *Psychological Review*, 3, 1-119.
- Zelaznik, H.N., Hawkins, B., & Kisselburgh, L. (1983). Rapid visual feedback processing in single-aiming movements. *Journal of Motor Behavior*, 15, 217-236.

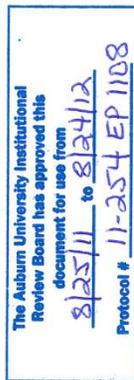
Appendix A
Informed Consent Form



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(NOTE: DO NOT SIGN THIS DOCUMENT UNLESS AN IRB APPROVAL STAMP WITH CURRENT DATES HAS BEEN APPLIED TO THIS DOCUMENT:)

**INFORMED CONSENT
for a Research Study entitled
“Online Control in Overarm Throwing”**



You are invited to participate in a research study to investigate online control in overarm throwing. The study is being conducted by Mike Urbin, Doctoral Candidate, under the direction of Dr. Mark Fischman, Professor, in the Auburn University Department of Kinesiology. You were selected as a possible participant because you have no history of musculoskeletal injury/surgery and are a skilled overarm thrower.

What will be involved if you participate? If you decide to participate in this research study, you will be asked to come to Motion Capture Lab (in Shop Building #3) on two separate days for testing. On the first day of testing, you will be asked to perform 10 maximal effort throws to a target located 30 feet away. Motion capture and EMG data will be collected from these throws. On the second day of testing, you will be asked to perform 30 maximal effort throws. The first day will require approximately 30 minutes; the second day will require approximately 60 minutes. You will be asked to come back for the second test day within 72 hours of the first test day.

Prior to and following the procedure associated with each day, you will be guided through a warm-up/cool-down to reduce the risk of injury.

Are there any risks or discomforts? Physical risks are similar to those that might result from participation in sport activities involving throwing. Specifically, shoulder, arm, and/or abdominal muscle soreness or joint strain are slight possibilities. We will minimize risk by providing a warm-up routine, limiting the number of trials, and allowing for rest periods between throws. We also will communicate with you during testing to ensure you are not experiencing any discomfort or pain. Additionally, you may experience skin irritation from the EMG electrodes. You are responsible for any costs associated with medical treatment you may seek.

Are there any benefits to yourself or others? The benefits of this study include understanding of the biomechanical/control mechanisms that affect throwing performance and injury. You will be given the opportunity to view three-dimensional animations of your throws, which can be used to improve performance. We cannot promise you that you will directly receive any or all of the benefits described.

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Participant's initials _____

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If you change your mind about participating, you can withdraw at any time during the study. Your participation is completely voluntary. If you choose to withdraw, your data can be withdrawn as long as it is identifiable. Your decision about whether or not to participate or to stop participating will not jeopardize your future relations with Auburn University or the Department of Kinesiology.

Your privacy will be protected. Any information obtained in connection with this study will remain anonymous, as it will correspond solely to an identification number. Information obtained through your participation may be published in a scientific journal and/or presented at a scholarly conference.

If you have questions about this study, please ask them now or contact Mike Urbin at mau0003@auburn.edu or Dr. Mark Fischman at fischmg@auburn.edu. A copy of this document will be given to you to keep.

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Participant's signature Date Investigator obtaining consent Date

Printed Name Printed Name

Co-Investigator Date

Printed Name

Appendix B

Subject Demographics & Ball Trajectory Data

Subject Demographics			
	Height (cm)	Mass (kg)	Age (years)
LM	182.88	89.80	24
JW	187.96	68.04	22
DR	187.96	83.91	21
KL	180.34	79.83	22
SN	177.80	74.84	21
JL	182.88	71.21	20
BD	187.96	81.65	21
TS	180.34	72.57	20
Total	183.52	77.73	21.38

Global x-Component (cm) of Ball's Landing Location				
	Pre-Test	Test-Center	Test-Left	Test-Right
LM	-16.51	-7.11	-115.06	78.99
JW	18.03	-18.03	-60.96	7.87
DR	-2.79	0.69	-70.36	69.60
KL	-11.18	-9.65	-134.62	104.90
SN	-10.92	14.55	-45.47	69.09
JL	-9.65	1.69	-113.61	132.84
BD	-18.80	-28.70	-119.63	37.85
TS	-26.92	-16.00	-67.82	73.15
Total	-9.84	-7.82	-90.94	71.79

