AN ANALYSIS OF THE DIFFERENT SPIKE ATTACK ARM SWINGS USED IN
ELITE LEVELS OF MEN'S VOLLEYBALL

by

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ABSTRACT

Objective

As part of this work, two preliminary studies were conducted that identified three possible swings used at the elite level of volleyball and the resulting ball velocities created using these swings. Therefore, the purpose of this work was to explore the kinematic aspects of the different spike attack arm swings (straight ahead (SA), cross body (CB) and outside (OS)) where each different swing was broken down into its constituent parts.

Methods

Six elite-level varsity players participated in this study. A motion tracking system was used to collect motion data which was used to calculate the kinematics of the upper arm during each of the swing types. A number of minimums and maximums were then calculated including maximum hand speed. To compare means between swings one-way ANOVA’s were used.

Results

Few differences were found between the swing types. The only difference seen between the SA CB swings was a more pronounced wrist flexion during the CB swing. It is possible that this helped propel the ball across the body during the CB. The OS swings differed from the CB and SA swings in that the OS was less horizontally adducted and there was a more pronounced external rotation during CB than during OS. These differences are likely to be responsible for the ball being hit away from the midline of the body during the OS swing. Typically, the hand speed results agreed with those of the
study done previously concerning resulting ball speeds when these swings were employed.

**Conclusions**

Between the SA, CB and OS swing types, only the OS was consistently different throughout the three studies. It is recommended that future studies attempt to examine the whole body during these types of swings. Also, it appears that elite-level players may be quite different kinematically, and each one should be treated as a separate case in a training situation. The findings of these studies may help coaches, trainers and athletes develop better training, injury prevention and rehabilitation programs in the sport.
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CHAPTER 1 - INTRODUCTION

Volleyball has more than 500 million registered players worldwide (Fédération Internationale de Volleyball, 2004) but despite its popularity little research has been done on shoulder motions and the resulting injuries. It is a high intensity sport that requires participants to generate large torques and high velocities at awkward (abducted and externally rotated) shoulder positions. Shoulder ailments due to these forces and positions account for 23% of all volleyball injuries (Byra & McCabe, 1981; Watkins & Green, 1992). Often overuse in nature, these injuries result in the longest loss of time among professional volleyball players and are matched in frequency only by overuse injuries of the back (Verhagen et al., 2004).

Not only is scientific knowledge of volleyball injuries limited but our understanding of the mechanics and forces involved is particularly deficient. Only a handful of studies have sought to gather information describing the relevant kinematics and kinetics of volleyball. For example, only recently has a proper and detailed five-phase explanation of the attack swing, similar to that seen for other overhead throwing motions, been depicted and used to describe volleyball spiking motions (Rokito et al., 1998). Studies prior to 1998 have used a simplified system with two phases; the ‘backswing’ or ‘preparatory’ phase and the ‘forward swing’ or ‘hitting’ phase (Chung et al., 1990; Coleman et al., 1993; Maxwell, 1981; Oka et al., 1975; Prsala, 1982).

Because of the differences between the current and previous phase descriptions, much work has gone into relating recent studies to those conducted prior to 1998. Through these efforts a fairly complete description of the hitting motion has been developed with one important limitation: to date, all studies have focused on forceful
straight ahead swings where the ball is contacted above and slightly anterior to the hitting shoulder. However, the ball being hit is not always in an ideal location so the swing may need to be adjusted. Furthermore, to increase their chances of scoring, volleyball players may swing across their bodies or to the side to avoid the block and/or defensive players. There is no academic knowledge regarding hits other than the standard, ideal straight ahead attack situation.

If one concentrates on the most common volleyball attack, which originates at the antennae, it appears as though there are three types of volleyball attack arm swings. First, there is a cross-body (CB) swing where the attacking arm is brought across the body with the ball positioned slightly medially to the shoulder. The deceleration phase of the cross-body swing likely requires the arm to be brought down towards the body’s midline as it is decelerated. Second, the straight ahead (SA) swing is used when the arm connects with the ball directly in front of the shoulder. The arm is then brought down along the side of the torso and slightly across towards the body’s midline during the deceleration phase. Last, there is an outside swing (OS) that likely has two different deceleration profiles. During this swing, the ball is contacted slightly lateral to the shoulder and the deceleration phase continues to take the arm to the lateral side. However, deceleration is problematic once the net is considered. Because touching the net is a violation, the entire arm swing motion must allow the player to avoid the net. Due to the angle of approach, incidental net violations may be more likely when a right handed hitter attacks out of position 2 on the volleyball court and when a left handed player attacks out of position 4 (Figure 1.1) using an outside swing. Conversely, when a right handed player hits from position 4 and a left handed player from position 2, net violations may be less likely to occur. Because of this hitting position discrepancy, there are two types of outside swings:
(1) when the player requires a high level of attention to avoid the net (OSN) and (2) when the player requires considerably less attention to avoid the net (OS).

Figure 1.1 – Positions of the volleyball court. The bold line at center of court represents the net. Positions 2 and 4 on each side of court are highlighted.
There is little information about the biomechanics of the shoulder during the volleyball swing. Not much is known about shoulder kinematics during the swing or about the relative importance of the muscles involved. Therefore, the purpose of this work is to explore the kinematic aspects of the different spike attack arm swings where each different swing is broken down into its constituent parts. This will allow a thorough description of each swing. The consequences of this work will hopefully be the ability for researchers, coaches, trainers or players to perceive aberration in specific movements and, thus hopefully, the cause of common upper-limb pathologies in the sport.
References


CHAPTER 2 - REVIEW OF LITERATURE

The following chapter provides a review of the biomechanical and pathological aspects of the overhead throwing motion. There are five sections, each with a number of subsections. First, an anatomical and biomechanical review of the glenohumeral joint is presented, followed by a review of the biomechanics of the overhead throwing motion and then, a more in-depth review of the volleyball spiking motion. Next, the injuries experienced in overhead throwing are reviewed and finally volleyball-specific injuries are discussed.

2.1 The Anatomy and Biomechanics of the Shoulder Joint

2.1.1 – GENERAL ANATOMY

The shoulder complex consists of three articulating bones (the humerus, the clavicle, and the scapula), which make up three articulations (the acromioclavicular, the glenohumeral, and the scapulothoracic). The coordinated motions of these three articulations as well as the sternoclavicular joint are required for normal shoulder function (Krishnan, 2004). The sternoclavicular joint is responsible for the connection of the upper extremity to the torso itself via the clavicle and sternum. Due to its high injury rate, the glenohumeral joint, formed by the articulation of the humerus and scapula, is a major consideration in most upper extremity studies that have examined overhead sports (Lapp, 1991).
2.1.2 – SHOULDER MUSCULATURE

The glenohumeral joint is surrounded, supported and stabilized by the rotator cuff muscles that consist of the supraspinatus, infraspinatus, teres minor, and subscapularis. The line of action for this important group of muscles is perpendicular to the glenoid fossa which stabilizes the shoulder by forcing the humeral head into the glenoid (Eberly et al., 1999). The supraspinatus originates in the supraspinous fossa of the scapula and inserts into the upper part of the greater tuberosity of the humerus as well as into the capsule of the glenohumeral joint. The supraspinatus assists the deltoid in abduction of the arm, draws the humerus toward the glenoid, and weakly flexes the arm. The infraspinatus muscle originates at the infraspinous fossa of the scapula and inserts into the middle facet of the greater tuberosity of the humerus as well as into the capsule of the glenohumeral joint. This muscle draws the humerus toward the glenoid fossa resisting posterior dislocation of the arm. The infraspinatus is also involved in external rotation, extension and abduction of the arm. Importantly, both the supraspinatus and infraspinatus are innervated by the suprascapular nerve (C5 and C5/C6 respectively).

The teres minor muscle originates on the upper two-thirds of the dorsal surface of the lateral border of the scapula and inserts into the lower facet of the greater tuberosity of the humerus as well as the capsule of the glenohumeral joint. Its action laterally rotates, and weakly adducts the arm, and draws the humerus toward the glenoid fossa. During external rotation and extension of the upper arm, the teres minor and infraspinatus muscles work synergistically to provide approximately 80% of the external rotation strength during humeral abduction (Krishnan, 2004). The subscapularis muscle originates in the subscapular fossa on the anterior surface of the scapula, and inserts onto the lesser
tuberosity of the humerus and the ventral aspect of the glenohumeral joint capsule. The subscapularis medially rotates the arm and depresses the humeral head.

The deltoid muscle surrounds the superior part of the glenohumeral shoulder complex and is the largest muscle in the shoulder girdle. It is often considered to be three separate muscles (anterior portion, middle portion, and posterior portion) due to its broad origin. The anterior deltoid originates at the anterior and superior aspect of the lateral third of the clavicle. The medial deltoid originates on the lateral border of the acromion process. Finally, the posterior deltoid originates on the inferior lip of the crest of the spine of the scapula. All three parts of the deltoid insert into the deltoid tuberosity of the humerus. These separate origins and common insertion give each portion of the deltoid its own, specific function. The anterior portion works to flex and medially rotate the arm, while the middle portion works solely to abduct the arm. The posterior portion works to extend and laterally rotate the arm.

Similarly to the deltoid, the trapezius is often separated into three distinct parts due its broad origin which begins superiorly from the medial nuchal line, external protuberance, passing inferiorly to the ligamentum nuchae, down to the level of C7 and finally along the spinous processes and the intervening supraspinous ligaments of C7 to T12. The upper part of the trapezius inserts onto the lateral third of the clavicle, while the middle and lower parts insert onto the acromion and crest of the spine of the scapula and the medial portion of the spine of scapula respectively. The upper trapezius is responsible for elevating and rotating the scapula helping to elevate the arm. The middle part retracts the scapula, and the lower part works to depress the scapula while working with the upper part to rotate, and thus, elevate the arm.
The latissimus dorsi muscle is responsible for the extension, adduction and medial rotation of the humerus. It also works to draw the shoulder inferiorly and posteriorly, and to keep the inferior angle of the scapula against the chest wall. The latissimus dorsi originates from the spinous processes of the lower six thoracic vertebrae, lumbar vertebrae, sacral vertebrae, the supraspinal ligament, and the posterior part of the iliac crest through the lumbar fascia, lower three ribs, and the inferior angle of the scapula. It inserts into the floor of the bicipital groove of the humerus.

Although the triceps brachii muscle is located on the upper arm, the long head of the muscle crosses the glenohumeral joint making it important when studying shoulder mechanics. The long head of the triceps originates at the infraglenoid tubercle of the scapula and inserts into the posterior portion of the olecranon process of the ulna. This allows it to extend the forearm as well as aid in the adduction of the arm when it is abducted.

The pectoralis major muscle originates in two areas. The clavicular component attaches to the medial half of the clavicle, while the sternocostal portion attaches to the sternum, the upper six costal cartilages, and the aponeurosis of the external oblique muscle. This relatively large muscle inserts into the lateral lip of the bicipital groove and the crest inferior to the greater tubercle of the humerus. Both parts of this muscle act together to adduct and medially rotate the arm while the clavicular portion also flexes the arm when extended and the sternocostal component extends it when flexed.

A number of muscles that cross the glenohumeral joint and affect its biomechanics have not been mentioned. Although they do contribute somewhat to the motion of the shoulder, they are rarely injured or thought to be the cause of injury. Because of this they have been deemed less important, and thus, do not lie within the scope of this review.
2.1.3 – THE GLENOHUMERAL JOINT

The glenohumeral joint is the articulation formed between the glenoid fossa and the humeral head. The glenoid fossa is smaller than the humeral head, covering only 25-35% of its surface (Saha, 1971; Sarrafian, 1983). The glenoid labrum, a fibrocartilaginous rim extending from the outer perimeter of the glenoid fossa, increases the contact area of the joint. The glenohumeral joint is relatively unstable with a potential for injuries such as subluxation.

The glenohumeral joint is enclosed by the joint capsule that consists of collagenous tissue attached to the perimeter of the glenoid labrum and inserts onto the anatomical neck of the humerus. The capsule is strengthened by the integration of the rotator cuff tendons as well as the tendon of the long head of the biceps brachii. The function of this glenohumeral envelope is to prevent excessive humeral head displacement in extreme glenohumeral positions (Rafii et al., 1986).

2.1.4 – THE SCAPULOOTHORACIC ARTICULATION

The area where the scapula articulates with the thorax is known as the scapulothoracic joint. Scapulothoracic motion is crucial to the normal functioning of the human shoulder. Movement of the scapula with respect to the thorax is accomplished via a number of scapulothoracic muscles including the trapezius, serratus anterior, pectoralis minor, levator scapulae, and the rhomboids. These muscles allow the scapula to be rotated superioinferiorly, anteroposteriorly, and moved mediolaterally as the shoulder is moved about in its extremely large range of motion. The scapula is protracted through the actions of the serratus anterior, while the middle trapezius and rhomboids retract it. The serratus anterior and the trapezius upwardly rotate the scapula, while the upper
The interrelated movements of the scapula with respect to the humerus are known as scapulothoracic rhythm. It is often and inaccurately accepted that there is approximately 1 degree of scapular movement for every 2 degrees of humeral movement (Inman et al., 1944). The actual relationship, however, is much more complex. In the first 30 degrees of abduction, humeral movement can be up to 7 times greater than scapular movement. Once the arm is raised in excess of 30 degrees the two joints begin to contribute equally (Doody et al., 1970; Poppen & Walker, 1976, McClure et al., 2001). The scapulothoracic rhythm, then, is non-linear during abduction with the two segments contributing more equally towards the end range of humeral motion. During lowering, this ratio is relatively linear (equivalent humeral and scapular movement) throughout the entire motion (McClure et al., 2001). Interestingly, the scapulothoracic rhythm appears to be affected by the velocity of the arm, where glenohumeral motion dominates at higher speeds (Sugamoto et al., 2004).

2.1.5 – LIGAMENTS OF THE SHOULDER COMPLEX

The three most intimate ligaments of the glenohumeral joint are the superior, middle and inferior glenohumeral ligaments, all of which lie within the joint capsule. The alignment of each of these ligaments suggests that their primary role is to protect against external rotation at extreme arm positions. External to the joint capsule are two important ligaments; the coracohumeral and the coracoacromial. The coracohumeral ligament runs from the base of the coracoid process to the bicipital groove stabilizing the glenohumeral
joint during elevation, flexion and especially external rotation of the arm. This is the most important ligament preventing excessive external rotation. The coracoacromial ligament runs from the coracoid process to the acromion process passing over the superior aspect of the glenohumeral joint creating the coracoacromial arch. This arch provides excellent protection from superior displacement of the humerus.

2.2 The Biomechanics of the Overhead Throwing Motion

2.2.1 – GOAL OF THE MOTION

The goal of the throwing motion is to develop kinetic energy and impart it into the object being manipulated (the ball in most sports) thereby maximizing the object’s velocity while maintaining an optimal level of accuracy (Fleisig et al., 1996; Meister, 2000a). In other words, the kinetic link principle is used to accelerate the end point of the throwing arm by the use of successively smaller body parts while transferring kinetic energy as efficiently as possible, in a manner that is controlled enough so that it allows high levels of accuracy.

2.2.2 – PHASES OF THE THROWING MOTION

In general, the throwing motion can be broken down into six phases. These include the windup, early cocking, late cocking, acceleration, deceleration, and follow-through phases (Christoforetti & Carroll, 2005; Meister, 2000a). The six phases, although entirely continuous, are often demarcated by changes in the forces and muscle activities that occur during the throwing cycle (Meister, 2000a). The baseball throwing motion is the most commonly used model when studying the phases of overhead motions, such as those seen in volleyball, due to the parallels between the motions (Meister, 2000a). The
following is a summary of each of the phases according to Meister (2000a) and Krishnan (2004).

PHASE I – Wind-Up – There is minimal muscular activity throughout this phase as the shoulder is abducted and slightly internally rotated.

PHASE II – Early Cocking – Also with minimal muscle activity, early cocking ends with the shoulder in 90 degrees of abduction and 15 degrees of horizontal abduction.

PHASE III – Late Cocking – This phase ends with the shoulder in a position of maximum external rotation and 15 degrees of horizontal adduction while shoulder abduction is maintained.

PHASE IV – Acceleration – The goal of the acceleration phase is to rotate the shoulder to the ball contact (volleyball, tennis) or release (baseball, football) position.

PHASE V – Deceleration – This phase is recognized as the most violent phase of the overhead throwing motion because the body must absorb any energy not transferred to the ball during release or contact. The deceleration phase ends with the shoulder in a position of 0 degrees internal rotation, 100 degrees of abduction and 35 degrees of horizontal adduction.

PHASE VI – Follow-Through – During the follow-through, shoulder external rotation increases to 30 degrees, horizontal adduction increases to 60 degrees, and shoulder abduction continues to be maintained at 100 degrees.

It is important to note that the kinematic and kinetic aspects of the glenohumeral joint and its surrounding musculature have been shown to vary for different overhead sports (Lapp, 1991; Meister, 2000a; Fleisig et al., 2003; Krishnan, 2004). For instance, quarterbacks in football rotate their shoulder earlier which, in turn, externally rotates their shoulder into the maximal position sooner than in baseball, possibly allowing more time
to accelerate the heavier ball (Meister, 2000a). Nevertheless, due to the consistencies between most overhead throwing motions, the baseball throw often serves as a universal example of this motion (Meister, 2000a).

2.2.3 – TEMPORAL PARAMETERS

In terms of a baseball throw, the entire throwing process takes less than 2 seconds. Not surprisingly, the final three stages (acceleration, deceleration and follow-through) take less than half a second to complete (Pappas et al., 1985; Fleisig et al., 1989; Dillman et al., 1993; Fleisig et al., 1995; Meister, 2000a; Krishnan, 2004). The wind-up and cocking phases take approximately 1.5 seconds to complete, while the acceleration and deceleration/follow-through phases taking roughly 0.05 and 0.35 seconds respectively. The temporal patterns for each of the phases of throwing in other sports differ by relatively small amounts. For instance, ignoring the wind-up phase, the football throw takes approximately one second to complete (early cocking, 0.5 seconds; late cocking, 0.2 seconds; acceleration, 0.15 seconds; and deceleration/follow-through, 0.16 seconds) (Kelly et al., 2002). Because of the increased mass of the football, it appears rational that the acceleration phase for this sport takes longer than the acceleration phase for a sport that uses a lighter ball (Meister, 2000a).

2.2.4 – KINEMATICS

Throughout the overhead throwing motion, a number of instances have been identified as critical. At these moments the athlete is highly vulnerable to injury due to the extremes of joint range and velocity that the glenohumeral joint is subjected to. For example, at the end of the late cocking phase the shoulder is in a position of maximal
external rotation of more than 170 degrees (Table 2.1) and more than 90 degrees abduction (Meister, 2000b). This is accepted as a dangerous position responsible for numerous injuries such as superior labral strain and impingement of various soft tissues (Bigliani et al., 1997; Fleisig, Andrews, Dillman, & Escamilla, 1995; Krishnan et al., 2004; Meister, 2000b). Similarly, at the end of the acceleration phase, or at the instant of ball release, the shoulder is in a position of more than 90 degrees abduction, and 130 degrees external rotation (Table 2.2). Furthermore, at ball release, the glenohumeral joint is internally rotating at more than 7000 degrees/sec (Table 2.3). Interestingly, horizontal adduction appears to be quite variable between studies ranging from approximately 0 degrees (neutral) to more than 35 degrees (Table 2.2).
Table 2.1 - A review of maximum glenohumeral joint angles attained during the cocking phase of the throwing motion presented in degrees. Ext. Rot. = external rotation. (Partially adapted from Fleisig et al., 1996).

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<tbody>
<tr>
<td>Feltner &amp; Dapena, 1986</td>
<td>Baseball</td>
<td>170 ± 10</td>
</tr>
<tr>
<td>Sakurai et al., 1993</td>
<td>Baseball</td>
<td>181 ± 6</td>
</tr>
<tr>
<td>Dillman et al., 1993</td>
<td>Baseball</td>
<td>178</td>
</tr>
<tr>
<td>Fleisig et al., 1995</td>
<td>Baseball</td>
<td>172 ± 12</td>
</tr>
<tr>
<td>Rash &amp; Shapiro, 1995</td>
<td>Football</td>
<td>164 ± 11</td>
</tr>
<tr>
<td>Fleisig et al., 1996</td>
<td>Football</td>
<td>164 ± 12</td>
</tr>
<tr>
<td>Fleisig et al., 1996</td>
<td>Baseball</td>
<td>173 ± 10</td>
</tr>
<tr>
<td>Fleisig et al., 1999</td>
<td>Baseball</td>
<td>175 ± 11</td>
</tr>
<tr>
<td>Werner et al., 2001</td>
<td>Baseball</td>
<td>184 ± 14</td>
</tr>
<tr>
<td>Stodden et al., 2005</td>
<td>Baseball</td>
<td>173 ± 11</td>
</tr>
<tr>
<td>Fleisig et al., 2006</td>
<td>Baseball</td>
<td>183 ± 10</td>
</tr>
</tbody>
</table>

Table 2.2 - A review of maximum glenohumeral joint angles attained during the acceleration phase of the throwing motion presented in degrees. Ext. Rot. = external rotation; Abd. = abduction; Hor. Add. = horizontal adduction. (Partially adapted from Fleisig et al., 1996).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Feltner &amp; Dapena, 1986</td>
<td>Baseball</td>
<td>92 ± 6</td>
<td>133 ± 23</td>
<td>2 ± 9</td>
</tr>
<tr>
<td>Sakurai et al., 1993</td>
<td>Baseball</td>
<td>79 ± 10</td>
<td>137 ± 20</td>
<td>14 ± 13</td>
</tr>
<tr>
<td>Dillman et al., 1993</td>
<td>Baseball</td>
<td>95</td>
<td>105</td>
<td>14</td>
</tr>
<tr>
<td>Fleisig et al., 1995</td>
<td>Baseball</td>
<td>9 ± 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rash &amp; Shapiro, 1995</td>
<td>Football</td>
<td>96 ± 7</td>
<td>136 ± 14</td>
<td>12 ± 9</td>
</tr>
<tr>
<td>Fleisig et al., 1996</td>
<td>Football</td>
<td>108 ± 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fleisig et al., 1996</td>
<td>Baseball</td>
<td>93 ± 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fleisig et al., 1999</td>
<td>Baseball</td>
<td>9 ± 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Werner et al., 2001</td>
<td>Baseball</td>
<td>14 ± 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stodden et al., 2005</td>
<td>Baseball</td>
<td>99 ± 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fleisig et al., 2006</td>
<td>Baseball</td>
<td>99 ± 10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2.3 - A review of the maximum internal rotation angular velocity attained during the throwing motion presented in degrees/sec. Asterisked values estimated. (Partially adapted from Fleisig et al., 1996).