Mean Radial Error (cm) of Ball's Landing Location				
	Pre-Test	Test-Center	Test-Left	Test-Right
LM	33.02	46.74	47.75	79.25
JW	39.88	55.63	95.25	150.88
DR	44.96	40.41	91.95	92.46
KL	30.23	32.77	33.02	57.40
SN	56.90	43.41	105.16	80.26
JL	32.00	46.57	60.96	52.07
BD	31.24	38.10	50.04	114.81
TS	46.74	42.67	79.50	74.42
Total	39.37	43.29	70.45	87.69

Mean Bivariate Variable Error (cm) of Ball's Landing Location				
	Pre-Test	Test-Center	Test-Left	Test-Right
LM	35.93	51.11	51.28	52.48
JW	42.02	51.18	59.85	57.93
DR	46.04	47.02	51.99	62.08
KL	23.35	36.90	32.15	56.30
SN	52.85	48.81	65.45	61.15
JL	41.59	51.84	56.27	62.89
BD	21.77	32.05	64.57	54.42
TS	36.34	48.15	84.79	60.70
Total	37.49	45.88	58.29	58.49

Mean Ball Speed (m/s, MPH)								
	Pre-Test		Test-Center		Test-Left		Test-Right	
	m/s	MPH	m/s	MPH	m/s	MPH	m/s	MPH
LM	33.62	75.20	32.19	72.00	31.29	70.00	32.23	72.10
JW	31.83	71.20	31.16	69.70	31.34	70.10	31.56	70.60
DR	39.97	89.40	37.59	84.09	37.55	84.00	37.42	83.70
KL	36.79	82.30	35.90	80.30	35.36	79.10	35.94	80.40
SN	36.93	82.60	34.95	78.18	34.82	77.90	34.42	77.00
JL	34.47	77.10	31.54	70.56	33.49	74.91	32.63	73.00
BD	34.15	76.40	31.74	71.00	32.63	73.00	32.32	72.30
Total	35.39	79.17	33.58	75.12	33.78	75.57	33.79	75.59

Appendix C
Positional Kinematic Data

Mean Maximum Humeral External Rotation (°)						
	Pre-Test		Test-Center		Test-Left	Test-Right
LM	146.95		147.09		147.12	147.17
JW	147.23		147.29		147.21	147.2
DR	147.26		147.29		146.41	147.28
KL	147.23		146.53		147.19	146.2
SN	147.21		147.16		147.23	145.69
JL	146.86		139.21		142.85	136.48
BD	144.54		140.58		143.2	140.97
TS	141.7		145.44		143.17	143.66
Total	146.12		145.074		145.55	144.33

Mean Humeral Horizontal Ab/Adduction (°) at Ball Release						
	Pre-Test		Test-Center		Test-Left	Test-Right
LM	-3.24		-7.49		-3.04	0.08
JW	9.34		5.33		3.81	5.93
DR	-6.69		-10.4		-13.98	-12.68
KL	-15.48		-8.32		-2.03	-7.22
SN	-11.98		-14.7		-9.42	-13.59
JL	-5.94		-14.71		-19.93	-19.48
BD	3.1		1.85		19.67	-0.95
TS	-17.19		-2.84		16.13	8.31
Total	-6.01		-6.41		-1.1	-4.95

Mean Trunk Forward Tilt (°) at Ball Release						
	Pre-Test		Test-Center		Test-Left	Test-Right
LM	25.73		26.17		25.98	22.7
JW	36.26		35.72		27.68	29.35
DR	24.23		34.3		33.03	35.54
KL	24.85		24.83		25.29	27.71
SN	28.94		24.78		25.32	24.65
JL	20.41		20.32		16.94	15.02
BD	15.71		13.73		10.7	14.94
TS	17.53		11.53		9.31	10.52
Total	24.21		23.92		21.78	22.55

Mean Trunk Lateral Tilt (°) at Ball Release							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	3.36		-2.98		-4.61		-4.13
JW	16.05		10.08		8.82		9.61
DR	26.49		9.81		10.47		10.07
KL	10.55		-0.06		2.3		-0.96
SN	20.51		12.22		11.51		12.15
JL	11.87		18.49		71.9		78.09
BD	10.98		6.41		2.3		7.79
TS	7.47		8.03		12.25		9.06
Total	13.41		7.75		14.37		15.21