<table>
<thead>
<tr>
<th>Author</th>
<th>Sport</th>
<th>Ball Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vaughn, 1985</td>
<td>Baseball</td>
<td>6073 ± 854</td>
</tr>
<tr>
<td>Pappas et al., 1985</td>
<td>Baseball</td>
<td>6180</td>
</tr>
<tr>
<td>Feltner &amp; Dapena, 1986</td>
<td>Baseball</td>
<td>6100 ± 1700</td>
</tr>
<tr>
<td>Dillman et al., 1993</td>
<td>Baseball</td>
<td>6940 ± 1080</td>
</tr>
<tr>
<td>Fleisig et al., 1995</td>
<td>Baseball</td>
<td>7290 ± 1090</td>
</tr>
<tr>
<td>Rash &amp; Shapiro, 1995</td>
<td>Football</td>
<td>2990 ± 1040</td>
</tr>
<tr>
<td>Fleisig et al., 1996</td>
<td>Football</td>
<td>4950 ± 1080</td>
</tr>
<tr>
<td>Fleisig et al., 1996</td>
<td>Baseball</td>
<td>7550 ± 1360</td>
</tr>
<tr>
<td>Fleisig et al., 1999</td>
<td>Baseball</td>
<td>7240 ± 1090</td>
</tr>
<tr>
<td>Hong et al., 2001</td>
<td>Throwing</td>
<td>4010*</td>
</tr>
<tr>
<td>Werner et al., 2001</td>
<td>Baseball</td>
<td>8286 ± 2777</td>
</tr>
<tr>
<td>Fleisig et al., 2006</td>
<td>Baseball</td>
<td>6520 ± 950</td>
</tr>
</tbody>
</table>

It is important to note that coordination of the entire body is necessary for the overhead movement to be efficient and effective. For instance, to take advantage of the throwing kinetic chain, an athlete must follow a specific sequence of movements: stride, pelvis rotation, upper torso rotation, elbow extension, shoulder internal rotation and wrist flexion (Fleisig et al., 1996). If any part of this chain is not properly applied, a loss in effectiveness and efficiency takes place. In fact, a 20% decrease in the amount of energy transfer between the trunk and the glenohumeral joint requires a 34% increase in rotational velocity at the shoulder to maintain ball release velocity (Kibler, 1988). Hence,
a complete transfer of kinetic energy produced in one area of the body to another is required to achieve maximum end-point velocity.

This is also true following the acceleration phase. Similar, but opposite, kinetic chains are employed during both the deceleration and follow-through phases to absorb any remaining energy after ball release or contact (Fleisig et al., 1996). Therefore, poor coordination of the kinetic chain during these phases leads to intensified shoulder stresses.

With respect to levels of expertise in the overhead throwing motion, shoulder mechanics do not change as the level increases (Fleisig et al., 1996). In other words, the mechanics of a young, amateur pitcher are not significantly different from the mechanics of an older, professional pitcher. This has important consequences in that differences in parameters such as resulting ball velocity are not affected by the mechanics of the throw, but, rather, by the kinetics, anthropometrics and other kinematic variables of the thrower, such as muscle strength, arm length, and muscle composition. Additionally, the type of backswing used during a tennis serve does not significantly change the resulting ball velocity (Fleisig et al., 2003). It seems then, that in some instances, the mechanics of the throwing motion may not be critical.

However, when the level of effort of the throwing athlete is analyzed, lower levels of exertion correspond with increased maximum horizontal adduction and decreased maximum external rotation during the cocking phase; decreased shoulder internal rotation velocity during the acceleration phase; and increased horizontal adduction at the instant of ball release (Fleisig et al., 1996). Therefore, the mechanics of the thrower are largely dependent on the type or intensity of the throw being performed, and the overhead
throwing motion should only be compared when analyzing performances of similar levels of effort.

The large forces and torques applied to and by the shoulder musculature (Fleisig et al., 1996; Fleisig et al., 1999; Pradhan et al., 2001; Manske et al., 2004), change the physical structure of the shoulder in high level overhead athletes. Repetitive stresses cause an increase in the shoulder’s passive external rotation and a decrease in its passive internal rotation when the hitting shoulder is compared to the non-hitting shoulder (Baltaci & Tunay, 2004). Interestingly, the decrease in passive internal rotation seen in athletes is a result of reactive fibrosis of the capsular tissue due to repetitive microtrauma (Pappas et al., 1985). Researchers focusing on other overhead sports such as javelin, football, and tennis, have found similar trends of increased external rotation and decreased internal rotation in the dominant shoulder (Brown et al., 1988; Bigliani et al., 1997; Baltaci & Tunay, 2004). Clearly the entire shoulder anatomy is heavily taxed during elite overhead throwing activities.

The scapulothoracic joint performs a number of essential roles in the throwing motion. Kibler (1998) has reported the five essential roles of the scapula in athletic situations requiring shoulder function. First, the scapula provides a stable base for the glenohumeral articulation. Second, the scapula allows the retraction and protraction of the shoulder complex along the scapular wall. Third, it acts both as an elevator of the acromion and, fourth, as a region for muscle attachment. Fifth, the scapula acts as a link between the trunk and arm through which forces can be transferred. To allow the scapula to perform these functions, the scapular musculature works in tandem pairs to provide stabilization and elevation of the acromion. The tandem pairs used in scapular stabilization include the upper and lower portions of the trapezius and rhomboid muscles,
paired with the serratus anterior muscle, while the tandem pairs used in acromial
elevation are the lower trapezius and serratus anterior muscles paired with the upper
trapezius and rhomboid muscles. Balance in these pairs is essential for proper shoulder
function during an overhead motion (Speer & Garrett, 1994). Similarly, balance between
each of the three trapezius muscle parts is necessary for scapular stability (Cools et al.,
2005).

2.2.5 – KINETICS

Several times during a single overhead throwing motion the shoulder is subjected
to large forces and torques. These extreme anatomical kinetics may cause damage to the
anatomy and function of the glenohumeral joint (Fleisig et al., 1996; Hutchinson et al.,
1995; Krishnan et al., 2004; Meister, 2000a). At the end of the cocking phase, due to the
large external rotation and elevation, and the shoulder musculature overcoming both
inertia and gravity, an internal rotation torque close to 100 N•m and an average horizontal
adduction torque of 91 N•m is produced (range 50 N•m to 125 N•m; Table 2.4). This
causes an average anterior force of more than 330 N (Table 2.5) and a compressive force
of 650 N within the shoulder complex (Meister, 2000a). Just prior to ball release or
contact, internal rotation torque peaks at more than 1500 N•m (Gainor et al., 1980).
During the deceleration and follow-through (i.e. after ball release or contact), adduction
and horizontal abduction torques can reach up to 127 N•m and 175 N•m respectively
(Table 2.6). During this time, the shoulder is also subjected to an external rotation torque
of almost 1,700 N•m (Gainor et al., 1980; Pappas et al., 1985). To stabilize the
glenohumeral joint throughout this demanding phase, a compressive force of more than
1000 N is created by the shoulder musculature, as well as a posterior force of almost 400 N (Table 2.7).

**Table 2.4** - A review of glenohumeral joint torques produced during the cocking phase of the overhead throwing motion presented in Newton•meters. Int. Rot. = internal rotation; Hor. Add. = horizontal adduction. Asterisked values estimated. (Partially adapted from Fleisig *et al.*, 1996).

<table>
<thead>
<tr>
<th>Author</th>
<th>Sport</th>
<th>Int. Rot.</th>
<th>Hor. Add.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feltner <em>et al.</em>, 1986</td>
<td>Baseball</td>
<td>90 ± 20</td>
<td>110 ± 20</td>
</tr>
<tr>
<td>Fleisig <em>et al.</em>, 1995</td>
<td>Baseball</td>
<td>100 ± 20</td>
<td></td>
</tr>
<tr>
<td>Rash &amp; Shapiro, 1995</td>
<td>Football</td>
<td>66 ± 18</td>
<td>50 ± 20</td>
</tr>
<tr>
<td>Fleisig <em>et al.</em>, 1996</td>
<td>Baseball</td>
<td>55 ± 10</td>
<td></td>
</tr>
<tr>
<td>Fleisig <em>et al.</em>, 1996</td>
<td>Football</td>
<td>54 ± 13</td>
<td>78 ± 19</td>
</tr>
<tr>
<td>Fleisig <em>et al.</em>, 1999</td>
<td>Baseball</td>
<td>68 ± 15</td>
<td></td>
</tr>
<tr>
<td>Werner <em>et al.</em>, 2001</td>
<td>Baseball</td>
<td>111 ± 17</td>
<td>125*</td>
</tr>
<tr>
<td>Elliot <em>et al.</em>, 2003</td>
<td>Tennis</td>
<td>64.9</td>
<td></td>
</tr>
<tr>
<td>Fleisig <em>et al.</em>, 2006</td>
<td>Baseball</td>
<td>84 ± 6</td>
<td></td>
</tr>
</tbody>
</table>
Table 2.5 - A review of glenohumeral joint forces produced during the cocking phase of the overhead throwing motion presented in Newtons. Ant. = anterior. (Partially adapted from Fleisig et al., 1996).

<table>
<thead>
<tr>
<th>Author</th>
<th>Sport</th>
<th>Ant.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feltner et al., 1986</td>
<td>Baseball</td>
<td>300</td>
</tr>
<tr>
<td>Fleisig et al., 1995</td>
<td>Baseball</td>
<td>380 ± 90</td>
</tr>
<tr>
<td>Rash &amp; Shapiro, 1995</td>
<td>Football</td>
<td>250 ± 85</td>
</tr>
<tr>
<td>Fleisig et al., 1996</td>
<td>Football</td>
<td>350 ± 80</td>
</tr>
<tr>
<td>Fleisig et al., 1999</td>
<td>Baseball</td>
<td>390 ± 90</td>
</tr>
</tbody>
</table>

Table 2.6 - A review of glenohumeral joint torques produced during the deceleration phase of the overhead throwing motion presented in Newton•meters. Add. = adduction; Hor. Abd. = horizontal abduction. Asterisked values estimated. (Partially adapted from Fleisig et al., 1996).

<table>
<thead>
<tr>
<th>Author</th>
<th>Sport</th>
<th>Add.</th>
<th>Hor. Abd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feltner et al., 1986</td>
<td>Baseball</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Fleisig et al., 1995</td>
<td>Baseball</td>
<td>83 ± 26</td>
<td>97 ± 25</td>
</tr>
<tr>
<td>Rash &amp; Shapiro, 1995</td>
<td>Football</td>
<td>20 ± 20</td>
<td>89 ± 74</td>
</tr>
<tr>
<td>Fleisig et al., 1996</td>
<td>Football</td>
<td>58 ± 34</td>
<td>80 ± 34</td>
</tr>
<tr>
<td>Fleisig et al., 1999</td>
<td>Baseball</td>
<td>109 ± 85</td>
<td></td>
</tr>
<tr>
<td>Werner et al., 2001</td>
<td>Baseball</td>
<td>26 ± 5</td>
<td>175*</td>
</tr>
<tr>
<td>Fleisig et al., 2006</td>
<td>Baseball</td>
<td>127 ± 127</td>
<td>130 ± 35</td>
</tr>
</tbody>
</table>
Table 2.7 - A review of glenohumeral joint forces produced during the deceleration phase of the overhead throwing motion presented in Newtons. Comp. = compressive; Post. = posterior. (Partially adapted from Fleisig et al., 1996).

<table>
<thead>
<tr>
<th>Author</th>
<th>Sport</th>
<th>Comp.</th>
<th>Post.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feltner et al., 1986</td>
<td>Baseball</td>
<td>860 ± 120</td>
<td></td>
</tr>
<tr>
<td>Fleisig et al., 1995</td>
<td>Baseball</td>
<td>1090 ± 110</td>
<td>400 ± 90</td>
</tr>
<tr>
<td>Rash &amp; Shapiro, 1995</td>
<td>Football</td>
<td>440 ± 120</td>
<td>100 ± 100</td>
</tr>
<tr>
<td>Fleisig et al., 1996</td>
<td>Football</td>
<td>660 ± 120</td>
<td>240 ± 120</td>
</tr>
<tr>
<td>Fleisig et al., 1999</td>
<td>Baseball</td>
<td>1070</td>
<td>390 N ± 240</td>
</tr>
<tr>
<td>Elliot et al., 2003</td>
<td>Tennis</td>
<td>608.3</td>
<td></td>
</tr>
<tr>
<td>Fleisig et al., 2006</td>
<td>Baseball</td>
<td>1145 ± 113</td>
<td></td>
</tr>
</tbody>
</table>

As pitching quality increases, most if not all shoulder kinetic parameters (i.e. shoulder internal rotation torque, shoulder anterior force, shoulder proximal force, shoulder posterior force, and shoulder horizontal abduction torque) increase as well (Fleisig et al., 1999). Similarly, tennis players demonstrate increased shoulder internal rotation torques at maximum external rotation, increased peak horizontal adduction torques, and increased shoulder compressive forces with higher service speeds (Fleisig et al., 2003). Similarly, different levels of effort in the overhead throwing motion have been shown to produce large and consistent differences in shoulder kinetics (Fleisig et al., 1996). Lower levels of effort correspond with decreased shoulder internal rotation torque and shoulder anterior force during the cocking phase; and decreased shoulder compressive force during the deceleration phase (Fleisig et al., 1996).

Differences in shoulder kinetics are seen both bilaterally and between elite and non-elite overhead athletes. For instance, there are significant differences in internal
rotation and abduction/adduction concentric strength between the dominant and non-dominant shoulders of professional pitchers (Sirota et al., 1997). As well, both concentric internal and eccentric external rotation strength at the end ranges is significantly greater on the dominant side compared to the non-dominant side in both baseball and badminton players (Ng & Law, 2002; Yildiz et al., 2006). When comparing elite and non-elite overhead athletes, for example, the latter demonstrate higher activity in all shoulder muscles when doing push and pull tasks (Illyes & Kiss, 2005).

Because the acceleration and deceleration phases of the glenohumeral joint during an overhead throw require predominantly the eccentric contraction of the external rotators and the concentric contraction of the internal rotators, an adequate ratio of strength of the former compared to the latter is critical for glenohumeral joint stability (Yildiz et al., 2006). Therefore, an increase in concentric internal rotation strength in the dominant shoulder should be accompanied by a similar increase in eccentric external rotation strength in the same throwing shoulder.

Although in vivo kinetic measures of the shoulder are not possible, there have been a few attempts to estimate the internal kinetics of the shoulder using an in vitro approach. One study in particular has found that anterior and posterior strain of the superior labrum significantly increases in a position that simulates the late-cocking phase of the throw compared to positions that simulate the early cocking, acceleration, deceleration, and follow-through phases (Pradhan, et al., 2001). This research also agrees with other works concluding that the maximal abduction and external rotation shoulder position attained during the late-cocking phase may be a crucial factor in the development of superior labrum, anterior-posterior (SLAP) lesions (Altchek & Hatch, 2001).
2.2.6 – ELECTROMYOGRAPHY

Although the timing and importance of the major shoulder muscles used during the overhead throwing motion were presented above, a number of studies have focused on other electromyographical differences between experts and novices. Two types of muscle activity have been associated with baseball pitching (Gowan et al., 1987). Group I muscles are more active during the early and late cocking phases and include the infraspinatus, the supraspinatus, and the biceps brachii muscles. Group II muscles were mostly active during the acceleration phase and include the subscapularis and the latissimus dorsi muscles. Similarly, studies have shown there to be distinct stabilizing muscles such as the infraspinatus, supraspinatus, and the deltoid while the subscapularis, pectoralis major, latissimus dorsi, and triceps brachii have been defined as accelerators (Gowan et al., 1987; Kelly et al., 2002).

When comparing experienced and recreational overhead athletes, large differences have been found. In fact, the activity of all shoulder muscles is higher in recreational athletes than professional javelin throwers during push and pull tasks (Illyes & Kiss, 2005). This may indicate an increased level of coordination in elite overhead athletes. More specifically, during a pulling task, recreational athletes used mainly their posterior deltoid to generate force, while professional javelin throwers used many ‘pull’ muscles so that all muscles worked at a reduced intensity. Other differences such as higher stabilizing muscle activity during maximal overhead throwing have also been found in elite overhead athletes compared to recreational non-overhead athletes (Illyes & Kiss, 2005).
2.3 The Biomechanics of the Volleyball Swing

2.3.1 – GOAL OF THE MOTION

Similar to pitching in baseball, the goal of the volleyball spike is to impart maximal kinetic energy to the ball while maintaining a certain level of accuracy (Abendroth-Smith & Kras, 1999). The large transfer of energy from the distal part of the upper extremity to the ball on impact results in increased ball speed, making it more difficult to defend. Factors, such as a player’s body mass, hours of muscular training per week, vertical jump height and time in the air, have been correlated with ball velocity after contact, which, in turn has been correlated with success in the sport (Forthomme, Croisier, Ciccarone, Crielaard, & Cloes, 2005).

2.3.2 – PHASES OF THE VOLLEYBALL SPIKE

A review of the current academic volleyball literature reveals discrepancies in the number of phases and the distinction between successive phases (Chung et al., 1990; Coleman et al., 1993; Maxwell, 1981; Oka et al., 1975; Prsala, 1982; Rokito et al., 1998). Earlier works (Chung et al., 1990; Coleman et al., 1993; Maxwell, 1981; Oka et al., 1975; Prsala, 1982) were based on the ‘backswing’ (or ‘preparatory’) phase and the ‘forward swing’ (or ‘hitting’) phase of the spiking motion. Studies analyzing other overhead sports divide the throwing motion into the wind-up, early-cocking, late-cocking, acceleration, deceleration and follow-through phases (Fleisig et al., 1996; Jobe et al., 1983; Krishnan et al., 2004; Meister, 2000a). More recently, the volleyball spike has been divided into phases that resemble a slightly simplified version of the general overhead throwing motion seen in baseball, based on findings regarding EMG signals in athletes’ shoulders during spiking (Rokito et al., 1998). In this system, five phases were defined, with a
general cocking phase encompassing both the early and late cocking phases of the overhand throw. Using this system, in earlier studies the wind-up and cocking phases were included in the backswing, while the acceleration, deceleration and follow-through phases were included in the forward swing phase (Figure 2.1). It should be noted that the end of the cocking phase was associated with the end of the backswing phase and the beginning of the forward swing, or hitting phase of the volleyball swing in studies conducted prior to 1998. Because of the lack of specificity used in volleyball spike phase definition prior to 1998, a review of the kinematic and kinetic aspects of each phase becomes difficult. For the purpose of this analysis, the following five phases will be used: the wind-up, cocking, acceleration, deceleration, and follow-through phases. A summary of each phase follows for a standard straight ahead volleyball attack swing.
Figure 2.1 - Phases of the volleyball spike. Each letter depicts the end of one phase and the start of the next. Windup: a-b, cocking: b-c, acceleration: c-d, deceleration: d-e, and follow-through: e-f.

PHASE I – Wind-up – (See Figure 2.1a-2.1b) During the wind-up, the shoulder is elevated to a position of more than 90 degrees from the anatomical position and is lightly horizontally abducted (Chung et al., 1990; Coleman et al., 1993; Rokito et al., 1998). Similar to the baseball pitch, this is done in a controlled manner with joints not reaching end range. The motions of this phase can be quite variable from person to person, but result in similar final arm and body positions (Rokito et al., 1998). Two primary wind-up styles have been identified: the elevation-style (or bow-and-arrow-style) wind-up and the backswing-style wind-up. The elevation-style wind-up refers to a motion where the
humerus is horizontally abducted above the horizontal plane of the shoulder and where the arm is raised relatively early in the sequence (Oka et al., 1975). On the other hand, the backswing-style wind-up refers to a motion where the humerus is horizontally abducted below the horizontal plane of the shoulder requiring the arm to be raised relatively late in the sequence (Maxwell, 1981; Oka et al., 1975).

It is important to note that a continuum exists and the backswing-style and elevation-style wind-up patterns represent two opposite ends of the movement. Numerous studies have reported this and shown that the majority of high-level volleyball players employ a slight elevation-style wind-up when performing the volleyball spike rather than a full form of either of the two (Bowman, 2001; Coleman et al., 1993; Maxwell, 1981; Oka et al., 1975). In fact, the backswing-style is used relatively infrequently at elite levels of the sport (Coleman et al., 1993; Maxwell, 1981; Oka et al., 1975). However, no differences have been found in pre-impact hand speed between the two styles of wind-up (Bowman, 2001).

PHASE II – Cocking – (See Figure 2.1b-2.1c) During the cocking phase of the volleyball spike, the humerus remains abducted and may be slightly lowered at the completion of the phase (Coleman et al., 1993). Additionally, late in the cocking phase, the humerus is in a position of maximal horizontal abduction and extreme external rotation (Maxwell, 1981; Rokito et al., 1998). Similar to the overhead throw, the dominant arm lags behind the attacker’s trunk during this phase (Chung et al., 1990). The cocking phase lasts from the end of the wind-up, which has the arm elevated and only marginally horizontally abducted, to a position of similar elevation but extreme horizontal abduction and external rotation of the humerus. The scapula has also been shown to upwardly rotate during this phase as well (Oka et al., 1975). Interestingly, when an
elevation-style wind-up is employed, the arm is cocked while remaining above the horizontal, however, when a backswing-style wind-up is used, the arm is cocked in a position slightly below the horizontal (Maxwell, 1981).

PHASE III – Acceleration – (See Figure 2.1c-2.1d) Although researchers agree that the goal of the acceleration phase during spiking is to achieve maximal velocity of the arm, research has shown that throughout this phase shoulder kinematics are quite variable (Coleman et al., 1993). According to a number of authors, humeral elevation is increased throughout this phase, reaching an angle between 25 degrees (Chung et al., 1990) and 60 degrees (Coleman et al., 1993) to the horizontal at impact. However, others have found that the arm is lowered during the middle portion of the phase (Chung et al., 1990) or just prior to ball contact (Rokito et al., 1998). While the degree of internal and external rotation also varies among volleyball players most researchers agree that leading up to contact attackers generally internally rotate their glenohumeral joint throughout the acceleration phase (Christopher, 2001; Chung, 1989; Maxwell, 1981; Oka et al., 1975; Prsala, 1982; Rokito et al., 1998).

Regardless of the exact mechanics used, the arm motion is such that the ball can be contacted with the humerus at approximately 140 to 170 degrees of adduction in neutral (internal/external) rotation (Kugler et al., 1996), or above and slightly anterior to the hitting shoulder (Coleman et al., 1993). This position is attained regardless of the wind-up style used, meaning that a number of corrections are done throughout the acceleration phase that place the arm in an optimal position for striking the ball (Coleman et al., 1993). Finally, no detailed description of scapular motions throughout the volleyball swing exists in any academic, peer-reviewed article. This is surprising considering its importance to shoulder motions and mechanics.
PHASE IV – Deceleration – (See Figure 2.1d-2.1e) The deceleration phase starts immediately after ball contact and ends when the forward momentum of the arm has been largely reduced. Similar to the overhead throwing motion, this phase of the volleyball spike is often considered a mirror image or the reverse of the acceleration phase (Coleman et al., 1993; Oka et al., 1975; Rokito et al., 1998). After ball contact, the arm continues forward and across the body while being horizontally adducted, internally rotated and lowered (adducted) with decreasing velocity (Chung et al., 1990; Rokito et al., 1998). The goal of this phase is to absorb any remaining kinetic energy that has not been imparted to the ball, and, therefore, it is quite similar to the deceleration phase of the throwing motion seen in baseball and other overhead sports (Coleman et al., 1993; Meister, 2000a; Oka et al., 1975; Rokito et al., 1998). Once this energy has been absorbed the follow-through phase begins.

PHASE V – Follow-Through – (See Figure 2.1e-2.1f) The goal of the follow-through is to stay technically clean (i.e. not commit a foul such as a net touch) and to bring the arm to a complete stop (Abendroth-Smith & Kras, 1999). The arm is slowly and gradually brought down and to the side of the player (Rokito et al., 1998).

The preceding was a summary of each phase of a standard straight ahead volleyball attack swing. The majority of volleyball studies have used ‘outside’ hitters as subjects and since players are primarily trained in certain positions and taught attack-specific arm mechanics for hitting this description may not apply to all hitters. It is possible that certain volleyball players employ different techniques than the ones that have been reported to date. In this case, studies focusing on position-specific mechanics may reveal currently unknown details involving the kinematics of the arm swing used by
the full range of volleyball players. These types of studies would allow coaches, athletes and trainers to apply performance, preventative and rehabilitative programs directly to players based on court position, strengths, weaknesses, and abilities.