Mean Elbow Flexion/Extension (°) at Ball Release							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	172.52		161.52		162.58		161
JW	151.91		156.54		160.32		154.55
DR	163.66		168.75		154.4		169.14
KL	171.02		168.46		155.98		170.32
SN	171.69		167.12		162.52		169.44
JL	159		173.31		161.97		128.33
BD	160.18		159.08		167.71		152.69
TS	147.65		143.28		158.67		159.63
Total	162.20		162.26		160.52		158.14

Pelvis Orientation (°) at Ball Release							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	96.62		99.17		98.4		98.33
JW	99.91		98.19		106		103.3
DR	111.61		103.47		104.31		97.64
KL	113.6		105.14		106.81		102.01
SN	105.08		106.95		107.25		107.25
JL	102.01		95.05		105.2		91.3
BD	97.07		102.44		102.25		101.11
TS	95.89		94.13		98.69		90.68
Total	102.72		100.57		103.61		98.95

Upper Torso Orientation (°) at Ball Release							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	101.37		106.45		110.63		105.79
JW	104.9		101.16		102.99		99.88
DR	115.91		109.8		106.85		109.84
KL	106.63		101.15		111.67		102.44
SN	108.29		107.45		107.93		108.43
JL	111.55		111.17		116.72		82.54
BD	106.48		98.81		93.61		100.64
TS	102.19		98.82		96.42		91.18
Total	107.17		104.35		105.85		100.09

Appendix D
Velocity Kinematic Data

Mean Maximum Pelvis Linear Velocity (m/s)						
	Pre-Test		Test-Center		Test-Left	Test-Right
LM	1.68		2.03		1.97	2.06
JW	2		2		2	2.13
DR	1.39		1.82		2.19	1.64
KL	1.71		1.87		1.75	1.94
SN	1.77		1.62		2.64	2.12
JL	2.4		3.02		2.31	2.7
BD	1.43		1.61		1.6	1.59
TS	2.24		2.29		2.12	2.34
Total	1.83		2.03		2.07	2.07

Mean Maximum Upper Torso Linear Velocity (m/s)						
	Pre-Test		Test-Center		Test-Left	Test-Right
LM	3.25		3.11		3.01	3.03
JW	3.32		3.37		3.23	3.5
DR	3.76		3.28		3.27	3.22
KL	3.21		3.73		3.46	3.47
SN	2.99		2.81		2.7	2.73
JL	3.42		2.71		2.68	2.73
BD	2.24		2.69		2.43	2.61
TS	2.84		3.78		2.76	3.28
Total	3.13		3.19		2.94	3.07

Mean Maximum Pelvis Angular Velocity (°/s)						
	Pre-Test		Test-Center		Test-Left	Test-Right
LM	752.2		691.89		688	645.7
JW	757.96		775.75		742.53	768.17
DR	772.58		907.84		844.05	956.99
KL	846.08		801.31		790.86	772.76
SN	922.62		886.37		967.42	1105.01
JL	945.73		811.68		762.72	926.63
BD	773.61		751.48		822.23	766.61
TS	776.77		654.87		717.49	619.85
Total	818.44		785.15		791.91	820.22

Mean Maximum Upper Torso Angular Velocity (°/s)						
	Pre-Test		Test-Center		Test-Left	Test-Right
LM	972.96		1029.22		1069.74	973.5
JW	923.87		854.08		1049.56	969.04
DR	1317.14		1072.22		1161.47	1085
KL	1122.91		917.07		1117.94	991.22
SN	1240.34		1196.84		1120.06	1127.51
JL	1090.12		1011.64		975.49	877.96
BD	950.93		1072.72		1208.06	1174.19
TS	1029.26		1562.5		1277.06	1227.86
Total	1080.94		1089.54		1122.4	1053.29

Mean Maximum Elbow Extension Angular Velocity (°/s)						
	Pre-Test		Test-Center		Test-Left	Test-Right
LM	3401.38		3418.9		3221.59	2953.93
JW	2910.13		3046.89		3785.22	3251.86
DR	3578.25		3342.92		3149.98	3170.89
KL	3195.28		3155.45		2718.91	2941.73
SN	2347.93		3296.04		2909.35	3147.25
JL	3238.18		3139.24		3727.5	3364.74
BD	2553.59		2024.56		2591.98	2101.04
TS	3150.72		2209.34		3140.31	2511.44
Total	3046.93		2954.17		3155.61	2930.36