2.3.3 – TEMPORAL PARAMETERS

There is little information on the temporal parameters of the volleyball spiking motion. One reason may be that volleyball research often focuses on the rehabilitation, training or coaching aspects of the sport and rarely are the temporal facets seen as important to these areas. Nevertheless, three authors have reported temporal findings using a cinematographic approach. However, because different phase conventions (two phases versus five) were used, a direct comparison between these studies is impossible. Also, because the deceleration and follow-through phases were analyzed in only one study (Rokito et al., 1998), little is known about these phases during the volleyball attack spike. From the start of wind-up to the end of cocking a period of $0.277 \pm 0.032$ seconds was found in one study (Chung et al., 1990) while $0.57 \pm 0.11$ seconds was reported in another (Rokito et al., 1998). From the end of cocking to the end of acceleration between $0.09$ and $0.123$ seconds elapse (Christopher, 2001; Chung et al., 1990; Rokito et al., 1998). Finally, the deceleration and follow-through phases have been shown to last approximately 0.10 seconds and 0.30 seconds respectively. The duration of the complete pre-impact arm swing (from approximately the start of wind-up to the end of acceleration) lasts $0.378 \pm 0.051$ seconds (Chung et al., 1990).

When compared to the elite-level overhead throwing motion, which takes almost 2 seconds (Meister, 2000a), it is clear that the entire elite-level volleyball attack sequence is significantly shorter. Interestingly, the baseball wind-up and cocking phases take
approximately 1.5 seconds to complete (Meister, 2000a), while the corresponding backswing for the volleyball spike takes less than a quarter of a second. The acceleration or forward swing phase of the volleyball spike, however, take roughly 0.101 seconds to complete, while during the baseball pitch, this same phase took only 0.05 seconds or half the time (Meister, 2000a).

No other authors have reported the temporal characteristics of the volleyball swing. This makes it difficult to compare the spiking motion to overhead movements in other sports. Perhaps a more thorough understanding of the temporal features of the volleyball swing is needed before it can be compared to other overhead swings and before the mechanisms of the spike attack and the injuries of the shoulder encountered in the sport are fully understood.

2.3.4 – KINEMATICS

It has been estimated that an elite attacker, who practices approximately 16-20 hours per week will spike 40,000 times in a single year (Dübotzky & Leistner, 1992). Clearly, a need exists for comprehensive knowledge of the kinematics of the motion so that proper (effective and efficient) techniques can be defined. An interesting aspect of the overhead spike is the kinematic variability of the upper arm exhibited by high level players during the acceleration phase of the swing in most studies (Coleman et al., 1993; Maxwell, 1981). The mechanics employed by professional baseball pitchers, conversely, tend to be similar (Jacobson & Benson, 2001). As mentioned above, although volleyball attackers can employ different styles, and therefore different kinematics, the ball is generally contacted above and slightly anterior to the hitting shoulder. As a result, the arm motion is constantly adjusted throughout the spike so that contact can occur in an
optimal location (Maxwell, 1981). This could lead one to hypothesize that the mechanics of the swing are not necessarily as important in volleyball as in other overhead sports such as baseball and football, or rather, that the dynamic aspect of the ‘set’ in volleyball requires attackers to be equally dynamic in their upper limb mechanics during an attack sequence.

Despite the variability in spiking kinematics at elite levels, the shoulder joint must be precisely manipulated so that the ball can be struck properly. For instance, researchers have reported that approximately 19% of peak arm velocity originates in the glenohumeral joint, the rest coming predominantly from the trunk and lower limbs (Chung et al., 1990; Dübotzky & Leistner, 1992). This corresponds to a humeral angular velocity of approximately 870 degrees/sec in top level international players which has been correlated to the resulting ball velocity (Coleman et al., 1993). Additionally, hand speeds reach a linear velocity of more than 20 meters/sec which result in ball velocities of up to 33.3 meters/sec (Chung et al., 1990; Coleman et al., 1993). Therefore, the more angular velocity that a volleyball attacker can impart onto the humerus during a spike, the higher the resulting ball velocity, and thus, the player’s chances of scoring.

2.3.5 – KINETICS

Only a small number of studies have analyzed the shoulder forces and torques experienced during a volleyball attack. Most notably, an unpublished thesis has focused on the shoulder kinetics of the volleyball swing (Christopher, 2001). According to Christopher (2001), just prior to ball contact, at the end of the acceleration phase, a maximum internal rotation torque of approximately 50 N•m is generated in the shoulder. Also, just after impact, an estimated maximum glenohumeral compressive force of more
than 800 N to more than 1500 N, and a shoulder adduction torque of approximately 115 N•m are experienced (Christopher, 2001; Rinderu, 1998).

A correlation has been found between maximum ball velocity and maximum shoulder compressive forces (Christopher, 2001). Similarly, compressive forces of the glenohumeral joint have been shown to increase with increasing humeral angular velocity (or ball speed) in other overhead sports (Elliott et al., 2003; Fleisig et al., 1996; Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999). High shoulder compressive forces result in a higher bone mass in the proximal humerus in elite volleyball attackers (Alfredson, Nordstrom, Pietila, & Lorentzon, 1998). Moderate positive correlations between maximum ball velocity and maximum anterior and superior shear forces appear to exist as well (Christopher, 2001).

Top-level attackers produce smooth changes in the kinetic patterns of the shoulder throughout the spike while less skilled attackers display more variable kinetic patterns (Maxwell, 1981). In other words, kinetic variables of the shoulder (internal rotation torque, glenohumeral compressive force, etc.) have been found to change more smoothly in highly skilled volleyball players than in less skilled volleyball players. Muscle recruitment may be a primary reason for this. For instance, during a novel pulling task, elite javelin throwers are capable of performing the same movements as sedentary adults while recruiting much more of their musculature which results in lower levels of activation across all the muscles recruited (Illyes & Kiss, 2005). It is possible that a similar mechanism may exist in volleyball, where elite attackers are capable of recruiting a wide range of musculature, reducing their overall muscle activation.
2.3.5 – ELECTROMYOGRAPHY

Only two studies have used electromyography to examine the shoulder musculature during the volleyball spiking motion, one with surface electrodes (Oka et al., 1975) and the other with intramuscular wire electrodes (Rokito et al., 1998). The following is a summary of those findings (refer to Figure 2.2 for a schematic representation of the actions of each of the major upper limb muscles):

During the wind-up phase of the swing, the biceps brachii long head, clavicular portion of the pectoralis major, supraspinatus and the anterior deltoid form a force couple to raise the arm over the spiker’s head. The supraspinatus acts to help the deltoid raise the arm rapidly and, most importantly, maintains glenohumeral congruency and stability. The infraspinatus and the teres minor, on the other hand, work to ‘fine-tune’ the position of the humeral head in the glenoid fossa, while the subscapularis helps compress and stabilize the glenohumeral joint on the superior portion of the anterior wall during the glenohumeral abduction by superiorly rotating the arm.

The cocking phase again has the biceps brachii long head, clavicular portion of the pectoralis major, anterior deltoid and the supraspinatus muscles functioning together to maintain humeral elevation while externally rotating the joint. The infraspinatus and teres minor muscles work together to externally rotate the arm. Due to the inherent instability of this position, the anterior wall muscles (subscapularis and pectoralis major) become highly active to stabilize and protect the glenohumeral joint from anterior subluxation or dislocation.

The acceleration phase is associated with a decrease in anterior deltoid and supraspinatus activity. The reduced activity of these humeral adductors indicates that the arm elevation is not maintained throughout the phase. The teres minor and infraspinatus
muscles work independently, with the teres minor muscle being much more active as it continues to fine-tune the position of the humeral head in the glenoid fossa. The activities of the subscapularis, teres major, latissimus dorsi, and pectoralis major muscles peak in this phase as they work to generate the power needed to accelerate the upper extremity. Also, discharges from the left and right side of the serratus anterior muscle indicate that the scapula was rotated and shifted upward.

The kinetic energy not imparted to the ball needs to be dissipated after ball contact. This explains the muscle activity seen during the deceleration phase of the volleyball spike. This muscle activity maintains shoulder stability during this particularly violent part of the swing. The humerus is lowered quite rapidly and, thus, the anterior and middle deltoid and the supraspinatus muscles are only moderately active towards the end of the phase. Again, the infraspinatus and teres minor muscles work to stabilize the glenohumeral joint while the serratus anterior continues to rotate the scapula upwards. The activity of the anterior wall muscles declines similarly towards the end of the phase.

The follow-through phase is associated with only minimal muscular activity, suggesting that this phase is not as critical in the volleyball spiking motion, just as in other overhead throwing motions. As the arm descends slowly and comes to rest, all muscle activity decreases, dissipating any remaining kinetic energy.

To date, no information has been gathered regarding the type of contraction (eccentric versus concentric) throughout the volleyball swing. Due to the importance of this knowledge in understanding the possible dangers associated with this movement, this is surprising. Studies analyzing the types of contractions taking place throughout the volleyball spike attack are greatly needed.
The positions, speeds, forces and muscular demands that the volleyball shoulder is placed under make the attack spike a deleterious motion. Many studies have focused on the injury types and rates associated with the swing. Therefore, understanding the biomechanics is important in understanding injury pathology. The following is a summary of current academic knowledge concerning the pathologies associated with the overhead throwing motion and the volleyball attack spike.
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<tr>
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- **Low Level Activity, Fine Tuning**
- **Stabilizing Glenohumeral Joint, Scapular Shift, Upper Limb Control**
- **Raising Arm, External Rotation, Upper Limb Forward Acceleration, Internal Rotation**

**Figure 2.2** - Schematic representation of the functions of the primary upper limb muscles throughout each phase of the volleyball attack swing. Low-level general activity, fine tuning, stabilization of the glenohumeral joint, shifting of the scapula, control of the upper limb, raising of the arm, external or internal rotation of the humerus, and forward acceleration of the upper limb are represented using three different bars.
2.4 Overhead Sport-Associated Shoulder Pathologies

2.4.1 – GENERAL

A major source of debate and confusion regarding shoulder injuries caused by the overhead throwing motion is the ability of some athletes to repeat frequent, high-velocity, and extremely forceful overhead motions without pain or injury while others cannot. Many researchers believe that the repetitive requirements of overhead sports lead to chronic adaptive changes in the anatomy of the dominant shoulder girdle. In fact, it has been shown that the repetitive and forceful requirements of overhead sports such as football, tennis, baseball, and javelin, can lead to injury by weakening the shoulder joint and its surrounding musculature (Hutchinson et al., 1995). In turn, these structural adaptations can include, among others, glenohumeral internal rotation deficit (GIRD), increased external rotation, differential bulk and strength of rotator cuff musculature, superior labral changes, and articular-sided rotator cuff pathologies (Meister, 2000a; Meister, 2000b; Altchek & Hatch; 2001; Meister & Seroyer, 2003, Cools et al., 2005).

The exact causes of the injuries commonly encountered in overhead sports have yet to be determined, although some attempts have been made to clarify possible mechanisms. For instance, a tight posterior capsule may cause anterosuperior translation of the humeral head when the shoulder is elevated and moved anteriorly (Baltaci & Tunay, 2004). These aberrant, and most often forceful movements, may contribute to shoulder impingement. On the other hand, injuries to the throwing shoulder could be caused by macroscale breakdowns in swing timing or arm position during the overhead throwing motion, inherent tissue weakness present in the shoulder girdle tissues, or degenerative consequences to overuse and adaptation (Christoforetti & Carroll, 2005).
However, it is not known which of these, if any, are more important to the injury mechanisms found in overhead athletes.

A better understanding of anatomical changes and adaptations of the shoulder girdle to repetitive and forceful overhead throwing motions is crucial. However, the complexity of this joint makes the study of injury pathologies extremely difficult. It is important to realize that overhead athletes require diagnosis as overhead athletes, not as common orthopedic patients. Failure to do so can lead to gross misdiagnoses of the affected populations (Christoforetti & Carroll, 2005).

2.4.2 – INJURIES TO THE ROTATOR CUFF

Injuries to the rotator cuff are often diagnosed using external-to-internal rotation strength measures (Christoforetti & Carroll, 2005). These types of tests can reveal the imbalances frequently encountered when certain types of pathologies begin to develop. Rotator cuff injuries can take several forms including, isolated undersurface partial-thickness cuff tears, undersurface partial tears with labral injury, undersurface partial tears with capsular injury, isolated bursal-side injury, and partial-thickness bursal tears with subacromial impingement (Altchek & Hatch, 2001). The latter of these is a major cause of infraspinatus muscle wasting which has affected a growing number of overhead athletes over the past decade. Although originally found in volleyball players, the wasting of the infraspinatus has also been located in a number of non-volleyball overhead athletes (such as tennis) (Christoforetti & Carroll, 2005).

Although there appears to be many mechanisms causing rotator cuff injuries, two processes through which these injuries happen have been widely accepted (Altchek & Hatch, 2001). First, tensile overload of the rotator cuff musculature could account for the
common undersurface partial-thickness tears. These tears are thought to occur during the deceleration phase of the overhead throwing motion due to the eccentric demands on the rotator cuff muscles. Second, internal impingement or abnormal contact between the rotator musculature and the underlying surfaces could account for the tears. This destructive contact occurs most commonly during the late cocking and acceleration phases of the overhead throwing motion. Regardless of which mechanism is more crucial to the rotator cuff injuries often encountered by overhead athletes, one thing that is known is that the forceful movements encountered near the end range of motion are extremely detrimental to the shoulder joint. The end range of motion is where the tensile overload and the abnormal contact between the musculature and the underlying surfaces are encountered.

2.4.3 – INJURIES TO THE SCAPULOTHORACIC JOINT AND MUSCULATURE

The scapulothoracic joint is a complex system of articulations and muscle crossings that is crucial to the proper functioning of the upper limb. However, overhead sports alter the performance of this joint (Speer & Garrett, 1994; Fleisig et al., 1996; Kibler, 1998; Meister, 2000a; Burkhart et al., 2003). Imbalance in the scapular musculature can results in the dysfunction of the tandem pairs that work synergistically to allow proper scapulothoracic rhythm (Speer & Garrett, 1994), which results in injury due to direct trauma and repetitive microtrauma of the musculature. Tightness in the posterior capsule and musculature can lead to increased protraction of the scapula during the cocking and follow-through phases that can, in turn, lead to loss of glenohumeral range of motion (Kibler, 1998). Increased protraction of the scapula results in amplified posterior
and inferior movement, and decreased subacromial arch space which can lead to increased impingement and decreased clearance for the rotator cuff (Fleisig et al., 1996).

Changes in optimal scapulothoracic joint function can result in significant disability in athletic situations. For instance, a decrease in the ability of an athlete to elevate the acromion during the cocking and follow-through phases can result in impingement problems, which can occur with inhibition or fatigue of the lower trapezius and serratus anterior muscles through a decrease in clearance through the coracoacromial arch (Kibler, 1998). Also, scapular dysfunction leads to a decrease in efficiency of the transfer of energy between the throwing arm and the torso (Meister, 2000a). In fact, as previously mentioned, a 20% decrease in the amount of energy transfer between the trunk and the glenohumeral joint, requires a 34% increase in rotational velocity at the shoulder to maintain ball release velocity (Kibler, 1998). In essence, a decrease in the performance of the scapulothoracic joint can lead to one of two things: modified biomechanics (in an attempt to make up for this deficiency) that puts more stress on other parts of the anatomy; or a decrease in end result performance with no change in biomechanics.

The serratus anterior and the lower trapezius have been found to be the most susceptible to these two types of dysfunction and trauma. They can, therefore, be used to determine pathology early in an overhead athlete’s career (Glousman et al., 1988). Other attempts have been made to identify pathologies before they become a problem. For instance, scapular inferior medial border prominence, coracoid pain and malposition, and dyskinesis of movement have been correlated with the presence of intraarticular labral pathologies (Burkhart et al., 2003).
2.4.4 – INTERNAL IMPINGEMENT OF THE SHOULDER COMPLEX

There are a number of different mechanisms that can promote shoulder joint impingement, including instability of the glenohumeral joint, fatigue of the shoulder musculature, and elongation of the soft tissues of the shoulder joint. A number of mechanisms where instability is related to shoulder injury have been proposed:

1. Abnormal translation of the humeral head may allow impingement of the rotator cuff or interval between the greater tuberosity and the coracoacromial arch to occur (Christoforetti & Carroll, 2005).

2. Abnormal translation of the humeral head may allow an internal impingement of the articular side of the rotator cuff or interval between the humeral head and glenoid or coracoid to occur (Christoforetti & Carroll, 2005).

3. Instability caused by fatigue within the shoulder girdle may allow the humeral head to shift to a position of excessive horizontal abduction outside of the scapular plane during the overhead throwing motion, allowing the deleterious contact between the rotator cuff and the labrum to occur. This can lead to acute injury (Jobe et al., 1989).

4. Elongation or stretching of the anterior capsule due to forceful movements at extremes of range of motion, as seen in overhead sports, can cause anterior instability which can allow abnormal movement of the humerus. This abnormal movement can lead to chronic injury (Jobe et al., 1989).

Researchers are unsure of which, if any, of these mechanisms are of primary concern to overhead athletes. What is known is that laxity of the inferior part of the glenohumeral joint is common in overhead athletes. In fact, 61% of baseball pitchers and 47% of
position baseball players show this type of laxity on their dominant side, making impingement a danger for many overhead athletes (Bigliani et al., 1997).

The most common type of shoulder impingement encountered in overhead sports is posterior impingement (Altchek & Hatch, 2001). Posterior impingement happens in the late cocking and early acceleration phases of the overhead throwing motion, when the infraspinatus (posterior cuff) is forced up against the posterior edge of the labrum causing a tear in the undersurface rotator cuff or a labrum (Altchek & Hatch, 2001). Less commonly, the anterior part of the rotator cuff is forced against the superior labrum, which can also tear the undersurface rotator cuff or a labrum (Altchek & Hatch, 2001). Interestingly, a new method of diagnosing rotator cuff tears and posterior labral pathology has been proposed. This method, called the internal impingement maneuver, uses pain as an indicator of identifying articular pathology that is 95% sensitive and 100% specific for overhead athletes (Meister et al., 2004). This will hopefully allow more accurate diagnosis and treatment of shoulder impingement.

2.4.5 – ANATOMICAL MANIFESTATIONS OF OVERHEAD ACTIVITY

A number of detrimental anatomical and performance-related effects have been found in high-level overhead athletes. The extreme demands on the shoulder during many overhead sports coupled with the general repetitive requirements of them often create a hazardous situation. A number of studies have identified common manifestations such as hypertrophy of the dominant arm in the anterior and posterior chest wall muscles, wasting of certain muscles such as the infraspinatus (often caused by nerve impingement), lateralized scapula, depressed playing shoulder, excessive laxity and instability of the shoulder, and scapular winging (Meister, 2000a; Meister, 2000b; Meister
& Seroyer, 2003; Burkhart et al., 2003; Krishnan, 2004). Although common, no one athlete is necessarily susceptible to all or any of these pathologies. As previously stated it is unknown why some athletes tend to encounter many of these pathologies, while others seem immune to them altogether.

2.5 Volleyball-Associated Shoulder Pathologies

2.5.1 – GENERAL

A volleyball player’s shoulder appears to be the most commonly injured body part (incidence rate of over 30% of elite-level players), rivaled only by the rate of knee injury (Augustsson et al., 2006; Lo et al., 1990; Verhagen et al., 2004). The most common pathological findings concerning elite-level volleyball athletes are suggestive of instability, impingement, and biceps involvement (Jacobson & Benson, 2001). These injuries are often encountered in a pattern of comorbidity, meaning certain injuries may be linked to a number of different shoulder injuries (Jacobson & Benson, 2001). Positionally, both blocking and spiking may cause the vast majority of the injuries encountered in volleyball (Aagaard & Jorgensen, 1996; Aagaard et al., 1997; Augustsson et al., 2006; Byra & McCabe, 1981; Verhagen et al., 2004). However, with respect to shoulder pain, the direct cause is either unknown or resulting from spiking without a proper warm-up (Kugler et al., 1996). A gradual onset appears to be the primary route for most shoulder pathologies seen in volleyball players. Although there is a large range of possible shoulder injuries, shoulder muscular imbalance, weakness and scapular asymmetry, in particular, have been linked to shoulder injury (Wang & Cochrane, 2001). Because of this, researchers have primarily focused on these injuries when dealing with volleyball attackers.
2.5.2 – INCIDENCE OF OVERUSE INJURIES

Because volleyball-related shoulder injuries are often overuse in nature, their causes can be difficult to identify. The incidence of overuse injuries is approximately 0.6 per 1000 hours of playing, with a mean loss of time from the sport of about 4 weeks (Verhagen et al., 2004). This makes long-term studies investigating the causes of overuse injuries important. However, because most injury studies are prospective, a major problem is encountered in that the full gamut of overuse injuries may not be identified due to the ability of athletes to play with them over a long period of time. Prospective studies often rely on the athletes, coaches or training staff to fill out injury reports. If a player has been playing with a painful shoulder for a period of time, the researchers may never find out about the ailment. For this reason, retrospective studies, which do not rely on medical examinations, may provide a more accurate representation of shoulder pathologies in volleyball.

2.5.3 – PHYSICAL SHOULDER MEASUREMENTS

Passive shoulder internal and external rotation range of motion has been examined in volleyball players. No differences in passive external rotation range of motion appear to exist between the dominant and non-dominant sides, however, the dominant side displays a lower passive internal rotation range (Baltaci & Tunay, 2004; Forthomme et al., 2005; Wang et al., 2000; Wang & Cochrane, 2001). Only one study has reported a significant increase in external rotation range of motion in the dominant arm of volleyball players (Briner & Kacmar, 1997). The large demands placed on the attacker’s shoulder appear to decrease the amount of effective internal rotation range of motion while not affecting the external rotation. Both basketball and handball players exhibit similar
values to those of volleyball players for internal and external rotation range of motion while baseball players display smaller internal and higher external rotation ranges (Baltaci & Tunay, 2004). Other shoulder range of motion parameters such as the horizontal and vertical adduction/abduction ranges have not been shown to change significantly in association with overhead sports.

The most common kinetic variable associated with volleyball attackers is the difference found in internal and external rotation strength between the dominant and non-dominant shoulders of volleyball attackers or between the dominant shoulders of attackers and non-athletes. During shoulder rotation at slow speeds (60 degrees/sec), elite volleyball players produced higher concentric internal rotation and eccentric external rotation strength on their dominant side compared to their non-dominant side. This relationship was not seen at higher speeds (120 degrees/sec) (Wang et al., 2000). However, internal rotation strength has been reported to be higher on the dominant side at both slow and fast speeds (Wang & Cochrane, 2001). Conversely, at both slow and fast speeds the concentric external rotation strength in the dominant shoulder is lower than in the non-dominant arm, while the internal rotators are both concentrically and eccentrically stronger in the dominant arm than the non-dominant arm (Wang et al., 2000). In concentric contraction, the ratio of external to internal strength is smaller on the dominant side than the non-dominant side, although in eccentric contraction, no difference exists. These results agree with studies concerning athletes involved in other overhead sports (Baltaci & Tunay, 2004; Manske et al., 2004; Yildiz et al., 2006).
2.5.4 – SHOULDER PAIN

Fifteen to twenty percent of all volleyball players participating at the elite level have experienced some sort of rotator cuff pain (Ferretti et al., 1998; Linder & Ferretti, 1996). While most studies focus on the pathologies that cause shoulder pain, only one study has analyzed its possible mechanisms. Jacobson & Benson (2001) found that players who experience occasional shoulder pain while hitting straight ahead could hit across their bodies without pain. The internal rotation of the glenohumeral joint and the pronation of the forearm during straight ahead hits were thought to be the cause of this pain. Internal rotation of the glenohumeral joint forces the greater tubercle of the humerus under the coracoacromial arch which can cause impingement pain as the arm is elevated up to 150 degrees when spiking (Coleman et al., 1993; Jacobson & Benson, 2001). It was proposed that hitting a ball across one’s body does not require such marked internal rotation of the glenohumeral joint decreasing the chance of subacromial impingement (Jacobson & Benson, 2001). Furthermore, as the arm is adducted horizontally across the body during a cross body swing, the glenohumeral joint may be better supported in the anterior part of the glenohumeral joint. This is thought to decrease anterior translation of the humeral head as the arm is decelerated. No other studies have looked at the possible kinematic and kinetic effects of the two types of swings (straight ahead and across the body).

2.5.5 – SHOULDER IMPINGEMENT

Little has been written on the possible impingement mechanisms for the sport of volleyball. Most studies refer to the motions seen in other overhead sports, such as baseball, to explain how the shoulder musculature can become impinged. Many
researchers have deemed secondary impingement (a decrease in the ability to maintain a neutral humeral head position in the glenoid fossa during arm movements) a possible result of both posterior tightness and anterior laxity (Kamkar et al., 1993; Meister & Andrews, 1993; Ticker et al., 1993). Although typically a tight posterior glenohumeral capsule can result in superior and/or anterior laxity of the joint and result in impingement of structures under the coracoacromial arch during adduction of the humerus, no correlation between posterior tightness and a positive impingement sign has been found in volleyball players (Jacobson & Benson, 2001). Despite the importance of these findings for the clinical aspect of shoulder pathologies in the sport of volleyball, little information exists on shoulder impingement in volleyball players. More information in this aspect could be greatly beneficial to the safety and health of these athletes.

2.5.6 – INJURY TO THE SUPRASCAPULAR NERVE

Injury mechanisms to the suprascapular nerve have been researched more for volleyball than for any other sport. This is because isolated atrophy of the infraspinatus muscle (a major symptom of suprascapular nerve injury) is found almost exclusively in volleyball players (Baltaci & Tunay, 2004; Ferretti et al., 1998). It has been estimated that up to 20% of elite level volleyball players experience painless wasting of the infraspinatus due to injury to the suprascapular nerve at the spinoglenoid notch (Ferretti et al., 1987), yet despite this, the majority of research in this area has been conducted as case studies (Ferretti et al., 1998; Tengan et al., 1993). Only surgery and time off have been shown to affect the outcome of this injury, and rarely does the wasted infraspinatus return to pre-injury form (Ferretti et al., 1998; Tengan et al., 1993).
The mechanism of this injury has been well documented. The suprascapular nerve is thought to be compressed during the extremes of elevation and external rotation (late cocking), between the rigid tendinous medial margin of the rotator cuff and the lateral border of the spine of the scapula (spinoglenoid notch); as the former is impinged against the latter mostly due to the action of the supraspinatus muscle (Sandow & Ilic, 1998). Hypertrophy of the subscapularis muscle might also obstruct this area and lead to compression on the suprascapular nerve (Bayramoglu et al., 2003). Because the subscapularis muscle is not affected by this type of nerve compression, it continues to damage the nerve, further wasting the infraspinatus. Ongoing nerve compression can cause almost a complete loss of external rotation strength and an inconsistent pain in anterior part of the shoulder (Ferretti et al., 1998). Although other possible sites for this type of impingement exist (including the suprascapular notch), these are thought to be of less significance in the sport of volleyball (Coelho, 1994; Ferretti et al., 1998).

The serving and spiking motions used in volleyball are the likely causes of impingement of the suprascapular nerve (Coelho, 1994). While this makes sense, some researchers blame only the float serve, which requires a sharp stop of the hitting arm at ball contact necessitating increased activity in the shoulder-stabilizing musculature (Ferretti et al., 1998). The sharp stopping movement requires a maximal contraction by the infraspinatus which stretches the suprascapular nerve across the lateral edge of the spine of the scapula (Ferretti et al., 1998). However, at elite levels of volleyball float serves are used infrequently, instead the more aggressive “jump serves” are used. It is unlikely that the float serve is the primary source of this type of injury.
2.5.7 – MUSCULAR IMBALANCES

In general, functional weakness of the external rotators, mobility impairment of the internal rotators, and muscular imbalances have been found in the dominant arm of volleyball players. It has been suggested that to maintain glenohumeral stability and to avoid rotator cuff injury the eccentric antagonist strength should be approximately double the concentric agonist strength (Yildiz et al., 2006). Unfortunately, this ratio has not been found in volleyball players, which may explain the high incidences of shoulder injury seen in the sport (Altchek & Hatch, 2001; Christoforetti & Carroll, 2005; Meister, 2000b; Verhagen et al., 2004).

What has been found is a negative correlation between the external/internal rotation strength ratio and the resulting ball speed of a given player (Forthomme et al., 2005). Because the players with the highest ball speeds were found to possess the lowest external/internal rotation strength ratios, there appears to be a trade-off between shoulder injury prevention and the ability of an attacker to score. That is, a high shoulder external/internal rotation isokinetic strength ratio may decrease injury incidence but this high ratio also decreases the attacker’s ability to attain high ball speed. Interestingly, the measured peak torque during internal rotation in all concentric conditions was found to have a good relationship with ball velocity (Forthomme et al., 2005).

2.5.8 – SHOULDER AND SCAPULAR ANATOMICAL DYSFUNCTION

As seen in other sports that require the repetitive use of a forceful overhead throwing motion, certain differences in the shoulder anatomy on the dominant side of volleyball athletes has also been found. For instance, competitive volleyball players have
depressed shoulders and lateralized scapulas on their dominant shoulder as compared to non-athletes, regardless of shoulder pain (Kugler et al., 1996).

With respect to shoulder pain, players exhibiting shoulder soreness demonstrate an increased distance between the epicondyle of the dominant arm and the acromion of the non-dominant arm, in maximal horizontal adduction (Kugler et al., 1996). This is attributed to a shortened dorsal capsule of the playing shoulder. This physical difference is only slightly evident in competitive volleyball players without shoulder pain. Similarly, an increased distance from the tip of the middle finger to the fifth lumbar vertebrae on maximum internal rotation of the shoulder up the back was seen in players with painful playing shoulders (Kugler et al., 1996). This is possibly due to a diminished ability to stretch the dorsal muscles.

Although seemingly harmless, these differences have detrimental effects. For instance, an asymmetry between the two scapulas surpassing 1 cm increases the potential for shoulder injury (Kibler, 1998). In addition, scapular dyskinesis, caused by the imbalance and/or weakness of the scapular musculature, may cause improper rotation of the acromion, causing impingement (Wang & Cochrane, 2001). In essence, the very function of the shoulder appears to be compromised when such changes occur. This highlights the necessity for understanding how resistance training and other forms of preventative and rehabilitative exercises can benefit volleyball players.

2.5.9 – LOWER LIMB AND CORE STRENGTH AND SHOULDER PAIN

The lack of proper conditioning in the throwing athlete’s legs and trunk may be a catalyst for shoulder pathology (Burkhart, Morgan, & Kibler, 2003). Because the legs and trunk are responsible for a large amount of the rotational force and kinetic energy
impacted to a ball during the overhand throwing motion (Watkins et al., 1989; Young et al., 1996) imbalances in these muscles ‘break the kinetic chain’ and require an increased reliance on the shoulder musculature. These imbalances increase posterior compression of the soft structures of the shoulder by placing the arm in an overly abducted and externally rotated position (Burkhart et al., 2003). Although this has not been tested in the volleyball attack swing, it may be possible that a similar cause-and-effect relationship exists between lower limb and core strength and shoulder pathology (Reeser, Verhagen, Briner, Askeland, & Bahr, 2006). Studies testing the effect of lower body imbalances on the shoulders of volleyball attackers would be greatly beneficial to the sport.

2.6 Conclusion

Although a limited number of studies have been conducted concerning the volleyball athlete’s shoulder, a wide range of topics have been explored. However, one of the most limiting features of these studies is that they exclusively examine balls that are struck in ideal situations, which has been questioned with regards to realism. Other important factors have been identified, however.

The cocking phase appears to be the most dangerous of the five phases due to the extremely externally rotated and abducted humeral position. Although some of the major motions of the shoulder are understood, no detailed descriptions of scapular motions and scapular mechanics exist, which is surprising considering the scapula’s importance to the spiking motion. The variability of the spiking motion may suggest that the mechanics of the swing are not as important as in other overhead sports; however, elite attackers have smoother kinetic profiles than novice attackers suggesting that the elite attackers are
recruiting muscles more efficiently. Very few studies have estimated shoulder kinetics indicating a need for such research.

Injuries to the shoulder result in the longest loss of time among elite volleyball players. Many studies have attempted to recognize and document these injuries; however, because they were done prospectively, results do not appear to be indicative of actual injury rates. For this reason, retrospective studies are suggested for injury research in this sport. A common ailment affecting volleyball players is suprascapular nerve impingement. Although not fully understood, the etiology of this injury is thought to be compression of the suprascapular nerve during late cocking in the spinoglenoid notch. Little is known about the majority of other pathologies affecting volleyball athletes.
References


CHAPTER 3 - STUDY #1

An epidemiological analysis of the different arm swing types used in elite levels of men’s volleyball

Introduction

A number of studies have examined the kinematics of the volleyball spike (Oka et al., 1975; Maxwell, 1981; Chung, 1989; Rinderu, 1998; Rokito et al., 1998; Chung et al., 1990; Coleman et al., 1993; Christopher, 2001; Marquez et al., 2005). However, in all of these studies the spike has been described as occurring roughly within the sagittal plane: the arm swing is such that the ball is contacted directly in front of and above the hitting shoulder. Since the straight ahead hitting motion is similar to the motions studied in other overhead sports such as baseball, football, and javelin it has been the focus of most volleyball-related research and allows comparison with these other sports.

Studies describing baseball shoulder mechanics and injuries, for example, often use pitchers as subjects because of the intensity with which they throw and the increased incidence of shoulder injury in pitchers compared to other positions (Borsa et al., 2005; Fleisig, Andrews, Dillman, & Escamilla, 1995; Fleisig et al., 2006; Krishnan et al., 2004; Meister, 2000a; Meister, 2000b; Stodden et al., 2005). Biomechanical studies of throwing in sports such as football (Kelly et al., 2002; Krishnan et al., 2004; Lapp, 1991; Meister, 2000a) and javelin (Illyes & Kiss, 2005; Krishnan et al., 2004) often compare their results to those from baseball due to the similarities in the throwing motions. As noted above, studies concerning the sport of volleyball have taken a similar approach and have historically concentrated solely on the straight ahead swing because of its similarity to other overhead motions.
Although the only kinematic data that has been reported concerns attack swings that direct the ball straight ahead, it is probable that other types of swings are used so the attacker can direct the ball and avoid the opposing team’s block or defense, and thus, increase their chances of scoring. At one extreme, this range could require the dominant arm of an attacker to be swung so that it crosses the midline of the body to direct the ball across the torso. At the other extreme, this motion could require the dominant arm to be horizontally abducted to direct the ball to the laterally, away from the midline of the body. Knowledge about these types of arm swings could influence training, improve injury prevention and help design better rehabilitation regimens.

Movements, especially forceful ones, at extreme ranges of motion are more deleterious to the soft tissue structures (muscles, tendons, and ligaments) than forceful movements done in neutral shoulder positions (Krishnan et al., 2004). It is possible that different swing types are not only used by volleyball athletes to help increase their chances of scoring, but to also decrease the incidence of shoulder pain. In fact, attackers who experience shoulder pain while spiking straight ahead are able to hit across their bodies without pain (Jacobson & Benson, 2001). This decrease in pain when hitting across one’s body may be due to a decrease in the degree of internal rotation. Excessive internal rotation may force the greater tubercle of the humerus under the coracoacromial arch that can cause impingement pain as the arm is elevated (Coleman et al., 1993; Jacobson & Benson, 2001).

Because attackers need to avoid the opposing team’s defence, the variability in the arm motions seen during volleyball spike attack sequences are an essential skill of a successful attacker. As a result, it is probable that elite level volleyball attackers use arm swings other than the straight ahead swing, the one most commonly reported on in
literature. Other arm swings are used to direct the ball either across the athlete’s body or away from their midline. These motions are not common in other overhead sports.

Examples of arm motion variability among volleyball players have already been reported for the wind up phase of the attack swing. During the windup, differences exist among players in how the arm is brought back prior to the cocking phase (Coleman et al., 1993; Maxwell, 1981; Oka et al., 1975). Although these differences exist, the majority of elite level volleyball players use a similar style wind-up technique known as the elevation-style, where the arm is brought back above the horizontal of the shoulder (Coleman et al., 1993; Maxwell, 1981; Oka et al., 1975). It is possible that differences occur within the swing throughout other phases as well, which could allow the ball to be contacted at various, predetermined locations within the attacker’s reach. These variations could effectively increase the offensive ‘choices’ an attacker has, which in turn could increase their probability of scoring.

The purpose of this study is to identify and quantify the frequency with which a number of different attack spike motions are used by male athletes in an elite level volleyball tournament. Four different swing types have been identified by the researchers for this purpose:

1. The cross-body (CB) swing, where the arm is horizontally abducted during the acceleration phase so that the ball is contacted medially and anteriorly to the hitting shoulder directing the ball to the side opposite the striking arm.

2. The straight ahead (SA) swing, where the ball is contacted superiorly and slightly anteriorly of the hitting shoulder directing the ball ahead of the athlete. This is the attack swing exclusively studied to date.
3. The outside swing without a net present (OS), where the ball is contacted laterally and anteriorly to the hitting shoulder, while the attacker does not need to avoid the net (i.e. when a right handed hitter attacks from the left side of the net, and when a left handed hitter attacks from the right side of the net). This swing directs the ball to the same side as the striking arm.

4. The outside swing with a net present (OSN), where the ball is contacted laterally and anteriorly to the hitting shoulder, while the attacker needs to avoid the net (i.e. when a right handed hitter attacks from the right side of the net, and when a left handed hitter attacks from the left side of the net). This swing also directs the ball to the same side as the striking arm but requires some additional adjustments to avoid contacting the net with the arm.

Methods

Previously recorded games from the 2006 Canadian Interuniversity of Sport (CIS) men’s volleyball national championship tournament were selected for analysis. All games were recorded by the Queen’s University men’s varsity volleyball team with a standard digital video camera (miniVD). A total of eight teams were analyzed with a minimum of seven athletes per team and a maximum of 13.

Taped matches were only deemed usable if the camera placement was behind one end of the court, between the side-lines, and perpendicular to the net and if the set (game) was complete. If part of a set was missed due to tape length or human error, that set was deemed unusable. Complete sets were essential for an unbiased record of shot-
types throughout each set. A total of 19 sets from six matches met these criteria and were used for analysis.

It was decided that only hits coming from the antennas (positions #2 and #4) would be used (Figure 3.1). This was done for two reasons. First, this decision allowed the protocol to be simplified in that most sets to either position #2 and #4 are similar in trajectory and speed, while the trajectories of sets to position #3 are often low and fast. Second, those playing in the middle (position #3) are often taught different arm swings than outside (antenna) players and the low level of video resolution made it difficult to accurately analyze position #3 swings. Back court attacks were also not considered.
The four swing types previously mentioned (CB, SA, OS, and OSN) were the focus of this study. However, due to the limited resolution of the camera, these swing-types could not be classified according to their kinematic subtleties during every hit attempt. Therefore, a swing-type protocol was developed to simplify the identification of these swings. The protocol used the approach of the athlete before the hit and the resulting ball direction after the hit to determine which of the four swing-types was used, taking into account the handedness of the athlete and the court position from which the attack came.
For each attack coming from position #2 or #4, three pieces of information were recorded. First, the type of approach was defined. Three approaches were possible:

1. Normal (N) – athlete approached at an angle from outside the court into his attack position located inside the court (between approximately 45 and 90 degrees to the net).

2. Inside-Out (IO) – athlete approached at an angle that took him away from the middle of the court, which regularly meant from inside the court towards the outside.

3. Outside-In (OI) – athlete approached at an angle that took him toward the middle of the court at an acute angle to the net (less than 45 degrees).

Although both the N and OI approaches assume a similar attack approach, the angle used during an OI is more acute to the net.

Second, the direction of the struck ball was recorded. This was done in terms of court location and allowed for three different directions: down the line, cross-court, and sharp cross-court. Because only balls hit from positions #2 and #4 were used, a similar protocol was used for both. For position #2:

1. Balls hit to positions #4 and #5 were considered down the line.

2. Balls hit to positions #1 and #6 were considered cross-court.

3. Balls hit to position #2 were considered sharp cross-court.

And for position #4:

1. Balls hit to positions #1 and #2 were considered down the line.

2. Balls hit to positions #5 and #6 were considered cross-court.

3. Balls hit to position #4 were considered sharp cross-court.
Finally, the handedness of the attacking player was recorded; either left or right.

A table was then used to identify which swing-type of SA, CB, OS, and OSN was used for each hit (Table 3.1).

Table 3.1 - Table used to determine correct swing-type for each attack sequence. Handedness of athlete and location of hit (positions #2 or #4) used to locate correct box, and approach and ball direction used to determine swing-type. Hit direction is shown in left hand column of each box according to position. R4 – right-handed hitter attacking from position #4, R2 – right-handed hitter attacking from position #2, L4 – left-handed hitter attacking from position #4, L2 – left-handed hitter attacking from position #2, N – normal approach, IO – inside-out approach, OI – outside-in approach, CB – cross body swing, SA – straight ahead swing, OS – outside swing with no net, and OSN – outside swing with net.

<table>
<thead>
<tr>
<th>R4</th>
<th>N</th>
<th>IO</th>
<th>OI</th>
<th>L4</th>
<th>N</th>
<th>IO</th>
<th>OI</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 – 1, 2</td>
<td>CB</td>
<td>SA</td>
<td>CB</td>
<td>4 – 1, 2</td>
<td>OSN</td>
<td>SA</td>
<td>OSN</td>
</tr>
<tr>
<td>4 – 5, 6</td>
<td>SA</td>
<td>OS</td>
<td>CB</td>
<td>4 – 5, 6</td>
<td>SA</td>
<td>CB</td>
<td>OSN</td>
</tr>
<tr>
<td>4 – 4</td>
<td>OS</td>
<td>OS</td>
<td>SA</td>
<td>4 – 4</td>
<td>CB</td>
<td>CB</td>
<td>SA</td>
</tr>
<tr>
<td>R2</td>
<td>N</td>
<td>IO</td>
<td>OI</td>
<td>L2</td>
<td>N</td>
<td>IO</td>
<td>OI</td>
</tr>
<tr>
<td>2 – 4, 5</td>
<td>OSN</td>
<td>SA</td>
<td>OSN</td>
<td>2 – 4, 5</td>
<td>CB</td>
<td>SA</td>
<td>CB</td>
</tr>
<tr>
<td>2 – 1, 6</td>
<td>SA</td>
<td>CB</td>
<td>OSN</td>
<td>2 – 1, 6</td>
<td>SA</td>
<td>OS</td>
<td>CB</td>
</tr>
<tr>
<td>2 – 2</td>
<td>CB</td>
<td>CB</td>
<td>SA</td>
<td>2 – 2</td>
<td>OS</td>
<td>OS</td>
<td>SA</td>
</tr>
</tbody>
</table>
Because the direction of the struck ball needed to be recorded for the protocol used, any ball that was touched by the block or hit the net in such a way that it changed its trajectory so that the original trajectory could not be tracked was not used. Also, attack swings that did not appear to be near maximal effort, such as a tip or a roll, as deemed by the researchers, were not used. This was done with the idea that these arm swings may have different mechanics than those being studied.

Once all videos were analyzed, the mean number of hits of each hit type was calculated by game and a Chi-Square test for goodness of fit was used to determine if there were any differences in the frequencies of the four hit types over the sets analyzed. Additionally, the means of the OS and OSN swing types were combined and compared to the CB and SA swings due to the expected kinematic similarities between the two outside swings. Pairwise Mann-Whitney U tests were then conducted to determine statistical differences between the means of each swing type including the summed OS and OSN means (OS+OSN). Alpha levels were adjusted to a conservative level based on the number of pairwise comparisons by multiplying attained alpha levels by the number of pairwise Mann-Whitney U tests conducted.

**Results**

The mean frequencies of hits per set during the 2006 Men’s CIS National Volleyball Championships were calculated for each of the four swing types identified (Table 3.2). The straight ahead swing was used more often by the attackers than any other swing per set. The cross body swing occurred significantly more than both of the outside swings but with a similar frequency to the combined outside swings (OS+OSN).
Furthermore, no significant difference was found between the frequencies of the outside swings, OS and OSN.

Table 3.2 - Means (standard deviations) of frequency of hit types per set during the 2006 Men's Canadian Interuniversity of Sport National Championships. SA – straight ahead swing, CB – cross-body swing, OS + OSN – combined outside swing without net and outside swing with net, OS – outside swing without net, and OSN – outside swing with net. Matching superscript letters signify a significant difference (p < 0.05) between those numbers.

<table>
<thead>
<tr>
<th></th>
<th>SA</th>
<th>CB</th>
<th>OS+OSN</th>
<th>OS</th>
<th>OSN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>7 (2.7)</td>
<td>4 (1.8)</td>
<td>3 (1.9)</td>
<td>2 (1.5)</td>
<td>1 (1.3)</td>
</tr>
</tbody>
</table>

Due to the strict criteria a swing/hit needed to meet to be considered usable (struck ball direction identified, near maximal hit, etc.) a number of hits were not used. As a result, the usable hits (n=272) accounted for only approximately 30% of the total attack attempts made (n=901).
Discussion

The purpose of this study was to identify and quantify the frequency with which a number of different attack spike motions are used by athletes at an elite level of volleyball. Although the results show that the SA swing type is the most common attack, it is clear that a number of different swing types are used (table 3.2). Likely, elite-level volleyball players use different swing types to increase their chances of scoring. For instance, if the opposing block is set up such that a SA swing would be likely blocked or dug, the attacker is capable of using either a cross-body or outside swing motion to avoid these defenses. In fact, it is possible that the four hit types defined herein do not represent four distinct mechanisms for attacking the ball, but rather, are part of a continuum of attack swings (ranging from CB to OS/OSN) that elite volleyball players can use to increase their chances of scoring.

It is interesting that when combined (OS+OSN), the frequency of outside swings is similar to the frequency of CB swings. This demonstrates that although the SA swing type is most frequently used, elite level volleyball players may hit the ball using either an outside- or cross-body-type swing with a similar frequency. It is possible then that elite players are most comfortable or confident using a SA swing (which is reflected in the frequency with which this swing is used), and that swings are used less frequently the further kinematically removed they are from this neutral SA swing type. However, it should be noted that because the protocol used did not allow the analysis of approximately 70% of the swings recorded, these frequencies may only relate to a fraction of the swings used in the sport.

It is somewhat surprising that the OS swing type was not used more frequently than the OSN swing type. It was expected that the added attention required to make
contact with a ball while not committing a net foul during the OSN swing would make this swing less desirable than the OS swing type, which requires little attention to not commit a net foul. However, this does not appear to be the case, and it is possible that very little attention is actually devoted to staying technically clean during an attack spike in volleyball.

A number of limitations exist in the protocol used in the current study. First, because it was not possible to get high quality video of the CIS championship tournament, swing-types were identified according to the protocol described, which included the location of the hit, the direction of the hit, and the handedness of the person hitting. It would have been more accurate to analyze each swing with respect to the actual arm orientation and location during ball contact. Furthermore, hits were not recorded if they were blocked, hit the net, or were interfered with in some other manner that did not allow the direction of the struck ball to be accurately identified. Therefore, while demonstrating the existence of a number of different spike attack swings, the results of this study may not be an accurate representation of the actual frequencies with which athletes use the SA, CB, OS, and OSN swings.

While the kinematics and kinetics of these attack swings are almost certainly different, it is probable that the mechanics used are similar with only small differences accounting for the altered ball contact locations and final ball trajectory. For instance, it is possible that when hitting across one’s body (CB), as opposed to directly ahead (SA), the arm is more horizontally adducted during the acceleration phase with no other biomechanical differences between the two swing types. Similarly, during a swing outside of the body (OS or OSN), a less marked increase in horizontal adduction during the acceleration phase may account for the different hitting position and ball trajectory.
However, it has been proposed that during a cross-body swing, less internal rotation is required which decreases the chances of subacromial impingement and thus pain (Jacobson & Benson, 2001). It is clear, therefore, that more research needs to be conducted on the mechanics used during the full range of swing-types that are used in the sport of volleyball.