Appendix E
Temporal Kinematic Data

Mean Time from Stride-Foot Contact to Ball Release (msec)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	207.39		187.06		201.83		194.44
JW	198.17		218.50		227.78		224.06
DR	150.00		211.11		250.00		270.39
KL	235.17		248.17		270.39		257.39
SN	181.50		183.33		183.33		181.50
JL	133.33		322.22		377.78		330.56
BD	214.83		251.83		253.72		251.83
TS	200.00		288.89		277.78		270.39
Total	190.05		238.89		255.33		247.57

Mean Time from Stride-Foot Contact to Peak Pelvis Angular Velocity (msec)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	127.78		101.83		112.94		118.50
JW	101.83		120.39		127.78		125.94
DR	62.94		155.56		180.56		203.72
KL	144.44		146.28		162.94		151.83
SN	103.72		111.11		107.39		96.28
JL	38.89		294.44		288.89		280.56
BD	151.83		179.61		200.00		175.94
TS	138.89		216.67		216.67		222.22
Total	108.79		165.74		174.65		171.88

Mean Time from Peak Pelvis to Peak Upper Torso Angular Velocity (msec)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	62.94		46.28		35.17		16.67
JW	33.33		38.89		90.72		35.17
DR	55.56		16.67		47.22		18.50
KL	51.83		16.67		55.56		46.28
SN	22.22		22.22		25.94		40.72
JL	44.44		77.78		72.22		27.78
BD	11.11		59.28		-31.50		9.28
TS	3.72		53.72		31.50		16.67
Total	35.65		41.44		40.85		26.38

Mean Time from Peak Upper Torso to Peak Elbow Extension Angular Velocity (msec)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	5.56		29.61		48.17		50.00
JW	53.72		46.28		1.83		55.56
DR	9.28		25.94		13.89		31.50
KL	29.61		77.78		40.72		48.17
SN	42.61		25.00		29.61		24.06
JL	42.61		22.22		0.00		25.00
BD	44.44		-1.83		75.94		55.56
TS	53.72		-3.72		16.67		24.06
Total	35.19		27.66		28.35		39.24

Mean Time from Peak Elbow Extension Angular Velocity to Ball Release (msec)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	11.11		9.28		5.56		9.28
JW	9.28		12.94		7.39		7.39
DR	22.22		12.94		8.33		16.67
KL	9.28		7.39		11.11		11.11
SN	12.94		25.00		20.39		20.39
JL	7.39		11.11		16.67		-2.78
BD	7.39		14.83		9.28		11.11
TS	3.72		22.22		16.67		7.39
Total	10.42		14.47		11.92		10.07

Appendix F

Electromyography Data

Mean Peak Anterior Deltoid EMG Activity (%)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	1.69		1.58		1.2		1.57
JW	1.34		1.68		2.08		1.53
DR	0.87		1.37		4.49		6.45
KL	2		1.46		3.27		1.24
SN	1.11		10.46		1.27		3.69
JL	0.66		5.87		4.54		7
BD	1.34		1.01		1.2		1.09
TS	1.49		2.49		2.38		2.1
Total	1.31		3.24		2.55		3.08

Mean Peak Pectoralis Major EMG Activity (%)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	1.48		1.33		1.73		1.52
JW	1.22		1.21		2.21		1.21
DR	1.06		3.46		3.22		3.24
KL	7.25		3.37		4.65		9.27
SN	1.38		4.37		3.04		7.47
JL	0.84		6.78		4.48		7.97
BD	5.45		4.68		1.44		1.32
TS	1.09		5.08		7		2.41
Total	2.47		3.79		3.47		4.30

Mean Peak Bicep EMG Activity (%)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	0.94		1.1		0.92		0.65
JW	1.61		0.69		0.89		0.65
DR	0.98		1.79		2.25		2.15
KL	1.2		4.12		6.44		4.24
SN	0.49		1.94		1.02		1.12
JL	3.3		1.81		1.5		1.74
BD	0.57		0.81		1.35		0.73
TS	0.79		0.86		0.81		0.83
Total	1.24		1.64		1.90		1.51

Mean Peak Tricep EMG Activity (%)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	16.53		9.57		8.57		10.75
JW	2.66		1.74		3.22		2.66
DR	2.03		5.42		6.28		7.43
KL	3.45		4.54		5.58		5.05
SN	8.57		41.83		22.28		47.48
JL	1.99		6.3		4.62		5.74
BD	8.49		40.76		55.94		13.42
TS	4.08		4.99		3.46		4.21
Total	5.98		14.39		13.74		12.09