Because most biomechanical studies of the volleyball swing to date have only considered balls that are hit directly ahead of the attacking player (Christopher, 2001; Chung, 1989; Chung et al., 1990; Coleman et al., 1993; Marquez et al., 2005; Maxwell, 1981; Oka et al., 1975; Rinderu, 1998; Rokito et al., 1998) the results identify a definite need for studies to take on a more thorough approach to analyzing the volleyball attack. Future research regarding the swings presented in this study may lead to a better and more detailed understanding of the demands placed on the upper limb in the sport of volleyball. This, in turn, could lead to better coaching, training, preventative and rehabilitative initiatives in the sport.
References


An analysis of the resulting velocities of balls struck using kinematically different volleyball attack swings

Introduction

Difficulty defending an attack in the sport of volleyball increases with increasing ball velocity (Forthomme et al., 2005b). Because of this, attackers attempt to impart maximal kinetic energy to the ball while maintaining accuracy (Abendroth-Smith & Kras, 1999). The high kinetic energies and subsequent ball velocities attained are achieved through the transfer of energy from the distal part of the upper extremity to the ball (Forthomme et al., 2005b). In fact, humeral angular velocities of approximately 870 degrees/sec have been found in top level international players and have been correlated with the resulting ball speeds (Chung et al., 1990; Coleman et al., 1993). However, a certain amount of accuracy is required and the concept of maximizing speed while maintaining accuracy is similar to that found in other overhead sports such as baseball, football, tennis and javelin (Christoforetti & Carroll, 2005; Elliott et al., 2003; Fleisig et al., 1996; Krishnan et al., 2004; Meister, 2000; Stodden et al., 2005; Stodden et al., 2005).

Ball velocity is a major predictor of a successful volleyball attack and significant differences in ball speeds have been found between various levels of elite volleyball (Forthomme et al., 2005b; Forthomme et al., 2005a). That is, at more elite levels, ball velocities reached during a spike attack are higher than at less elite levels (Forthomme et al., 2005b). Elite-level average ball speeds of almost 100 km/h (27.8 m/s) and top speeds of approximately 120 km/h (33.3 m/s) have been reported (Kugler et al., 1996). Table 4.1
demonstrates the average ball speeds for the volleyball attack spike for both males and females. With such high velocities and with approximately a 50 N·m internal rotation torque at the end of the acceleration phase, as well as an 800 N compressive force and a 115 N·m adduction torque at the start of the deceleration phase (Christopher, 2001), it is clear that a large amount of force is exerted through the shoulder musculature.

In fact, it has been estimated that although much of the peak angular humeral velocity originates within the trunk and lower limbs, approximately 19% of the velocity originates within the glenohumeral joint, which, considering the size and instability of this joint, is substantial (Chung et al., 1990; Dübotzky & Leistner, 1992). Although volleyball attack spike ball velocity data does exist, as demonstrated above, little is known about the ball speeds attained during kinematically different arm swings used in the sport, such as swings directed across the body.
Table 4.1 – Published ball speed averages and standard deviations for males and females during straight ahead volleyball spike attacks. D1 – First division Belgium league, D2 – Second division Belgium league, NCAA – National Collegiate Athletic Association, NTNU – National Taiwan Normal University. * Standard deviation unknown.

<table>
<thead>
<tr>
<th>Author</th>
<th>Sex</th>
<th>Level</th>
<th># of Subjects</th>
<th>Ball Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forthomme et al., 2005</td>
<td>Male</td>
<td>Professional - D1</td>
<td>11</td>
<td>101 ± 6.0</td>
</tr>
<tr>
<td>Forthomme et al., 2005</td>
<td>Male</td>
<td>Professional - D2</td>
<td>8</td>
<td>90 ± 8.3</td>
</tr>
<tr>
<td>Christopher, 2001</td>
<td>Male</td>
<td>NCAA</td>
<td>5</td>
<td>102 ± 27</td>
</tr>
<tr>
<td>Chenfu et al., 1999</td>
<td>Male</td>
<td>NTNU</td>
<td>8</td>
<td>99 ± 11.9</td>
</tr>
<tr>
<td>Coleman et al., 1993</td>
<td>Male</td>
<td>International</td>
<td>10</td>
<td>97 ± 3.2</td>
</tr>
<tr>
<td>Chung et al., 1990</td>
<td>Male</td>
<td>Semi-Professional</td>
<td>7</td>
<td>93 ± 4.6</td>
</tr>
<tr>
<td>Christopher, 2001</td>
<td>Female</td>
<td>NCAA</td>
<td>6</td>
<td>64 ± 13</td>
</tr>
<tr>
<td>Bowman, 2001</td>
<td>Female</td>
<td>NCAA</td>
<td>10</td>
<td>46 ± 4.7</td>
</tr>
<tr>
<td>Chung, 1988</td>
<td>Female</td>
<td>NCAA</td>
<td>Unknown</td>
<td>68*</td>
</tr>
</tbody>
</table>

Volleyball ball velocity is affected by the kinematics of the arm during the wind-up phase of the swing (Bowman, 2001). Variations have been found in the wind-up phase of the volleyball attack swing and have been grouped into two primary styles (Maxwell, 1981; Oka et al., 1975; Rokito et al., 1998). First, the elevation-style wind-up refers to a motion where the humerus is horizontally abducted above the horizontal plane of the shoulder and where the arm is raised relatively early in the sequence (Oka et al., 1975). The backswing-style wind-up, on the other hand, refers to a motion where the humerus is horizontally abducted below the horizontal plane of the shoulder, requiring the arm to be raised relatively late in the sequence (Maxwell, 1981; Oka et al., 1975). Although these differences in spiking motion have not been correlated to differences in pre-impact hand speeds, they have been correlated with differing ball speeds (Bowman,
2001). Other mechanical factors, such as ball-hand contact time and transfer of angular momentum appear to also be responsible for these differences (Bowman, 2001). Additional differences may be due to gender.

Regarding male and female volleyball players, disparities between the sexes have only partly been documented. For instance, male volleyball players have higher values for all glenohumeral kinetic variables that have been measured (Christopher, 2001; Rinderu, 1998), however, few kinematic comparisons between the sexes have been done. Differences during the attack strike are thought to be due to the inability of most females to reach the same height above the net as men (Jacobson & Benson, 2001). It is logical then that certain kinematic differences would exist between the sexes due to differences of attack height (and thus ball clearance above the net), as well as resulting ball velocities (Table 4.1). Because research findings from studies on one sex can not be applied to the other, the present work focuses solely on male athletes whose biomechanics and pathologies have been more thoroughly represented in scientific literature.

A previous study (see Chapter 3) demonstrated that at elite levels of volleyball, although straight ahead swings were used predominantly, a range of arm swings were, in fact, used by attackers possibly to help maximize their chances of scoring. The four arm swings tested were as follows:

1. The cross-body (CB) swing, where the arm is horizontally abducted during the acceleration phase so that the ball is contacted medially and anteriorly to the hitting shoulder directing the ball to the side opposite the striking arm. This directs the ball across the midline of the body.
2. The straight ahead (SA) swing, where the ball is contacted superiorly and slightly anteriorly of the hitting shoulder directing the ball ahead of the athlete. This is the attack swing exclusively studied to date.

3. The outside swing without a net present (OS), where the ball is contacted laterally and anteriorly to the hitting shoulder, while the attacker does not need to avoid the net (i.e. when a right handed hitter attacks from the left side of the net, and when a left handed hitter attacks from the right side of the net). This swing directs the ball laterally and away from the midline of the body.

4. The outside swing with a net present (OSN), where the ball is contacted laterally and anteriorly to the hitting shoulder, while the attacker needs to avoid the net (i.e. when a right handed hitter attacks from the right side of the net, and when a left handed hitter attacks from the left side of the net). This swing also directs the ball laterally and away from the midline of the body, with some possible adjustments to avoid hitting the net.

The primary goal of this study was to assess the ball speeds that elite volleyball players can attain using these four arm swings. Because of the implications of both attack efficiency (higher ball speeds have been correlated with a greater ability to score (Forthomme et al., 2005b)) and training (i.e., injury prevention and rehabilitation) knowing the velocity of the balls at the elite levels using these swings is important.

It is expected that the differing mechanics of the four swings being examined in this study will affect ball velocity. It is likely that the SA and CB swings will achieve the highest ball speeds and that the CB will produce higher ball speeds than the SA. This is because the mechanics employed during the SA and CB swings put the hitting arm in a position where it can use the large internal rotators (e.g., latissimus dorsi and pectoralis
major), adductors (e.g., latissimus dorsi) and horizontal adductors (e.g., pectoralis major). In contrast, it is expected that the OS and OSN swings will attain lower ball velocities because of the relatively weak muscle contribution available during an abducted and internally rotated arm. Furthermore, because the athlete will not have to pay as much attention to the net during an OS swing, compared to an OSN swing, it is expected that OS swings will result in higher ball velocities than the OSN swing type.

Methods

Nine subjects with an average age of 21 ± 1.6 years, height of 1.91 ± 0.071 meters, and weight of 83 ± 5.4 kilograms from the Canadian Interuniversity of Sport (CIS) Queen’s University men’s varsity volleyball team participated in this study (Table 4.2). Average years spent at the elite level were 2.8 ± 0.97 and all but one player were right handed. Subjects were not screened based on their regular playing position (i.e. middle, left side, right side, setter, and libero) and none had a previous record of shoulder surgery or shoulder pain in the six months prior to participation. This study was approved by the Queen’s University General Research Ethics Board (GREB) and all participants signed a letter of informed consent (Appendix A).
Table 4.2 - Subject information with averages and standard deviations presented. ‘Elite’ represents years of participation at the interuniversity level or above, and ‘Experience’ represents the total number of years subjects have participated in the sport at any level.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>Elite (Years)</th>
<th>Experience (Years)</th>
<th>Handedness</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>19</td>
<td>1.80</td>
<td>75</td>
<td>2</td>
<td>8</td>
<td>R</td>
</tr>
<tr>
<td>S02</td>
<td>21</td>
<td>1.82</td>
<td>84</td>
<td>4</td>
<td>8</td>
<td>R</td>
</tr>
<tr>
<td>S03</td>
<td>23</td>
<td>2.00</td>
<td>93</td>
<td>4</td>
<td>7</td>
<td>R</td>
</tr>
<tr>
<td>S04</td>
<td>22</td>
<td>1.91</td>
<td>85</td>
<td>2</td>
<td>8</td>
<td>R</td>
</tr>
<tr>
<td>S05</td>
<td>20</td>
<td>1.91</td>
<td>79</td>
<td>2</td>
<td>7</td>
<td>R</td>
</tr>
<tr>
<td>S06</td>
<td>23</td>
<td>1.89</td>
<td>82</td>
<td>4</td>
<td>10</td>
<td>L</td>
</tr>
<tr>
<td>S07</td>
<td>20</td>
<td>1.96</td>
<td>86</td>
<td>3</td>
<td>9</td>
<td>R</td>
</tr>
<tr>
<td>S08</td>
<td>20</td>
<td>1.88</td>
<td>77</td>
<td>2</td>
<td>9</td>
<td>R</td>
</tr>
<tr>
<td>S09</td>
<td>19</td>
<td>2.00</td>
<td>85</td>
<td>2</td>
<td>9</td>
<td>R</td>
</tr>
<tr>
<td>Average</td>
<td>21</td>
<td>1.91</td>
<td>83</td>
<td>2.8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>1.6</td>
<td>0.071</td>
<td>5.4</td>
<td>0.97</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

A full sized 9 meter by 18 meter volleyball court with a net height of 2.43 meters (official Fédération Internationale de Volleyball (FIVB) men’s height) was used throughout this study (Figure 4.1). Official CIS approved size and weight volleyballs were used in all hitting trials. A volleyball setting machine (VB Attack – Sports Attack LLC, Verdi, NV) ‘set’ the volleyballs eliminating the need for a setter. This removed setting variability from the trials. A standard handheld RADAR gun (Muni Quip K-GP – Tribar Industries Inc., North York, ON) measured ball speeds. The accuracy of the RADAR gun was tested and speeds were found to be very close to those calculated using high speed digital video (Appendix C). Because RADAR guns work on the basis of
Doppler shift, it was necessary to place the gun in the line of the trajectory of the struck ball. To do this, and to protect the RADAR gun and the investigators, subjects were asked to aim their attacks at one of two protective nets, behind which the investigator was stationed (Figure 4.2).

**Figure 4.1** - Standard volleyball court. Court dimensions are shown as 18m along the full length of the court, and 9m along the width. Bold line at center of court represents the net. Volleyball position numbers are shown on the right side of the court.
Subjects had a full warm-up prior to commencing the study and were given as much time as necessary between trials to ensure they did not fatigue. There were five trials for each of the CB, SA, OS, and OSN swings. All trials were randomized resulting in a total of 20 trials per subject. However, due to lack of accuracy and/or power from subjects on some swings as well as the inability of the RADAR gun to measure certain hits, the number of trials completed was closer to 40 per subject. Nevertheless, the first 20 useable trials for each subject were recorded and used for further statistical analysis.
The trials were set-up such that there was a predetermined approach that the hitter would use and a target for the hitter to aim at (one of the two protective nets) for each trial, which ‘forced’ that hitter to use a particular swing type. For each of the swings, the approach and target were as follows:

1. Cross Body (CB) – Athletes approached at an angle of approximately 45 degrees to the net and hit the ball down the line, towards the protective netting (Figure 4.3). Therefore, a right handed person hit from position 4 towards the opposing side’s position 1, while a left handed person hit from position 2 towards the opposing side’s position 5.

![Figure 4.3 - Cross body (CB) hitting setup. Approach direction is indicated by the grey arrow, and resulting ball direction is shown by the black arrow for both right (R) and left (L) handed players. The RADAR gun is depicted behind the protective netting.](image)
2. **Straight Ahead (SA)** – Athletes approached at an angle perpendicular to the net and hit the ball down the line, towards the protective netting (Figure 4.4). Therefore, a right handed person hit from position 4 towards the opposing side’s position 1, while a left handed person hit from position 2 towards the opposing side’s position 5.

![Figure 4.4 – Straight ahead (SA) hitting setup. Approach direction is indicated by the grey arrow, and resulting ball direction is shown by the black arrow for both right (R) and left (L) handed players. The RADAR gun is depicted behind the protective netting.](image-url)
3. Outside Swing Without Net (OS) – Athletes approached at an angle perpendicular to the net and hit the ball cross court, towards the protective netting (Figure 4.5). Therefore, a right handed person hit from position 4 towards the opposing side’s position 5, while a left handed person hit from position 2 towards the opposing side’s position 1.

**Figure 4.5** – Outside Swing Without Net (OS) hitting setup. Approach direction is indicated by the grey arrow, and resulting ball direction is shown by the black arrow for both right (R) and left (L) handed players. The RADAR gun is depicted behind the protective netting.
4. Outside Swing With Net (OSN) – Athlete approached at an angle approximately 45 degrees to the net and hit the ball down the line, towards the protective netting (Figure 4.6). Therefore, a right handed person hit from position 2 towards the opposing side’s position 5, while a left handed person hit from position 4 towards the opposing side’s position 1.

Figure 4.6 - Outside Swing With Net (OS) hitting setup. Approach direction is indicated by the grey arrow, and resulting ball direction is shown by the black arrow for both right (R) and left (L) handed players. The RADAR gun is depicted behind the protective netting.
For each trial, the subjects were told which swing type would be performed and were reminded of the approach to use. One of the researchers loaded the setting machine with a volleyball and, once the subject was ready, the ball was released and the subject approached and hit the ball at near maximal speed towards the target. Occasionally adjustments needed to be made to the setting machine in terms of angle of release and speed of the delivery. In these cases, balls were released and once the subjects were satisfied with the ‘set’, the trials were started again.

There were some problems when measuring the ball speed with the RADAR gun. In some cases when the ball was hit directly towards the target/RADAR gun, no speed reading was given. The trial was repeated if the target area was not hit or a ball speed was not measured. Also, after each successful trial, subjects were asked if they hit the ball using the pre-determined swing type and near their maximal capacity. If subjects felt they could hit significantly harder, the trial was repeated. Subjects were not made aware of their measured ball speeds until after all trials were completed.

Once all data was collected, it was normalized by subject to the subject’s highest recorded ball speed using the SA swing. This was done due to the predominance of SA swing data in the literature. Normalizing to the fastest SA arm swing meant that some swings might reach more than 100%. Once ball speed was normalized, average normalized subject data for each swing type was calculated and standard one-way ANOVA’s with repeated measures were used to compare the means of each swing types. To account for the number of comparisons made, a Bonferroni correction was used and a result of p < 0.05 was considered significant.
Results

The CB and SA swing types produced the highest velocities (87 \( \pm \) 6.8 km/h and 88 \( \pm \) 6.7 km/h respectively) followed by the OS (79 \( \pm \) 6.2 km/h) and OSN (74 \( \pm \) 4.3 km/h) swing types (Table 43). As shown in Table 4.3, the ball velocities produced using the CB and SA swings were not statistically different. Both of these swings did, however, produce greater ball velocities than ether of the OS and OSN swing types. Finally, the OS swing type produced significantly higher ball velocities than the OSN swing type.

Table 4.3 - Average resulting ball velocities and standard deviations produced using each of the four swing types given in km/h and m/s using all swings from each subject (n = 45). Also, average normalized velocities and standard deviations are shown, which were calculated as a percentage of the fastest recorded SA swing for each subject. CB – cross body, SA – straight ahead, OS – outside swing without net, and OSN – outside swing with net. Matching superscript letters signify statistical difference (p < 0.05) between those numbers.

<table>
<thead>
<tr>
<th></th>
<th>CB</th>
<th>SA</th>
<th>OS</th>
<th>OSN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball Velocity (km/h)</td>
<td>87 (6.8)(^{a,b})</td>
<td>88 (6.7)(^{c,d})</td>
<td>79 (6.2)(^{a,c,e})</td>
<td>74 (4.3)(^{b,d,e})</td>
</tr>
<tr>
<td>Ball Velocity (m/s)</td>
<td>24 (1.9)(^{a,b})</td>
<td>25 (1.8)(^{c,d})</td>
<td>22 (1.7)(^{a,c,e})</td>
<td>21 (1.2)(^{b,d,e})</td>
</tr>
<tr>
<td>Normalized</td>
<td>92 (5.8)(^{a,b})</td>
<td>93 (3.8)(^{c,d})</td>
<td>85 (5.8)(^{a,c,e})</td>
<td>78 (4.4)(^{b,d,e})</td>
</tr>
</tbody>
</table>
The ball speeds attained were normalized to the fastest ball velocity measured using each subject’s SA swings. This resulted in average normalized percentages that allowed direct comparison between swing types. Similar to the results attained when each subject’s ball velocities were used, the normalized data for the CB and SA swings was not different. As well, both of these swings produced greater ball velocities than both the OS and OSN swing types. Finally, the OS swing type produced higher ball velocities than the OSN swing type (Table 4.3).

Discussion

This study measured the resulting ball speeds of four kinematically different, near-maximal, volleyball attack spike arm swings (CB, SA, OS, and OSN). Compared to previous ball speed data collected from males (Table 4.1), the velocities attained during this study (Table 4.3) are slightly lower (88 ± 6.7 km/h during SA swings in this study, compared to speeds between 90 ± 8.3 km/h and 102 ± 27 km/h in others). Considering the higher level of athletes tested in all but two of the studies (Chenfu, Gin-Chang, & Tai-Yen, 1999; Christopher, 2001) this is not surprising. It is interesting, however, that the two other studies, which, like this study, analyzed university-level athletes, measured average ball speeds more than 10 km/h faster. Because more elite levels of volleyball are associated with greater ball velocities (Forthomme et al., 2005b), Canadian university volleyball players may be less skilled than university volleyball players from the United States and Taiwan. However, it should be noted that each of these studies only drew players from one team in their respective countries, and thus, the results for all three
studies are biased towards those teams. Therefore, these studies may not be accurate predictors of the average ball speeds attained at the university level in these countries.

Originally, it was thought that the CB swing would produce the highest ball velocities due to the large adduction and horizontal adduction muscles involved in the movement, such as the pectoralis major and latissimus dorsi. However, as shown in Table 4.3, the ball speeds attained when using the CB and SA attacks were not different. These similarities may have been caused by a number of different factors. For instance, the line of action of the abdominal muscles can create a large upper trunk forward rotational torque. During baseball pitching, the abdominals are very active and provide force for the forward rotation of the trunk which is then transferred to the throwing arm (Hirashima, Kadota, Sakurai, Kudo, & Ohtsuki, 2002; Watkins et al., 1989). Similarly, in volleyball, the rectus abdominis muscles have been found to be extremely active during the forward swing (late cocking and acceleration phases) of the SA volleyball spike (Oka et al., 1975). It is possible that the momentum caused by the action of the abdominal muscles during the SA swing is able to increase the hand speed and, therefore, the resulting ball velocity during the SA swing (Oka et al., 1975). However, during a CB swing such abdominal assistance is reduced as the arm is most likely horizontally adducted across the chest. A strong abdominal contraction during this swing would flex the trunk, lowering the height of the already horizontally adducted arm which would place it in a position that would make contact with the ball much more difficult.

Another possibility for the similarity in ball speeds found between the CB and SA swings is the fact that the mechanics of the SA swing enable it to take full advantage of the forward momentum of the body as it moves through the air. Again, because the CB swing forces the ball across the body, it is not likely that this swing can take advantage of
this forward momentum. Regardless of the reason, the CB and SA swings resulted in roughly the same average ball speeds, which are significantly faster than both the OS and OSN swing types.

Although the horizontally adducted arm position and the high ball velocities attained during the CB swing may seem potentially hazardous to the shoulder’s soft tissue structures, the CB swing has, in fact, been found to be associated with less pain during spiking than the SA swing (Jacobson & Benson, 2001). Decreased internal rotation of the glenohumeral joint (which can cause impingement pain), decreased pronation of the forearm, as well as more structural support anteriorly (which decreases anterior translation of the humeral head as the arm is horizontally adducted and decelerated), are thought to be the causes of this difference in pain between the CB and SA swing types (Coleman et al., 1993; Jacobson & Benson, 2001). Since ball velocities have been correlated with compressive forces of the glenohumeral joint (Christopher, 2001), it would be interesting to determine how these increased levels of compressive force would affect the soft tissues within the glenohumeral joint at the extreme range used during the CB swing. More research on the kinematics of the full range of attack spike arm swings used in the sport of volleyball needs to be done.

The lower ball speeds for the OS and OSN swings compared to the CB and SA swings are not surprising. The two outside swings necessitate extreme pronation of the arm, moderate horizontal abduction and a moderate decrease in arm elevation. Only one of the major upper limb muscles is in a position to supply a large amount of force in this position: the latissimus dorsi. The latissimus dorsi, a major adductor, internal rotator, and extender of the arm, is most likely extremely active during the OS and OSN attack swings. Conversely, many of the larger movers of the upper limb are in a position to be
active during the CB and SA swings. In fact, during the acceleration phase of the SA swing, these muscles (pectoralis major, latissimus dorsi, teres major, and subscapularis) are highly active (Oka et al., 1975; Rokito et al., 1998). Due to the arrangement of these muscles it would be difficult for any of them, aside for the aforementioned latissimus dorsi, to provide any significant amount of force for the outside swings. In the future, it would be interesting to use electromyography to identify the muscles of primary action during each one of the swings.

With respect to the two outside swings, the OS swing type produced faster ball speeds than the OSN swing type, which was expected. It is probable that this is at least partly due to the increased possibility of touching the net during an OSN swing compared to an OS swing. However, the decreased speed associated with the OSN swing may be partly due to the setup of the hitting trials (Figure 4.5 and Figure 4.6). The OS was set up such that the athletes would hit the ball in essentially the opposite direction of the set ball’s trajectory (i.e. cross court), whereas during the OSN hitting trials, the ball would be hit perpendicular to the set ball trajectory (i.e. down the line). This concept is similar to that seen in baseball where it is easier for a batter to use the high momentum of a fastball to hit a homerun compared to a ball moving slowly such as a changeup. Because of the angles of the incoming ball it is likely that the OS swing type had an advantage in producing high ball velocities.

There were a number of limitations to this study. First, it was difficult for the hitters to properly time their approach with the release of the ball from the setting machine. In game and practice situations, hitters appear to take a number of cues from the incoming pass, which is then set, to adjust the timing of their approach. Without this incoming pass, it may have been difficult for the subjects to hit at their maximal intensity.
Also, because RADAR guns work on line-of-sight Doppler shift, any balls that were not hit directly towards the RADAR gun may have resulted in a lower measured ball speed. Because the subjects were asked to hit directly at the target nets, behind which the RADAR gun was positioned, this was minimized as much as possible. However, ideally, the ball would hit the net directly in front of the RADAR gun which was not very probable due to the precision required to hit such a small target.

A couple of the swings were also not very realistic. First, the SA swing had the athletes approaching down the line and hitting the ball down the line. Higher, and more realistic, ball velocities would possibly be attained had the athlete approached at approximately a 45 degree angle to the net and hit the ball cross court. This was, unfortunately, not considered until after all of the data had been collected. Similarly when an OS swing is used in a practice or match situation the ball is usually directed at a very acute angle to the net, cross court. Although this would not change body positioning, the measured ball velocities may be higher in these situations. Due to the design of the study and the need to minimize the movement of the targets these ‘ideal’ ball trajectories were not possible.

It is clear that the different swings used by elite-level volleyball players in the sport of volleyball produce different resulting ball speeds. These speeds are greatest when using either a CB or SA swing, and lowest when using an OS-type swing. These differences in resulting ball speeds may indicate that the four swings studied herein are also kinematically different from each other.
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CHAPTER 5 – STUDY #3

A kinematic analysis of various attack spike arm motions commonly utilized in the sport of volleyball

Introduction

Research concerning the attack swing in the sport of volleyball has focused almost exclusively on the straight ahead swing (Christopher, 2001; Chung, 1989; Chung et al., 1990; Coleman et al., 1993; Marquez et al., 2005; Maxwell, 1981; Oka et al., 1975; Rinderu, 1998; Rokito et al., 1998). Because of the frequency with which elite volleyball players use forceful attack swings (up to 40,000 times per year (Dübotzky & Leistner, 1992)) a complete understanding of the full range of swings used in the sport is necessary.

Volleyball differs from other overhead sports (such as baseball) in that a similar kinematic pattern is not necessarily used during each throwing/spiking motion (Jacobson & Benson, 2001). For example, elite volleyball players have been found to demonstrate a large amount of variability during the acceleration phase of the attack swing (Coleman et al., 1993; Maxwell, 1981). It has been hypothesized that this variability allows the attacker to contact the moving ball at an optimal location (often above and slightly anterior to the hitting shoulder) each time (Maxwell, 1981).

Recently, a five-phase system has been used to describe the volleyball attack swing, similar to that describing the throwing motions seen in other overhead sports such as baseball (Rokito et al., 1998). This system includes: the wind-up, the cocking, the acceleration, the deceleration, and the follow-through phases (Figure 5.1). Although the majority of studies conducted concerning the kinematics of the volleyball spike were done before 1998 and, therefore, used a more simplified two-phase system (backswing
phase, and forward swing phase) (Chung et al., 1990; Coleman et al., 1993; Maxwell, 1981; Oka et al., 1975; Prsala, 1982) it is useful to attempt to apply their findings to the more recent five-phase system.

**Figure 5.1** - Phases of the volleyball spike. Each letter depicts the end of one phase and the start of the next. Windup: a-b, cocking: b-c, acceleration: c-d, deceleration: d-e, and follow-through: e-f.
A specific and distinct kinematic pattern is seen throughout each of the five phases, with the cocking, acceleration and deceleration phases being the most crucial. During these phases, the upper limb is at the extremes of the range of motion while being subjected to large forces of 50 N•m at the end of the acceleration phase, and more than 1500 N of glenohumeral compression as well as 115 N•m of shoulder adduction torque at the start of the deceleration phase (Christopher, 2001; Rinderu, 1998). Because of the importance of the cocking, acceleration and deceleration phases they will be the focus of this study. For a complete description of all phases for the straight ahead swing, see Chapter 2.

During the late stages of the cocking phase (Figure 5.1b-5.1c), the humerus of the hitting arm is in a position of maximal horizontal abduction and extreme external rotation while it lags behind the attacker’s trunk (Chung et al., 1990; Maxwell, 1981; Rokito et al., 1998). Although the kinematics of the upper limb are quite variable between athletes throughout the acceleration phase (Figure 5.1c-5.1d), in general, the arm motion is such that the ball can be contacted with the humerus at approximately 140 to 170 degrees of adduction in neutral (internal/external) rotation (Kugler et al., 1996), or above and slightly anterior to the hitting shoulder (Coleman et al., 1993). The deceleration phase (Figure 5.1d-5.1e) starts immediately after ball contact and ends when the arm’s forward momentum is reduced to zero. The goal of this phase is to absorb any remaining kinetic energy that has not been imparted to the ball (Coleman et al., 1993; Oka et al., 1975; Rokito et al., 1998).

Because approximately 19% of the hand velocity is generated by the shoulder joint, the demands placed on the shoulder joint are large (Chung et al., 1990; Dübotzky & Leistner, 1992). For example, top level international players are able to produce humeral
angular velocities of approximately 870 degrees/sec which has been correlated to resulting ball velocities (Coleman et al., 1993). Furthermore, elite volleyball players strive for increased humeral angular velocities which have been correlated with level of play (Coleman et al., 1993; Forthomme, Croisier, Ciccarone, Crielaard, & Cloes, 2005). Although a lot of data has been gathered concerning the mechanics of the straight ahead swing, little is known about its temporal characteristics.

The few studies that have reported the temporal aspect of the volleyball attack swing have not taken into account either the deceleration or follow-through phases. What has been found is that the swing takes 0.28 ± 0.032 seconds from the start of wind-up to the end of cocking (Chung et al., 1990). Furthermore, the swing lasts between 0.10 and 0.13 seconds from the end of cocking to the end of the acceleration phase (ball contact) (Christopher, 2001; Chung et al., 1990). The duration of the complete pre-impact arm swing (from approximately the start of wind-up to the end of acceleration) is 0.38 ± 0.051 seconds (Chung et al., 1990). No data has been collected on swings that are kinematically different than the straight ahead swing.

Despite the fact that research concerning the volleyball swing has concentrated solely on the straight ahead swing, recent research has established that, in fact, a full range of arm swings are frequently used (See Chapter 3). This study identified four separate arm swing used at the elite level:

1. The cross-body (CB) swing, where the arm is horizontally abducted during the acceleration phase so that the ball is contacted medially and anteriorly to the hitting shoulder directing the ball to the side opposite the striking arm. This directs the ball across the midline of the body.
2. The straight ahead (SA) swing, where the ball is contacted directly superiorly and slightly anteriorly of the hitting shoulder directing the ball ahead of the athlete. This is the attack swing exclusively studied to date.

3. The outside swing without a net present (OS), where the ball is contacted laterally and anteriorly to the hitting shoulder, while the attacker does not need to avoid the net (i.e. when a right handed hitter attacks from the left side of the net, and when a left handed hitter attacks from the right side of the net). This swing directs the ball laterally and away from the midline of the body.

4. The outside swing with a net present (OSN), where the ball is contacted laterally and anteriorly to the hitting shoulder, while the attacker needs to avoid the net (i.e. when a right handed hitter attacks from the right side of the net, and when a left handed hitter attacks from the left side of the net). This swing also directs the ball laterally and away from the midline of the body, with some possible adjustments to avoid hitting the net.

Additionally, another study has examined the ball speeds attained when these arm swings were used (See Chapter 4). CB and SA swings produced the fastest resulting ball speeds whereas SA and OSN produced the slowest. To date, however, no kinematic data has been gathered concerning these arms swings.

The purpose of this study is to examine the kinematics of three of the four volleyball attack arm swings previously described (CB, SA, OS). Only three swings are being examined because it was thought that the kinematic differences between the OS and OSN swing types would most likely not be sufficient enough to necessitate analysis. As this is the first study of its kind, it will be descriptive in nature. Because only SA type arm swings have been scientifically examined to date, the findings herein may shed some
light on certain aspects of training, injury prevention, and rehabilitation. For instance, knowledge about the kinematics of the CB swing may allow coaches to develop proper muscular training regimes that allow development of these muscles to appropriately prepare athletes for future competition.

**Methods**

Six subjects with an average age of 22 ± 1.5 years, height of 1.9 ± 0.08 meters, and weight of 84 ± 6 kilograms from the Canadian Interuniversity of Sport (CIS) Queen’s University men’s varsity volleyball team participated in this study (Table 5.1). Because subjects are often taught different arm swings when playing either the ‘outside’ position or the ‘middle’, all selected participants were ‘outside’ or antennae players to limit the differences between subjects. The years spent at the elite level was 3 ± 1.5 and all but two players were right handed. To determine the number of subjects needed for statistical significance in a number of kinematic measures, a power analysis was conducted (Appendix D). Subjects had no previous record of shoulder surgery and had not had shoulder pain in the six months prior to participation. This study was approved by the Queen’s University Graduate Research Ethics Board (GREB) and all participants signed a letter of informed consent (Appendix B).
Table 5.1 - Subject information with averages and standard deviations presented. ‘Elite’ represents years of participation at the interuniversity level or above, and ‘Experience’ represents the total number of years subjects have participated in the sport at any level.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>Elite (years)</th>
<th>Experience (years)</th>
<th>Handedness</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>24</td>
<td>1.85</td>
<td>90.7</td>
<td>5</td>
<td>10</td>
<td>R</td>
</tr>
<tr>
<td>S02</td>
<td>23</td>
<td>1.88</td>
<td>83.0</td>
<td>4</td>
<td>11</td>
<td>L</td>
</tr>
<tr>
<td>S03</td>
<td>21</td>
<td>1.83</td>
<td>79.4</td>
<td>1</td>
<td>4</td>
<td>L</td>
</tr>
<tr>
<td>S04</td>
<td>20</td>
<td>1.80</td>
<td>74.8</td>
<td>2</td>
<td>8</td>
<td>R</td>
</tr>
<tr>
<td>S05</td>
<td>22</td>
<td>2.01</td>
<td>86.2</td>
<td>4</td>
<td>8</td>
<td>R</td>
</tr>
<tr>
<td>S06</td>
<td>21</td>
<td>1.96</td>
<td>88.5</td>
<td>3</td>
<td>9</td>
<td>R</td>
</tr>
<tr>
<td>Average</td>
<td>22</td>
<td>1.9</td>
<td>84</td>
<td>3</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td>1.5</td>
<td>0.08</td>
<td>6</td>
<td>1.5</td>
<td>2.4</td>
<td></td>
</tr>
</tbody>
</table>

A nine-camera Vicon 512 motion tracking system (Vicon Motion Systems Limited, Oxford, UK) was used to collect all kinematic data. Data was collected at 120 Hz and cameras were placed in a 3/4 circle around the hitting area, between 5 and 7 meters away and between 2.0 and 2.3 meters high (Figure 5.2). Eleven 2.5 cm retro-reflective markers were used to track the body in space. Ten were mounted on stiff arrays such that three markers were placed on the trunk (medial-lower border of the scapula), three on the upper arm (proximal 1/3 of the humerus), two on the forearm (proximal 1/3 of the lower arm), and two on the hand (running diagonally across the dorsal aspect, from the lateral side of the distal part of the 1st metacarpal to the lateral side of the distal part of the 5th metacarpal). The 11th marker was adhered directly to the skin on the styloid process of the ulna. This configuration kept the markers on the styloid process of the ulna and the 1st metacarpal side of the marker array of the hand far enough apart that they would not interfere with each other. The arrangement of all eleven markers allowed the
trunk and upper arm to be tracked using three distinct markers each, while the lower arm and wrist were each tracked using two distinct markers and one common marker (styloid process of the ulna) (Figure 5.3).

Figure 5.2 – Layout of nine-camera Vicon motion tracking system for a right-handed subject. Cameras were positioned in a ¾ circle primarily around the hitting shoulder, approximately 5 to 7 meters away and 2.0 to 2.3 metres high. All cameras faced the hitting area marked by an X in the figure. Approach of subject is shown as a grey arrow, and net as bold line at center of court. A mirror-image of this set-up was used for left-handed subjects.
**Figure 5.3** – Placement of retro-reflective markers on subjects. Rigid plastic plates are shown in black with markers shown as white dots. The trunk and upper arm were both fitted with three markers while the lower arm and hand were both fitted with an individual array of two markers and a single marker common to both, situated on the styloid process of the ulna.
Because of the way the marker data was used to calculate segment positions and joint angles, exact placement of the marker arrays on each segment was not critical. However, it was important that once secured to the subject’s body, the arrays moved as little as possible from their original position. Because the markers were fastened to the body in such a way, reference positions were recorded once at the start of each subject’s session. If an individual marker or marker array moved or fell off, it was secured on the subject again and a new reference position was taken. All subsequent data was associated with the new reference position. All arrays were fastened with tape and a spray-on adhesive.

Due to scheduling and logistical issues, data could not be collected in a gymnasium using an actual volleyball court. Instead, a long rectangular space with high ceilings was chosen. In this area, a regulation-height volleyball net (2.43 meters) was set up. Due to the space available, and the risk posed to the motion tracking cameras during hitting trials if balls were struck and not restrained, the ball was suspended from the ceiling to a height chosen by each individual subject. The ball was placed in a nylon mesh bag and hung using a nylon rope. When asked about this setup prior to data collection, none of the subjects found it awkward or that they felt that different kinematics were used to hit the ball. This set up also eliminated timing issues found in the previous study (see Chapter 4). Subjects were informed about the structure of the study and were asked to practice swinging using all three swings. Once subjects were warmed up, all markers were affixed to the subject. Subjects were then asked to complete a few trials of each swing type at full effort to see if any of the markers or arrays were impeding their movement and if the position of the suspended ball was appropriate. Once everything was properly set up, and the subjects were comfortable with the format of the
swings, the trials commenced. It should be noted that if the placement (usually height) of the suspended ball changed during the session due to it being struck a number of times, it was adjusted such that it was at a comfortable and realistic height for the subjects.

The motion tracking cameras were calibrated such that residuals (a measure within the Vicon software used to determine the accuracy of the system set-up) were less than 3mm, meaning that for the volume within which each subject’s movements were recorded, a positional error of less than 3mm was associated with each marker. A right-handed orthogonal coordinate system was set up at a height of 1m, directly below the suspended ball. This global coordinate system was set up such that the positive X-axis pointed in the direction of approach for the subject (at an angle of roughly 45 degrees towards the net), the positive Z-axis extended upwards from the origin towards the suspended ball, and the positive Y-axis pointed to the left of the subject’s approach direction.

For this study, right-handed subjects approached the hitting area using a similar approach to that which they would use when attacking a ball out of position 4 on a volleyball court. Left-handed subjects used a similar, but opposite approach from position 2 (Figure 5.4, Figure 5.5). Because the approaches for each subject were similar, only the swing types were changed between trials.
Figure 5.4 – Positions of the volleyball court. Bold line at center of court represents the net. Although a full sized volleyball court was not used for this study, right and left handed subjects approached as though they were hitting a ball from position 4 and 2 respectively.

Figure 5.5 – Illustration of the set up of all hitting trials. Bold line at center represents the net. Grey arrows represent the subject’s approach (identical for each swing type) and black arrows represent ball spike direction. Right handed players hit from position 4 while left handed players hit from position 2, both shown. CB – cross body, SA – straight ahead, OS – outside swing.
Each session consisted of 7 randomized trials per swing type for a total of 21 trials. After each trial the data was verified using the Vicon software to ensure completeness of that trial and athletes were asked about their level of fatigue. If fatigue began to take effect (heavy breathing or light headedness) the subjects were instructed to take a break. Also after each trial, ball height and position were corrected to the subject’s specifications, if necessary. Also, if a ball was not struck well and a ‘solid’ connection was not made or the rope from which the ball was suspended was contacted, the trial was repeated. Although not tracked, approximately 25-30 trials were done by each participant because of this.

Once the data was collected, each marker was labelled. While labelling, at least two cameras were required to ‘see’ each marker for its three-dimensional position to be recreated. Due to the complexity of the motion, there were times when individual markers were lost during data collection. Using spline functions within the Vicon software, it was possible to join marker trajectories such that data for the lost markers was reconstructed. If this was not possible and too many frames of data were missing to recreate a reasonable trajectory, the trial was discarded. This was decided using a visual inspection of the resulting marker trajectory. If the motion did not look smooth or ‘human-like’, the trial was not used. Unfortunately, this could only be done once all of the trials were collected from a subject making it impossible to recollect those trials if this was the case. As it turned out, at most, one trial was removed from any set of swings associated with a swing type by any subject (Table 5.2). Once the data had been analyzed, each trial was saved to disk for the calculation of segment positions and joint angles.
<table>
<thead>
<tr>
<th>Subject</th>
<th>SA</th>
<th>CB</th>
<th>OS</th>
</tr>
</thead>
<tbody>
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<td>6</td>
</tr>
<tr>
<td>S02</td>
<td>6</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>S03</td>
<td>6</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>S04</td>
<td>6</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>S05</td>
<td>6</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>S06</td>
<td>6</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>36</td>
<td>41</td>
<td>40</td>
</tr>
</tbody>
</table>

**Figure 5.2** – Number of trials per swing type per subject is shown as well as the total number of trials per swing. None of the swing types were associated with less than 6 swings per subject. For all subsequent statistical evaluations, these values represent the n for each category.

For the calculation of three-dimensional segment positions and joint angles, the MatLab programming language (MathWorks Inc., v. 6.1) was used (Appendix E). First, Cardan angle and Joint Coordinate System (Appendix F) approaches were attempted, but due to the large range of motion associated with the shoulder and the error associated with these two methods, they were deemed unusable for the upper limb. Instead, a planar projection approach was used to calculate the angles. This approach was adapted from a number of sources (Christopher, 2001; Feltner & Nelson, 1996; Robertson et al., 2004). The following describes the approach:

First, the marker data were used to create a local coordinate system (LCS) for each body segment. The three markers for each segment (trunk, upper limb, lower limb, and hand) were designated as $\vec{p}_1$, $\vec{p}_2$, $\vec{p}_3$. For each segment, marker $\vec{p}_1$ was designated
as the origin of the LCS. With this, vectors $\vec{j}$, $\vec{i}$, and $\vec{k}$ were calculated such that vector $\vec{j}$ described the antero-posterior direction (with positive values located anteriorly to the origin), vector $\vec{i}$ described the medio-lateral direction (with positive values located laterally to the origin), and vector $\vec{k}$ described the longitudinal axis of the segment (with positive values located superiorly to the origin).

For the trunk this was done using the following sequence:

$$\vec{i} = \frac{(p_3 - p_1) \times (p_2 - p_1)}{||(p_3 - p_1) \times (p_2 - p_1)||}$$

(1)

$$\vec{k} = \frac{(p_1 - p_2)}{||(p_1 - p_2)||}$$

(2)

$$\vec{j} = (\vec{k} \times \vec{i})$$

(3)

For the upper arm, the following sequence was used:

$$\vec{i} = \frac{(p_2 - p_1) \times (p_3 - p_1)}{||(p_2 - p_1) \times (p_3 - p_1)||}$$

(4)
\( \vec{k} = \frac{(\vec{p}_2 - \vec{p}_1)}{\|(\vec{p}_2 - \vec{p}_1)\|} \)

(5)

\( \vec{j} = (\vec{k} \times \vec{i}) \)

(6)

For the lower arm this was done using the following sequence:

\( \vec{\text{tempi}} = \frac{(\vec{p}_2 - \vec{p}_1)}{\|(\vec{p}_2 - \vec{p}_1)\|} \)

(7)

\( \vec{k} = \frac{(\vec{p}_3 - \vec{p}_1)}{\|(\vec{p}_3 - \vec{p}_1)\|} \)

(8)

\( \vec{i} = \frac{(\vec{k} \times \vec{\text{tempi}})}{\|(\vec{k} \times \vec{\text{tempi}})\|} \)

(9)

\( \vec{j} = (\vec{k} \times \vec{i}) \)

(10)

Finally, for the hand this was done using the following sequence:

\( \vec{i} = \frac{(\vec{p}_1 - \vec{p}_3) \times (\vec{p}_1 - \vec{p}_2)}{\|(\vec{p}_1 - \vec{p}_3) \times (\vec{p}_1 - \vec{p}_2)\|} \)

(11)
To align the LCS with the GCS, subjects were placed in the anatomical position so that the LCS (x, y, z axes) coincided with the GCS (X, Y, Z axes). This reference position was then captured for approximately 5 seconds. From this reference data, transformation matrices were calculated that would later be applied to the trial data. First, a 3 x 3 reference coordinate system matrix \([\text{RefCS}]\) was created for each segment from its \(\vec{i}, \vec{j}, \text{ and } \vec{k}\) vectors such that:

\[
(15) \quad [\text{RefCS}] = \begin{bmatrix}
i_x & j_x & k_x \\
i_y & j_y & k_y \\
i_z & j_z & k_z
\end{bmatrix}
\]

The columns of \([\text{RefCS}]\) represented the 3-D coordinates of the \(\vec{i}, \vec{j}, \text{ and } \vec{k}\) unit vectors of the LCS of the reference frame. The rotation matrix \([\text{RTM}]\) was then calculated as the inverse of the calibration:
The matrix $[\text{RTM}]$ was used to define the zero orientation of the segment relative to the GCS. Therefore, if a segment achieved an orientation identical to the reference position (and, therefore, to the GCS), an identity matrix would result for that segment’s coordinate system. Using each segment’s $[\text{RTM}]$, the LCS for that segment was calculated through each instant (i) in time and designated the provisional coordinate system $[\text{PCS}]$. The same method used to calculate $[\text{RefCS}]$ (eq. 1 through 15), was used to calculate $[\text{PCS}]$. At each instant in time, $[\text{PCS}]$ was multiplied by the $[\text{RTM}]$ to generate the segmental coordinate system matrix $[\text{SCS}]$. The $[\text{SCS}]$ became the new LCS for the segment and was then used in all subsequent calculations.

$$[\text{SCS}]_i = [\text{PCS}]_i [\text{RTM}]$$

Next, planar projections were used to calculate the joint angles for the shoulder, elbow and wrist. First unit vectors $\vec{u}_1$ and $\vec{u}_2$ coincided with the long axes of the upper and lower arms respectively (Note: for all subsequent notation, lowercase t, u, l, and h letters represent the trunk, upper arm, lower arm, and hand respectively).

$$\vec{u}_1 = \vec{k}_u$$
The abduction angle of the shoulder, $\alpha_s$, was calculated as the angle between $\vec{u}_3$ and $\vec{k}_r$, where $\vec{u}_3$ was the projection of $\vec{u}_1$ onto the plane formed by $\vec{i}_r$ and $\vec{k}_r$.

\begin{equation}
\vec{u}_3 = \frac{(\vec{u}_1 - (\vec{u}_1 \cdot \vec{j}_r) \times \vec{j}_r)}{\| (\vec{u}_1 - (\vec{u}_1 \cdot \vec{j}_r) \times \vec{j}_r) \|}
\end{equation}

\begin{equation}
\alpha_s = \arccos(\vec{u}_3 \cdot \vec{k}_r)
\end{equation}

The abduction angle ranged from 0 degrees when in the anatomical position to 180 degrees at full abduction.