Mean Total Anterior Deltoid EMG Activity (%)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	1.14		1.14		0.84		0.98
JW	0.79		1.06		1.48		0.92
DR	0.41		0.85		2.53		3.82
KL	1.26		0.71		1.39		0.56
SN	0.7		3.2		0.88		1.45
JL	0.37		2.65		2.51		3.63
BD	0.93		0.73		0.89		0.8
TS	0.89		1.4		1.45		1.38
Total	0.81		1.47		1.50		1.69

Mean Total Pectoralis Major EMG Activity (%)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	0.96		0.86		1.24		1
JW	0.78		0.88		1.54		0.86
DR	0.68		1.81		1.8		1.32
KL	4.27		0.77		1.25		1.93
SN	0.94		1.54		1.81		2.56
JL	0.47		3.46		2.54		4.39
BD	1.61		3.09		1.03		0.75
TS	0.83		3.19		4.07		1.61
Total	1.32		1.95		1.91		1.80

Mean Total Bicep EMG Activity (%)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	0.55		0.57		0.57		0.37
JW	0.6		0.26		0.37		0.23
DR	0.55		0.94		0.92		1.07
KL	0.65		1.11		1.89		1.63
SN	0.3		0.69		0.53		0.59
JL	1.76		0.94		0.91		0.88
BD	0.22		0.45		0.58		0.51
TS	0.67		0.72		0.65		0.74
Total	0.66		0.71		0.80		0.75

Mean Total Tricep EMG Activity (%)							
	Pre-Test		Test-Center		Test-Left		Test-Right
LM	3.84		6.06		4.92		6.57
JW	1.76		1.05		2.02		1.65
DR	1.49		3.46		3.27		4.11
KL	1.86		2.28		2.54		2.32
SN	3.93		13.26		6.08		17.71
JL	1.39		2.36		1.71		2.33
BD	4.53		9.28		17.58		4.64
TS	2.26		1.97		1.62		2.08
Total	2.63		4.97		4.97		5.18

Appendix G
ANOVA Summary Tables

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power ^a
xComponent	Sphericity Assumed	105941.625	3	35313.875	45.990	.000	.868	137.969	1.000
	Greenhouse-Geisser	105941.625	1.385	76474.463	45.990	.000	.868	63.710	1.000
	Huynh-Feldt	105941.625	1.618	65491.242	45.990	.000	.868	74.395	1.000
	Lower-bound	105941.625	1.000	105941.625	45.990	.000	.868	45.990	1.000
Error(xComponent)	Sphericity Assumed	16125.202	21	767.867					
	Greenhouse-Geisser	16125.202	9.697	1662.865					
	Huynh-Feldt	16125.202	11.324	1424.045					
	Lower-bound	16125.202	7.000	2303.600					

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power ^a
xComponent	Sphericity Assumed	105941.625	3	35313.875	45.990	.000	.868	137.969	1.000
	Greenhouse-Geisser	105941.625	1.385	76474.463	45.990	.000	.868	63.710	1.000
	Huynh-Feldt	105941.625	1.618	65491.242	45.990	.000	.868	74.395	1.000
	Lower-bound	105941.625	1.000	105941.625	45.990	.000	.868	45.990	1.000
Error(xComponent)	Sphericity Assumed	16125.202	21	767.867					
	Greenhouse-Geisser	16125.202	9.697	1662.865					
	Huynh-Feldt	16125.202	11.324	1424.045					
	Lower-bound	16125.202	7.000	2303.600					

a. Computed using alpha = .05

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power ^a	
BVE	Sphericity Assumed	2515.094	3	838.365	11.913	.000	.630	35.739	.998
	Greenhouse-Geisser	2515.094	1.664	1511.289	11.913	.002	.630	19.826	.959
	Huynh-Feldt	2515.094	2.120	1186.182	11.913	.001	.630	25.260	.985
	Lower-bound	2515.094	1.000	2515.094	11.913	.011	.630	11.913	.840
Error(BVE)	Sphericity Assumed	1477.847	21	70.374					
	Greenhouse-Geisser	1477.847	11.649	126.860					
	Huynh-Feldt	1477.847	14.842	99.570					
	Lower-bound	1477.847	7.000	211.121					