Shoulder horizontal abduction/adduction angles, $\beta_s$, were calculated as the angle between vectors $\vec{u}_4$ and $-\vec{j}_r$. Where vector $\vec{u}_4$ was the projection of $\vec{u}_1$ onto the plane formed by $\vec{i}_r$ and $\vec{j}_r$.

\begin{equation}
\vec{u}_4 = \frac{(\vec{u}_1 - (\vec{u}_1 \cdot \vec{k}_r) \times \vec{k}_r)}{\| (\vec{u}_1 - (\vec{u}_1 \cdot \vec{k}_r) \times \vec{k}_r) \|}
\end{equation}

\begin{equation}
\beta_s = \arccos(\vec{u}_4 \cdot -\vec{j}_r)
\end{equation}
Viewed from directly above, counter clockwise positions of \( \vec{u}_1 \) relative to \( \vec{j}_r \) (horizontal adduction) were considered negative angles, while clockwise positions (horizontal abduction) were considered positive.

Internal and external rotation angles of the shoulder, \( \gamma_s \) were calculated as the angle between vectors \( \vec{u}_5 \) and \( \vec{u}_6 \), where \( \vec{u}_5 \) and \( \vec{u}_6 \) were the projections of \( \vec{k}_r \) and \( \vec{i}_l \), respectively, onto the plane formed by \( \vec{j}_u \) and \( \vec{i}_w \).

\[
\begin{align*}
\vec{u}_5 &= \frac{\vec{k}_r - (\vec{k}_r \cdot \vec{k}_u) \times \vec{k}_u}{\left\| \vec{k}_r - (\vec{k}_r \cdot \vec{k}_u) \times \vec{k}_u \right\|} \\
\vec{u}_6 &= \frac{\vec{i}_l - (\vec{i}_l \cdot \vec{k}_u) \times \vec{k}_u}{\left\| \vec{i}_l - (\vec{i}_l \cdot \vec{k}_u) \times \vec{k}_u \right\|} \\
\gamma_s &= \arccos(\vec{u}_5 \cdot \vec{u}_6)
\end{align*}
\]

In this manner, internal and external rotation angles could range from -90 degrees in full internal rotation to 180 degrees in maximal external rotation.

Elbow flexion/extension angles, \( \alpha_E \), were calculated as the angle between \( -\vec{u}_1 \) and \( \vec{u}_2 \).

\[
\alpha_E = \arccos(-\vec{u}_1 \cdot \vec{u}_2)
\]
Flexion and extension angles of the elbow could range from 180 degrees when fully extended to 30 degrees when fully flexed.

Pronation and supination angles of the elbow, $\beta_E$, were calculated as the angle between vectors $\vec{u}_7$ and $\vec{j}_L$, where $\vec{u}_7$ was the projection of $\vec{j}_H$ onto the plane defined by $\vec{i}_L$ and $\vec{j}_L$.

\[
\vec{u}_7 = \frac{(\vec{j}_H - (\vec{j}_H \cdot \vec{k}_L) \times \vec{k}_L)}{\left\| (\vec{j}_H - (\vec{j}_H \cdot \vec{k}_L) \times \vec{k}_L) \right\|}
\]

(28)

\[
\beta_E = \arccos(\vec{u}_7 \cdot \vec{j}_L)
\]

(29)

In full supination, $\beta_E$ was 0 degrees with positive angles representing pronation.

Flexion/extension angles of the wrist, $\alpha_W$, were calculated as the angle between vectors $\vec{u}_8$ and $\vec{j}_H$, where $\vec{u}_8$ was the projection of $\vec{u}_2$ onto the plane formed by $\vec{j}_H$ and $\vec{k}_H$.

\[
\vec{u}_8 = \frac{\vec{u}_2 - (\vec{u}_2 \cdot \vec{i}_H) \times \vec{i}_H}{\left\| \vec{u}_2 - (\vec{u}_2 \cdot \vec{i}_H) \times \vec{i}_H \right\|}
\]

(30)

\[
\alpha_W = \arccos(\vec{u}_8 \cdot \vec{j}_H) - \frac{\pi}{2}
\]

(31)
Negative values of $\alpha_w$ represented wrist flexion, while positive values represented wrist extension.

Finally, radial and ulnar deviations of the wrist, $\beta_w$, were calculated as the angle between vectors $\vec{u}_9$ and $\vec{i}_H$, where $\vec{u}_9$ was the projection of $\vec{u}_2$ onto the plane defined by $\vec{i}_H$ and $\vec{k}_H$.

\[
\vec{u}_9 = \frac{(\vec{u}_2 - (\vec{u}_2 \cdot \vec{j}_H) \times \vec{j}_H)}{\|\vec{u}_2 - (\vec{u}_2 \cdot \vec{j}_H) \times \vec{j}_H\|}
\]

\[
\beta_w = \arccos(\vec{u}_9 \cdot \vec{i}_H) - \frac{\pi}{2}
\]

Positive angles of $\beta_w$ represented ulnar deviation while negative angles represented radial deviation.

To calculate the instantaneous velocity of the hand, the positional data of the most distal hand marker, $\vec{p}_2$, was used.

\[
\mathbf{v} = \frac{\|\vec{p}_2(t+1) - \vec{p}_2\|}{t \times 100}
\]
Where \( t \) is the inter-frame time of 0.0083 seconds, \( i \) is the frame number and positions of \( p_2 \) are given in millimetres.

Data was filtered using a 2\(^{nd}\) order, zero-phase, digital Butterworth filter. A residual analysis, as described by Winter (1990), was done to determine the proper filter frequency for each calculated angle for each subject. That is, the root mean square (RMS) difference was calculated between the filtered and unfiltered data for all frequencies between 0Hz and 60Hz (half of the full data collection frequency of 120Hz) in 1Hz increments using the following equation:

\[
R(f) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (X_i - \overline{X}_i)^2}
\]  

(35)

Where \( N \) is the number of sample points contained in the signal, \( X_i \) is the raw (unfiltered) data at the \( i \)th sample, and \( \overline{X}_i \) is the filtered data at the \( i \)th sample. All of the RMS values that were calculated for all of the angles for each joint were then plotted against the frequencies and a manual/visual approach was used to select optimal filter frequencies for each swing type (Appendix G1 – Table 5.1).
Table 5.3 - Butterworth filter frequencies (Hz) attained from residual analysis. Angles represented as follows: $\alpha_S =$ shoulder abduction/adduction angle, $\beta_S =$ shoulder horizontal abduction/adduction angle, $\gamma_S =$ shoulder internal/external rotation angle, $\alpha_E =$ elbow flexion/extension angle, $\beta_E =$ pronation/supination of the hand, $\alpha_W =$ wrist flexion/extension angle, and $\beta_W =$ wrist ulnar/radial deviation angle. Subject numbers listed in left hand column.

<table>
<thead>
<tr>
<th></th>
<th>$\alpha_S$</th>
<th>$\beta_S$</th>
<th>$\gamma_S$</th>
<th>$\alpha_E$</th>
<th>$\beta_E$</th>
<th>$\alpha_W$</th>
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<td>19</td>
<td>23</td>
<td>17</td>
<td>17.5</td>
</tr>
</tbody>
</table>

Once the data was filtered, predefined maximum and minimum values for the calculated angles were extracted. These included:

1. Maximum abduction of the shoulder
2. Maximum horizontal abduction of the shoulder
3. Maximum horizontal adduction of the shoulder
4. Maximum external rotation of the shoulder
5. Maximum internal rotation of the shoulder
6. Maximum extension of the elbow
7. Maximum flexion of the elbow
8. Maximum pronation of the elbow
9. Maximum flexion of the wrist
10. Maximum ulnar deviation of the wrist

11. Maximum radial deviation of the wrist

Also, the maximum hand speed was calculated for each swing trial. These values were then compared between each of the three swing types (SA, CB and OS). To test for differences, one-way ANOVA’s with repeated measures were run. Once significant differences were identified, a Tukey post hoc test was run to identify where those differences lay. It should be noted that because of the way the data was collected, identifying the exact beginning or end of any of the phases (except for the start of the cocking phase and end of the deceleration phase) was difficult except by analyzing the angles of the upper limb. Because of this, the phases of the swing will only be discussed anecdotally.

Results

Shoulder Abduction/Adduction

Individually, mean maximum shoulder abduction did not differ between the three swings (both as a total and within subjects), except with one subject (Table 5.4). Subject S06 had a more abducted shoulder during the OS swing (153 ± 16 degrees) versus the CB swing (124 ± 11 degrees).

When all subject data was combined there were no differences present between the three swings (SA - 126 ± 31 degrees, CB - 119 ± 31, and OS - 127 ± 32).
Table 5.4 – Mean maximum angles attained during abduction of the shoulder, given in degrees (standard deviation = SD), for each subject and for all subjects combined. A value of 0 degrees represents a shoulder position where the arm is in an anatomical position, or hanging alongside the body. A value of 180 degrees represents an arm in full abduction, pointing straight up. SA – straight ahead; CB – cross body; OS – outside swing; \(^a\) signifies a significant difference (p < 0.05).

<table>
<thead>
<tr>
<th></th>
<th>SA</th>
<th>CB</th>
<th>OS</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>165 (4)</td>
<td>162 (7)</td>
<td>161 (7)</td>
</tr>
<tr>
<td>S02</td>
<td>88 (45)</td>
<td>67 (26)</td>
<td>100 (61)</td>
</tr>
<tr>
<td>S03</td>
<td>123 (3)</td>
<td>123 (11)</td>
<td>127 (13)</td>
</tr>
<tr>
<td>S04</td>
<td>118 (4)</td>
<td>122 (11)</td>
<td>112 (6)</td>
</tr>
<tr>
<td>S05</td>
<td>114 (6)</td>
<td>118 (11)</td>
<td>111 (6)</td>
</tr>
<tr>
<td>S06</td>
<td>145 (24)</td>
<td>124 (11)</td>
<td>153 (16)</td>
</tr>
</tbody>
</table>

| All Subjects | 126 (31) | 119 (32) | 127 (33) |

Typical shoulder abduction/adduction curves for each swing from one subject (S01) are compared in Figure 5.6 and representative shoulder abduction/adduction angles for each of the three swings for each subject are shown in Figure 5.9. Visually, the curves are similar with only slight differences throughout the majority of the swing. Cocking begins with the arm at approximately 100-125 degrees of abduction and is slightly elevated towards ball contact (approximately 150-175 degrees). During each swing, the arm drops to approximately 0 degrees in all subjects but is then elevated to approximately 10 to 20 degrees.
Figure 5.6 – Abduction/adduction angles of the shoulder for all three swings. Angles could range from 0 degrees in anatomical position to 180 degrees in full abduction. All curves taken from subject S01. SA – straight ahead; CB – cross body; OS – outside swing.

Shoulder Horizontal Abduction/Adduction

When considering each subject individually, differences of maximal shoulder horizontal abduction (at the end of the cocking phase) between the swings varied greatly (Table 5.5). For instance one subject (S04) displayed differences between the CB and OS swings (CB – 64 ± 6.7, OS – 102 ± 26), another displayed differences between the SA and CB swings (SA – 108 ± 19, CB – 89 ± 5.1), and the rest had no differences.

When all of the trials from each subject were taken into account, no differences between the swings were present (SA - 104 ± 34 degrees, CB - 105 ± 40 degrees, OS - 112 ± 35 degrees) with respect to maximum horizontal abduction. This appears to be due
to the large amount of variation seen between the swings (standard deviations of more than 30 degrees for each swing).

Table 5.5 – Mean maximum angles attained during horizontal abduction of the shoulder, given in degrees (SD), for each subject and for all subjects combined. A value of 0 degrees represents a shoulder position where the arm is pointing directly in front of the body, with positive numbers representing horizontal abduction. SA – straight ahead; CB – cross body; OS – outside swing; \(^{a}\) and \(^{b}\) signify a significant difference (p < 0.05).

<table>
<thead>
<tr>
<th></th>
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<th>CB</th>
<th>OS</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>61 (5)</td>
<td>92 (48)</td>
<td>72 (19)</td>
</tr>
<tr>
<td>S02</td>
<td>128 (49)</td>
<td>152 (28)</td>
<td>165 (17)</td>
</tr>
<tr>
<td>S03</td>
<td>102 (15)</td>
<td>101 (30)</td>
<td>107 (30)</td>
</tr>
<tr>
<td>S04</td>
<td>91 (32)</td>
<td>64 (7)(^{a})</td>
<td>102 (26)(^{a})</td>
</tr>
<tr>
<td>S05</td>
<td>108 (19)(^{b})</td>
<td>89.3 (5)(^{b})</td>
<td>95 (4)</td>
</tr>
<tr>
<td>S06</td>
<td>132 (16)</td>
<td>129 (27)</td>
<td>134 (19)</td>
</tr>
<tr>
<td>All Subjects</td>
<td>104 (34)</td>
<td>105 (40)</td>
<td>112 (35)</td>
</tr>
</tbody>
</table>

Individually, 3 subjects (S03, S05, S06) displayed more mean maximum horizontal adduction of the upper arm during either SA or CB swings than during OS swings (Table 5.6). A fourth subject (S04) displayed more mean maximal horizontal adduction during CB swings than during both SA and OS swings. Neither of the other
two subjects displayed any trends with respect to mean horizontal adduction of the shoulder.

When all subject data was taken into account, SA and CB swings were associated with a more pronounced mean maximal horizontal adduction angle of the shoulder than OS swings (SA – 15 ± 13 degrees, CB – 13 ± 10 degrees, and OS – 31 ± 16 degrees)

Table 5.6 – Mean maximum angles attained during horizontal adduction of the shoulder, given in degrees (SD), for each subject and for all subjects combined. A value of 0 degrees represents a shoulder position where the arm is pointing directly in front of the body, with positive numbers representing horizontal abduction. SA – straight ahead; CB – cross body; OS – outside swing; a, c, d, and e signify a significant difference (p < 0.05) between OS and the other two swing types; b signifies a significant difference (p < 0.05) between CB and the other two swings.

<table>
<thead>
<tr>
<th></th>
<th>SA</th>
<th>CB</th>
<th>OS</th>
</tr>
</thead>
<tbody>
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<td>6 (3)</td>
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<tr>
<td>S02</td>
<td>17 (8)</td>
<td>17 (8)</td>
<td>21 (11)</td>
</tr>
<tr>
<td>S03</td>
<td>9 (9)a</td>
<td>11 (14)a</td>
<td>38 (11)a</td>
</tr>
<tr>
<td>S04</td>
<td>35 (5)b</td>
<td>20 (10)b</td>
<td>42 (3)b</td>
</tr>
<tr>
<td>S05</td>
<td>6 (12)c</td>
<td>11 (10)c</td>
<td>39 (20)c</td>
</tr>
<tr>
<td>S06</td>
<td>14 (9)d</td>
<td>10 (9)d</td>
<td>30 (9)d</td>
</tr>
<tr>
<td>All Subjects</td>
<td>15 (13)e</td>
<td>13 (10)e</td>
<td>31 (16)e</td>
</tr>
</tbody>
</table>
Typical shoulder horizontal abduction/adduction angles are shown in Figure 5.7 (subject S03) and representative angles for each subject are shown in Figure 5.9, comparing SA, CB, and OS swing types. Cocking began with the arm horizontally abducted between 50 and 100 degrees for all swings (Figure 5.9). Horizontal adduction of the arm then slightly decreased during the cocking phase and increased during the acceleration phase and deceleration phases. There were no differences in maximum horizontal abduction angles of the shoulder between the three swings (Table 5.5). During the OS swing the arm remained in more horizontal abduction throughout the swing than either the SA or CB swings (Figure 5.7). While the OS swing showed only slight arm adduction to within 50 degrees of the vertical, the arm during the SA and CB swings was adducted to almost 0 degrees.
Figure 5.7 – Horizontal abduction/adduction angles of the shoulder for all three swings. Angles could range from -90 degrees in full horizontal adduction to 180 degrees in full horizontal abduction. All curves taken from subject S03. SA – straight ahead; CB – cross body; OS – outside swing.

Shoulder Internal/External Rotation

Only one subject (S05) displayed a difference in external rotation at the end of the cocking phase between swings (SA - 119 ± 4.5 degrees, CB - 125 ± 4.6 degrees, and OS - 117 ± 3.4 degrees) (Table 5.7). This difference was present during CB swings, which had less external rotation than the other two swings.

When all subject data was combined, a difference was seen between the CB and OS swings (CB - 131 ± 19 degrees, OS - 121 ± 19 degrees), with CB being associated with more external rotation.
Table 5.7 – Mean maximum angles attained during external rotation of the shoulder, given in degrees (SD), for each subject and for all subjects combined. Internal/external shoulder rotation angles could range from approximately -90 degrees in full internal rotation to 180 degrees in full external rotation. SA – straight ahead; CB – cross body; OS – outside swing; \(^a\) signifies a significant difference (p < 0.05) between CB and the other two swings; \(^b\) signifies a significant difference (p < 0.05).

<table>
<thead>
<tr>
<th></th>
<th>SA</th>
<th>CB</th>
<th>OS</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>109 (7)</td>
<td>130 (20)</td>
<td>117 (26)</td>
</tr>
<tr>
<td>S02</td>
<td>145 (18)</td>
<td>161 (4)</td>
<td>153 (15)</td>
</tr>
<tr>
<td>S03</td>
<td>105 (2)</td>
<td>109 (2)</td>
<td>104 (3)</td>
</tr>
<tr>
<td>S04</td>
<td>128 (24)</td>
<td>126 (4)</td>
<td>115 (3)</td>
</tr>
<tr>
<td>S05</td>
<td>119 (5)(^a)</td>
<td>125 (5)(^a)</td>
<td>117 (3)(^a)</td>
</tr>
<tr>
<td>S06</td>
<td>133 (3)</td>
<td>137 (16)</td>
<td>125 (2)</td>
</tr>
<tr>
<td><strong>All Subjects</strong></td>
<td>123 (18)</td>
<td>131 (19)(^b)</td>
<td>121 (19)(^b)</td>
</tr>
</tbody>
</table>

Individually, mean maximum internal rotation angles of the shoulder were fairly similar between all swings (Table 5.8). However, one subject (S04) displayed more internal rotation during the CB swing (4 ± 3 degrees) than during the OS swing (13 ± 9 degrees). Another subject (S06) displayed more internal rotation during the SA swing (7 ± 2 degrees) compared to the OS swing (3 ± 3 degrees). No trends were seen for any of the other subjects.

When all of the subjects’ data was combined, no differences between the swings were seen (SA – 8 ± 6 degrees, CB – 5 ± 4 degrees, and OS – 7 ± 8 degrees).
Table 5.8 – Mean maximum angles attained during internal rotation of the shoulder, given in degrees (SD), for each subject and for all subjects combined. Internal/external shoulder rotation angles could range from approximately -90 degrees in full internal rotation to 180 degrees in full external rotation. SA – straight ahead; CB – cross body; OS – outside swing; * and ** signify a significant difference (p < 0.05).

<table>
<thead>
<tr>
<th></th>
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<th>CB</th>
<th>OS</th>
</tr>
</thead>
<tbody>
<tr>
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<td>14 (8)</td>
<td>7 (7)</td>
<td>7 (13)</td>
</tr>
<tr>
<td>S02</td>
<td>8 (4)</td>
<td>6 (5)</td>
<td>8 (9)</td>
</tr>
<tr>
<td>S03</td>
<td>3 (3)</td>
<td>4 (3)</td>
<td>6 (4)</td>
</tr>
<tr>
<td>S04</td>
<td>9 (6)</td>
<td>4 (3)*</td>
<td>13 (9)*</td>
</tr>
<tr>
<td>S05</td>
<td>8 (5)</td>
<td>7 (4)</td>
<td>8 (8)</td>
</tr>
<tr>
<td>S06</td>
<td>7 (2)**</td>
<td>5 (3)</td>
<td>3 (3)**</td>
</tr>
<tr>
<td><strong>All Subjects</strong></td>
<td>8 (6)</td>
<td>5 (4)</td>
<td>7 (8)</td>
</tr>
</tbody>
</table>

At the beginning of the cocking phase, the shoulder was externally rotated to between approximately 0 and 50 degrees during all three swings (Figure 5.8, Figure 5.9). The shoulder was then externally rotated to between approximately 100 and 125 degrees. As seen in Table 5.7 and Figure 5.8, the arm was externally rotated more during CB swings than OS swings. During all three swings, the arm was then internally rotated to almost a neutral position (0 degrees). After this, during all three swings, the arm was slightly externally rotated to approximately 25 degrees.
Figure 5.8 – Internal/external rotation angles of the shoulder for all three swings. Angles could range from -90 degrees in full internal rotation to 180 degrees in full external rotation. All curves taken from subject S04. SA – straight ahead; CB – cross body; OS – outside swing.
Figure 5.9 – Calculated shoulder angles from each subject. Curves were chosen based on their ability to generally represent the shapes of all other curves within that swing type and were not necessarily taken from the same trial for each subject per swing type. Curves have different x-axis values as these represent frame numbers for the longest trial in that set. SA – straight ahead; CB – cross body; OS – outside swing; Abd. – shoulder abduction (could range from 0 degrees in anatomical position to 180 degrees in full abduction); Hor. Abd./Add. – shoulder horizontal abduction/adduction (could range from -90 degrees in full horizontal adduction to 180 degrees in full horizontal abduction); Int./Ext. Rot. – shoulder internal/external rotation (could range from -90 degrees in full internal rotation to 180 degrees in full external rotation).
Elbow Flexion/Extension

Mean maximum flexion angles of the elbow were not found to differ between swings both individually and when all subject data was combined (Table 5.9).

Table 5.9 – Mean maximum angles attained during flexion of the elbow, given in degrees (SD), for each subject and for all subjects combined. Values could range from 0 degrees in full flexion, to approximately 180 degrees in full extension. SA – straight ahead; CB – cross body; OS – outside swing.

<table>
<thead>
<tr>
<th></th>
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<th>CB</th>
<th>OS</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>101 (4)</td>
<td>97 (15)</td>
<td>99 (4)</td>
</tr>
<tr>
<td>S02</td>
<td>47 (37)</td>
<td>21 (8)</td>
<td>19 (17)</td>
</tr>
<tr>
<td>S03</td>
<td>85 (3)</td>
<td>77 (23)</td>
<td>76 (23)</td>
</tr>
<tr>
<td>S04</td>
<td>85 (2)</td>
<td>83 (2)</td>
<td>83 (4)</td>
</tr>
<tr>
<td>S05</td>
<td>73 (2)</td>
<td>76 (5)</td>
<td>74 (3)</td>
</tr>
<tr>
<td>S06</td>
<td>73 (4)</td>
<td>66 (24)</td>
<td>71 (8)</td>
</tr>
<tr>
<td>All Subjects</td>
<td>77 (22)</td>
<td>70 (28)</td>
<td>71 (27)</td>
</tr>
</tbody>
</table>

Only one subject’s (S06) maximum elbow extension angles were smaller during the CB swing (161 ± 5 degrees) than during either the SA (168 ± 2 degrees) or OS (168 ± 4 degrees) swings (Table 5.10). Because of the variability within swings this trend was not significant in any other subject.
When all subject data was combined, no differences in mean maximum extension of the elbow between the swings were seen.

Table 5.10 – Mean maximum angles attained during extension of the elbow, given in degrees (SD), for each subject and for all subjects combined. Values could range from 0 degrees in full flexion, to approximately 180 degrees in full extension. SA – straight ahead; CB – cross body; OS – outside swing; a signifies a significant difference (p < 0.05) between CB and the two other swings.