a. Computed using alpha = .05

Tests of Within-Subjects Effects

Measure:MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power ^a
RE	Sphericity Assumed	12647.127	3	4215.709	12.805	.000	.647	38.415	.999
	Greenhouse-Geisser	12647.127	1.838	6881.328	12.805	.001	.647	23.534	.980
	Huynh-Feldt	12647.127	2.461	5139.354	12.805	.000	.647	31.511	.996
	Lower-bound	12647.127	1.000	12647.127	12.805	.009	.647	12.805	.864
Error(RE)	Sphericity Assumed	6913.729	21	329.225					
	Greenhouse-Geisser	6913.729	12.865	537.396					
	Huynh-Feldt	6913.729	17.226	401.357					
	Lower-bound	6913.729	7.000	987.676					

a. Computed using alpha = .05

Tests of Within-Subjects Effects

Measure:MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power ^a
BallSpeed	Sphericity Assumed	108.236	3	36.079	18.931	.000	.730	56.792	1.000
	Greenhouse-Geisser	108.236	2.054	52.686	18.931	.000	.730	38.891	.999
	Huynh-Feldt	108.236	2.919	37.083	18.931	.000	.730	55.254	1.000
	Lower-bound	108.236	1.000	108.236	18.931	.003	.730	18.931	.959
Error(BallSpeed)	Sphericity Assumed	40.023	21	1.906					
	Greenhouse-Geisser	40.023	14.381	2.783					
	Huynh-Feldt	40.023	20.431	1.959					
	Lower-bound	40.023	7.000	5.718					

a. Computed using alpha = .05

Multivariate^{c,d}

Within Subjects Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power ^a
Positional Kinematics									
condition	Pillai's Trace	.812	.902	21.000	51.000	.590	.271	18.939	.574
	Wilks' Lambda	.357	.896	21.000	43.622	.596	.291	17.870	.520
	Hotelling's Trace	1.352	.880	21.000	41.000	.615	.311	18.475	.529
	Roy's Largest Root	.920	2.235 ^b	7.000	17.000	.083	.479	15.646	.650

a. Computed using alpha = .05

b. The statistic is an upper bound on F that yields a lower bound on the significance level.

c. Design: Intercept

Within Subjects Design: condition

d. Tests are based on averaged variables.

Multivariate^{c,d}

Within Subjects Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power ^a
Velocity Kinematics									
condition	Pillai's Trace	.738	1.239	15.000	57.000	.271	.246	18.585	.684
	Wilks' Lambda	.398	1.249	15.000	47.331	.271	.264	17.002	.613
	Hotelling's Trace	1.189	1.242	15.000	47.000	.277	.284	18.625	.663
	Roy's Largest Root	.863	3.278 ^b	5.000	19.000	.027	.463	16.388	.783

a. Computed using alpha = .05

b. The statistic is an upper bound on F that yields a lower bound on the significance level.

c. Design: Intercept

Within Subjects Design: condition

d. Tests are based on averaged variables.

Multivariate^{c,d}

Within Subjects Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power ^a
Temporal Kinematics									
condition	Pillai's Trace	.798	1.377	15.000	57.000	.190	.266	20.659	.743
	Wilks' Lambda	.369	1.373	15.000	47.331	.200	.283	18.670	.665
	Hotelling's Trace	1.284	1.342	15.000	47.000	.217	.300	20.123	.707
	Roy's Largest Root	.844	3.209 ^b	5.000	19.000	.029	.458	16.044	.773

a. Computed using alpha = .05

b. The statistic is an upper bound on F that yields a lower bound on the significance level.

c. Design: Intercept

Within Subjects Design: condition

d. Tests are based on averaged variables.

Multivariate^{d,e}

Within Subjects Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power ^a
EMG									
condition	Pillai's Trace	.328	1.371	6.000	42.000	.248	.164	8.229	.476
	Wilks' Lambda	.694	1.338 ^b	6.000	40.000	.263	.167	8.031	.462
	Hotelling's Trace	.411	1.302	6.000	38.000	.280	.171	7.814	.447
	Roy's Largest Root	.314	2.197 ^c	3.000	21.000	.119	.239	6.590	.479
muscle *	Pillai's Trace	.205	.799	18.000	126.000	.699	.102	14.373	.551
condition	Wilks' Lambda	.805	.787 ^b	18.000	124.000	.712	.103	14.168	.542
	Hotelling's Trace	.229	.776	18.000	122.000	.725	.103	13.961	.533
	Roy's Largest Root	.135	.942 ^c	9.000	63.000	.496	.119	8.478	.423

a. Computed using alpha = .05

b. Exact statistic

c. The statistic is an upper bound on F that yields a lower bound on the significance level.

d. Design: Intercept

Within Subjects Design: muscle + condition + muscle * condition

e. Tests are based on averaged variables.