<table>
<thead>
<tr>
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</thead>
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<td>176 (1)</td>
<td>175 (2)</td>
</tr>
<tr>
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<td>134 (40)</td>
<td>118 (25)</td>
<td>124 (32)</td>
</tr>
<tr>
<td>S03</td>
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<td>162 (11)</td>
<td>173 (6)</td>
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<td>159 (5)</td>
<td>159 (8)</td>
</tr>
<tr>
<td>S05</td>
<td>169 (7)</td>
<td>169 (5)</td>
<td>171 (5)</td>
</tr>
<tr>
<td>S06</td>
<td>168 (2)a</td>
<td>161 (5)a</td>
<td>168 (4)a</td>
</tr>
<tr>
<td>All Subjects</td>
<td>163 (21)</td>
<td>157 (22)</td>
<td>162 (21)</td>
</tr>
</tbody>
</table>

Flexion/extension angles of the elbow can be seen in Figures 5.10 and 5.12. It is clear from these figures and from Tables 5.8 and 5.9 that not much variation exists in flexion/extension of the elbow between swings. In general, the elbow is in approximately 100 degrees of extension at the start of the cocking phase. During the acceleration phase...
it increases quickly to more than 150 degrees. The elbow then remains in roughly this position as it is decelerated after ball contact.

Figure 5.10 – Flexion/extension angles of the elbow for all three swings. Angles could range from approximately 40 degrees in full flexion to 180 degrees in full extension. All curves taken from subject S04. SA – straight ahead; CB – cross body; OS – outside swing.
Elbow Pronation

Because of the large variability in elbow pronation (standard deviations as high as 45 degrees) only a single subject (S05) displayed a difference between swings (Table 5.11). This subject’s elbow was significantly less pronated during the CB swing (73 ± 12 degrees) compared to the other two swings (SA – 86 ± 5 degrees, OS – 90 ± 9 degrees).

When all subject data was combined no differences between subjects were seen with respect to mean maximum pronation angles.

**Table 5.11** – Mean maximum angles attained during pronation of the elbow, given in degrees (SD), for each subject and for all subjects combined. Values of 0 degrees represented full supination while positive numbers represented increasing pronation, to approximately 180 degrees in full pronation. SA – straight ahead; CB – cross body; OS – outside swing; *a* signifies a significant difference (p < 0.05) between CB and the two other swing types.

<table>
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<tr>
<th></th>
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<th>CB</th>
<th>OS</th>
</tr>
</thead>
<tbody>
<tr>
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<td>93 (12)</td>
<td>107 (12)</td>
<td>105 (11)</td>
</tr>
<tr>
<td>S02</td>
<td>98 (40)</td>
<td>81 (39)</td>
<td>108 (47)</td>
</tr>
<tr>
<td>S03</td>
<td>79 (7)</td>
<td>91 (43)</td>
<td>87 (10)</td>
</tr>
<tr>
<td>S04</td>
<td>92 (18)</td>
<td>99 (37)</td>
<td>108 (27)</td>
</tr>
<tr>
<td>S05</td>
<td>86 (5)*a</td>
<td>73 (12)*a</td>
<td>90 (9)*a</td>
</tr>
<tr>
<td>S06</td>
<td>77 (8)</td>
<td>77 (15)</td>
<td>112 (45)</td>
</tr>
<tr>
<td><strong>All Subjects</strong></td>
<td>87 (19)</td>
<td>87 (32)</td>
<td>102 (29)</td>
</tr>
</tbody>
</table>
Pronation of the elbow was quite variable both between trials and between swings (Figures 5.11 and 5.12). Elbow pronation ranged between 50 and 100 degrees for the majority of the swing with a large fluctuation of approximately 25 to 50 degrees during the middle of the swing.

**Figure 5.11** – Pronation angles of the elbow for all three swings. Angles could range from approximately 0 degrees in full supination to 180 degrees in full pronation. All curves taken from subject S01. SA – straight ahead; CB – cross body; OS – outside swing.
Figure 5.12 – Calculated elbow angles from each subject. Curves were chosen based on their ability to generally represent the shapes of all other curves within that swing and were not necessarily taken from the same trial for each subject per swing type. Curves have different x-axis values as these represent frame numbers for the longest trial in that set. SA – straight ahead; CB – cross body; OS – outside swing; Flex./Ext. – elbow flexion/extension (could range from approximately 40 degrees in full flexion to 180 degrees in full extension); Pro. – elbow supination/pronation (full supination at 0 degrees, with pronation increasing with increasing positive angles).
**Wrist Flexion**

Individually, no differences in maximum wrist flexion between the swings were present (Table 5.12).

When all of the subject data was combined, the SA swing (-6 ± 21 degrees) was associated with significantly less maximum wrist flexion than the CB swing (-20 ± 27 degrees). The average maximum wrist flexion attained during the OS swing (-18 ± 27 degrees) was not significantly larger than during the SA swing type.

**Table 5.12** – Mean maximum angles attained during flexion of the wrist, given in degrees (SD), for each subject and for all subjects combined. Positive values represent wrist extension, while negative numbers represent wrist flexion. SA – straight ahead; CB – cross body; OS – outside swing; a signifies a significant difference (p < 0.05).

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
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<td>19 (9)</td>
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<td>15 (21)</td>
</tr>
<tr>
<td>S02</td>
<td>-16 (30)</td>
<td>-38 (29)</td>
<td>-33 (30)</td>
</tr>
<tr>
<td>S03</td>
<td>-29 (6)</td>
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</tr>
<tr>
<td>S04</td>
<td>-2 (18)</td>
<td>-8 (15)</td>
<td>-17 (30)</td>
</tr>
<tr>
<td>S05</td>
<td>2 (6)</td>
<td>-16 (14)</td>
<td>-10 (21)</td>
</tr>
<tr>
<td>S06</td>
<td>-7 (12)</td>
<td>-27 (24)</td>
<td>-28 (25)</td>
</tr>
<tr>
<td><strong>All Subjects</strong></td>
<td>-6 (21)a</td>
<td>-20 (27)a</td>
<td>-18 (27)</td>
</tr>
</tbody>
</table>
Flexion/extension angles of the wrist are presented in Figures 5.13 and 5.15. At the beginning of the cocking phase the wrist was in a slightly extended position of between 0 and 30 degrees, which increased a small amount through to the end of the cocking phase. The wrist was actively flexed throughout the acceleration phase. However, during the acceleration phase the wrist was more flexed during the CB swing than during the SA swing. During SA swings the wrist was only flexed to approximately a neutral (0 degrees) position while this angle increased to approximately 20 degrees during CB and OS swings.

**Figure 5.13** – Flexion/extension angles of the wrist for all three swing types. Positive angles represent extension, negative angles represent flexion. All curves taken from subject S01. SA – straight ahead; CB – cross body; OS – outside swing.
Wrist Ulnar/Radial Deviation

Maximum ulnar deviation differed between swings in a seemingly random fashion (Table 5.13). For instance, one subject (S01) had significantly more ulnar deviation during the OS swing (51 ± 20 degrees) compared to the CB swing (33 ± 3 degrees) while another subject (S02) had significantly more ulnar deviation during the CB swing (47 ± 26 degrees) than during the SA swing (14 ± 11 degrees). Another subject (S06) displayed a trend for the OS swing (43 ± 14 degrees) to be associated with the least amount of ulnar deviation (SA – 16 ± 10 degrees, and CB – 16 ± 6 degrees). Other subjects did not display trends in this measure.

When all the subject data was combined and analyzed together there were no differences between swings.
Table 5.13 – Mean maximum angles attained during ulnar deviation of the wrist, given in degrees (SD), for each subject and for all subjects combined. 0 degrees represents a neutral wrist (no deviation), with positive numbers representing increasing ulnar deviation. SA – straight ahead; CB – cross body; OS – outside swing; \(^a\), \(^b\) signify a significant difference (p < 0.05); \(^c\) signifies a significant difference (p < 0.05) between OS and the other two swings.

<table>
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<tbody>
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<td>40 (9)</td>
<td>33 (3) (^a)</td>
<td>51 (20) (^a)</td>
</tr>
<tr>
<td>S02</td>
<td>14 (11) (^b)</td>
<td>47 (26) (^b)</td>
<td>41 (19)</td>
</tr>
<tr>
<td>S03</td>
<td>5 (21)</td>
<td>10 (22)</td>
<td>5 (22)</td>
</tr>
<tr>
<td>S04</td>
<td>28 (32)</td>
<td>17 (10)</td>
<td>29 (18)</td>
</tr>
<tr>
<td>S05</td>
<td>29 (9)</td>
<td>41 (21)</td>
<td>25 (12)</td>
</tr>
<tr>
<td>S06</td>
<td>16 (10) (^c)</td>
<td>16 (8) (^c)</td>
<td>43 (14) (^c)</td>
</tr>
<tr>
<td>All Subjects</td>
<td>22 (20)</td>
<td>27 (21)</td>
<td>32 (22)</td>
</tr>
</tbody>
</table>

Maximum radial deviation did not differ between swings for five of the six subjects (Table 5.14). Subject S05 displayed more radial deviation during SA swings (46 ± 10 degrees) than during CB swings (28 ± 8 degrees).

No differences in wrist radial deviation were seen when the subject data was combined (SA - 33.4 ± 18.22 degrees; CB - 31.7 ± 20.1 degrees; and OS - 33.3 ± 15.9 degrees).
Table 5.14 – Mean maximum angles attained during radial deviation of the wrist, given in degrees (SD), for each subject and for all subjects combined. 0 degrees represents a neutral wrist (no deviation), with negative numbers representing increasing radial deviation. SA – straight ahead; CB – cross body; OS – outside swing; * signifies a significant difference (p < 0.05).

<table>
<thead>
<tr>
<th></th>
<th>SA</th>
<th>CB (SD)</th>
<th>OS (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>-42 (2)</td>
<td>-48 (18)</td>
<td>-31 (9)</td>
</tr>
<tr>
<td>S02</td>
<td>-22 (10)</td>
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<td>-37 (24)</td>
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<tr>
<td>S03</td>
<td>-35 (5)</td>
<td>-38 (10)</td>
<td>-37 (4)</td>
</tr>
<tr>
<td>S04</td>
<td>-27 (27)</td>
<td>-23 (19)</td>
<td>-34 (21)</td>
</tr>
<tr>
<td>S05</td>
<td>-46 (10)*</td>
<td>-28 (8)*</td>
<td>-36 (10)</td>
</tr>
<tr>
<td>S06</td>
<td>-29 (21)</td>
<td>-32 (30)</td>
<td>-27 (21)</td>
</tr>
<tr>
<td>All Subjects</td>
<td>-33 (18)</td>
<td>-32 (20)</td>
<td>-34 (16)</td>
</tr>
</tbody>
</table>

Similar to that seen in Table 5.14, the radial/ulnar deviation angles shown in Figures 5.14 and 5.15 appear to be very random and no definite trends could be seen. In general, during all swing types, the cocking phase was begun in ulnar deviation of about 25 degrees. Then during the late cocking and early acceleration phases the wrist was put into radial deviation of over 25 degrees. Finally, as the ball was being struck (late acceleration) and during the deceleration phase the wrist was again put into a position of ulnar deviation of approximately 25 degrees.
Figure 5.14 – Radial/ulnar deviation angles of the wrist for all three hitting types. Positive angles represent ulnar deviation, while negative angles represent radial deviation. All curves taken from subject S01. SA – straight ahead; CB – cross body; OS – outside swing.
Figure 5.15 – Calculated wrist angles from each subject. Curves were chosen based on their ability to generally represent the shapes of all other curves within that swing and were not necessarily taken from the same trial for each subject per swing type. Curves have different x-axis values as these represent frame numbers for the longest trial in that set. SA – straight ahead; CB – cross body; OS – outside swing; Flex./Ext. – wrist flexion/extension (positive numbers representing wrist extension and negative numbers representing wrist flexion); Rad./Uln. Dev. – wrist ulnar/radial deviation (positive numbers representing ulnar deviation and negative numbers representing radial deviation).
Hand Speed

Five of the six subjects had slower average maximum hand speeds during the OS attack swing than during either one or both of the CB or SA swings (Table 5.15).

When all subject data was combined no differences existed between the swings (SA – 17 ± 2 m/s, CB – 17 ± 2 m/s, and OS – 16 ± 2 m/s).

Table 5.15 – Mean maximum hand speed, given in meters/second (SD), for each subject and for all subjects combined. Maximum speeds were attained at or near ball contact in all cases. SA – straight ahead; CB – cross body; OS – outside swing; \(^{a}\), \(^{b}\) and \(^{c}\) signify a significant difference (p < 0.05); \(^{d}\), and \(^{e}\) signify a significant difference (p < 0.05) between OS and the other two swings.

<table>
<thead>
<tr>
<th></th>
<th>SA</th>
<th>CB</th>
<th>OS</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>15 (1)</td>
<td>15 (0.8)</td>
<td>16 (1)</td>
</tr>
<tr>
<td>S02</td>
<td>18 (0.6)</td>
<td>19 (0.3)(^{a})</td>
<td>18 (1)(^{a})</td>
</tr>
<tr>
<td>S03</td>
<td>18 (0.5)(^{b})</td>
<td>17 (0.3)</td>
<td>17 (0.6)(^{b})</td>
</tr>
<tr>
<td>S04</td>
<td>16 (0.6)</td>
<td>17 (0.6)(^{c})</td>
<td>16 (0.6)(^{c})</td>
</tr>
<tr>
<td>S05</td>
<td>15 (0.4)(^{d})</td>
<td>15 (0.2)(^{d})</td>
<td>14 (0.5)(^{d})</td>
</tr>
<tr>
<td>S06</td>
<td>20 (0.7)(^{e})</td>
<td>20 (0.6)(^{e})</td>
<td>18 (0.6)(^{e})</td>
</tr>
<tr>
<td>All Subjects</td>
<td>17 (2)</td>
<td>17 (2)</td>
<td>16 (2)</td>
</tr>
</tbody>
</table>
Hand speed was very similar between swings (Figure 5.16 and 5.17). The hand would increase speed to approximately 5 m/s as it was cocked back and was then slowed towards the end of the cocking phase to approximately 2.5 m/s. During the acceleration phase the hand was quickly accelerated to between 15 and 20 m/s. After the ball was contacted the arm was decelerated slowly to approximately 5 m/s where the follow-through phase presumably began.

**Figure 5.16** – Hand speed-time graph for all three swings. Speeds given in m/s. All curves taken from subject S06. SA – straight ahead; CB – cross body; OS – outside swing.
Figure 5.17 – Hand speed for each subject separated by swing type. Curves were chosen based on their ability to generally represent the shapes of all other curves within that swing type. Curves have different x-axis values as these represent frame numbers for the longest trial in that set. SA – straight ahead; CB – cross body; OS – outside swing.
Discussion

The purpose of this study was to examine the kinematics of three volleyball attack arm swings: the straight ahead arm swing (SA), where the ball is hit directly ahead of the attacking player; the cross body arm swing (CB), where the ball is hit across the body, towards, and then past the midline of the body; and the outside arm swing (OS), where the ball is hit on the same side as the hitting arm, away from the midline of the body. This is the first study to examine these swings, as all previous research studies have looked exclusively at the SA arm swing. Presumably this bias towards the SA swing is because of the similarities in mechanics between the SA swing and other, more researched, overhead throwing movements, such as those seen in baseball, javelin, tennis, and football (Elliott et al., 2003; Fleisig et al., 1989; Fleisig et al., 1999; Jobe et al., 1983; Kelly et al., 2002; Pappas et al., 1985; Tripp et al., 2006).

Shoulder Abduction/Adduction

When all subject data was combined, no significant differences were found to exist between the three different swing types. It is possible that a larger subject pool or more trials could reduce the variation and allow differences to come to light. For instance, one subject (S06) displayed significantly more abduction during the CB attack swing (Table 5.4).

Other studies have reported maximum shoulder abduction during the volleyball spike between 115 and 160 degrees from the vertical (Chung et al., 1990; Coleman et al., 1993). Mean maximum abduction angles seen during this study fall within this range (119 ± 32 degrees to 127 ± 33 degrees) for all three swings. These values are higher than those typically seen in other overhead sports, which range between 90 and 110 degrees of
abduction (Feltner & Nelson, 1996; G. S. Fleisig et al., 1996; G. S. Fleisig et al., 2006; Stodden et al., 2005).

Shoulder Horizontal Abduction/Adduction

During the cocking phase of the volleyball attack spike, the arm is horizontally abducted prior to being accelerated towards the ball. This study found no common trends among the six subjects that would point to a consistent difference between the three swings studied (Table 5.5, Figure 5.7, Figure 5.9). Similarly, when all of the subject data was combined, no differences between the swings were present. This may be due to the variation in this measure (standard deviations of between 35 and 40 degrees). However, these results are not surprising as it was previously thought that the mechanics of the cocking phase would play only a small role in where the ball was contacted and how the arm was rotated to get to that position.

Few previous volleyball-related studies have published horizontal abduction data so comparisons are difficult to make. One study has reported mean maximum horizontal abduction angles of 97 ± 14 degrees (Chung et al., 1990). This is quite close to the values seen in this study which ranged from 104 ± 34 degrees (SA) to 112 ± 35 degrees (OS). Little data has been published regarding maximum horizontal abduction angles of the shoulder during other overhead sports.

Horizontal adduction of the shoulder peaks close to ball contact during the volleyball spike. Not surprisingly, the OS attack swings were associated with less horizontal adduction than both the SA and CB swings both within subjects and when all subject data was combined (Table 5.6, Figure 5.7, and Figure 5.9). This can be seen most visibly in Figure 5.7.
Surprising is the lack of difference in maximum horizontal adduction when comparing the SA and CB swing types. It was expected that because of the difference in the ball trajectory during a CB swing compared to a SA swing, the horizontal adduction would be greater during the CB swing. It is possible that instead of increasing horizontal adduction elite volleyball players are able to rotate their trunks so that the CB swing closely resembles the SA swing. Other results from this study also point towards this hypothesis. However, an interesting question is why these athletes are able to rotate their body when hitting using a CB swing but not when hitting using an OS swing (assumed due to differences in horizontal adduction).

Little published information exists regarding horizontal adduction angles of the shoulder during a spike attack. Comparisons can be made to other overhead throwing sports where horizontal adduction ranges between 50 and 90 degrees from directly ahead of the athlete during the acceleration phase (Feltner & Nelson, 1996; G. S. Fleisig et al., 1996; G. S. Fleisig et al., 2006; Stodden et al., 2005; Werner et al., 2001). In general, the shoulder is much more horizontally adducted during spiking, which ranges from approximately 12 degrees (CB) to 30 degrees (OS). This difference between volleyball and other overhead sports may be due to the inclusion of the deceleration phase during this study, where the arm could be continually horizontally adducted, while overhead studies analyzing other overhead sports have only considered the acceleration phase when calculating horizontal adduction angles.

Shoulder Internal/External Rotation

External rotation of the shoulder peaked near the end of the cocking phase during all swings (Figure 5.8). The mean maximal external rotation was higher during CB
swings than during OS swings (Table 5.7). Although this outcome was surprising at first, a possible explanation exists if the movement of the whole body is considered. First, as previously mentioned, it may be that during a CB swing the upper body is rotated so that the arm does not have to be horizontally adducted more than during the SA swing (Table 5.6). It is possible that during a CB swing, as the trunk is rotated to allow for this to happen, more torque is placed on the trailing arm and, as a result, the hitting arm is externally rotated more than during the OS swing type. More research, taking into account the body as a whole would need to be done to test this hypothesis.

Average maximum shoulder external rotations were measured at 123 ± 18 degrees during SA swings, 131 ± 19 degrees during CB swings, and 121 ± 19 degrees during OS swings near the end of the cocking phase. This was more than the 102 ± 47 degrees a previous study had reported (Chung et al., 1990). Other volleyball studies have reported that the shoulder is placed in a position of maximum external rotation during the end of the cocking phase (Maxwell, 1981; Rokito et al., 1998). Similarly, studies examining other overhead throwing motions have found that this position of maximum external rotation during the end of the cocking phase places the arm in approximately 105 to 135 degrees of external rotation (Dillman et al., 1993; Feltner & Nelson, 1996). Clearly, measures of maximum external rotation of the SA, CB, and OS swings in this study are within this range, which appears to be near the maximal physiological limit for this motion.

Peak internal rotation angles of the shoulder were not significantly different between swings (Table 5.8). This was surprising as it was thought that the CB swing would be associated with more internal rotation than either of the other two swings. This
could be a function of the small number of subjects used in this study, or simply that, again, the CB swing is such that it mechanically resembles the SA swing.

It was interesting that none of the three swing types were associated with an internal rotation of the shoulder past the neutral position (Figure 5.8 and Figure 5.9). This has been previously documented for the SA spike attack (Coleman et al., 1993; Kugler et al., 1996). It is possible that this neutral position is attained during contact with the ball so as to limit the stress on the soft tissues of the shoulder joint that can occur in externally or internally rotated positions. Few studies looking at other overhead sports have published internal rotation angles, making comparison to other sports difficult.

Elbow Flexion/Extension

No kinematic differences were found between the three swings for elbow flexion and extension (Table 5.9, Table 5.10, Figure 5.10, Figure 5.12). This was initially surprising because it was hypothesized that during the CB swings the arm would be horizontally adducted and the elbow flexed, thus potentially decreasing maximum extension of the arm during this type of swing. Because horizontal adduction was not found to increase during CB swings it makes sense that elbow extension was similar to that of the SA swings.

Another study found approximately 122 ± 10 degrees of elbow extension at the end of the acceleration phase which was approximately 30 degrees less than what was seen in this study (Chung et al., 1990). Because the flexion/extension angles of the elbow were calculated using the same method in both of these studies, it is unknown why this large discrepancy exists between the two.
Elbow Pronation

Only one subject (S05) displayed a difference in elbow pronation between swings. For this subject, OS swings were associated with a higher mean maximum pronation angle than either SA or CB swings (Table 5.11, Figure 5.11, Figure 5.12). This was not surprising as it was expected that during OS swings, attackers would have to pronate their elbows to allow the ball to be hit in the desired direction. If the hand was not pronated in such a fashion the ball would have to be struck either with the side of the hand or in a more anterior direction (as opposed to laterally, away from the subject). However, as mentioned, this was only visible in one of the subjects and when all of the subject data was combined no differences were present.

No studies have been found that have published data concerning pronation of the elbow during overhead throwing motions, so comparisons to other literature are impossible. It would also be difficult to give values for general elbow pronation as the values were so variable.

Wrist Flexion/Extension

As seen in Table 5.12, the wrist was significantly more flexed during CB swings than during SA swings. Therefore, when the ball is being hit directly ahead the wrist is in more neutral position. Whereas when a CB swing is used the wrist is more flexed. It is possible that the wrist plays a major role in directing the ball across the body during a CB swing. This would possibly allow the shoulder and elbow to remain in mechanically similar positions throughout both the SA and CB swings. No studies have been found that have published any data concerning flexion/extension of the wrist during overhead throwing motions so comparisons to other literature are impossible.
Wrist Ulnar/Radial Deviation

Both radial and ulnar deviations of the wrist were quite variable during each of the three swings (Table 5.13, Table 5.14). Furthermore, little was found in the form of trends between the SA, CB, and OS swings.

Again, no studies have been found that have published any data concerning flexion/extension of the wrist during overhead throwing motions, so comparisons to other literature are impossible.

Hand Speed

The OS swing was typically (5 out of 6 subjects) associated with a slower hand speed than either the SA or the CB swings (Table 5.15, Figure 5.16, Figure 5.17). Furthermore, the SA and CB swings differed very little in this respect and often were associated with maximum hand speeds that were within a few tenths of a m/s of each other. Interestingly, when all of the subject data was combined no differences were seen between any of the swing types.

Regardless, individually, differences in hand speed existed for nearly all subjects, and often the hand speed during OS swings was slower than during either the SA, CB or both. It is possible that this is largely due to the motion of the arm when the OS swing is employed. As shown above, the shoulder is more horizontally abducted during OS swings and this horizontally abducted position may make it difficult to properly transfer a large amount of energy through the kinetic chain to create hand speed. The similarities in hand speed between the SA and CB swings are not surprising considering the mechanical similarities between these two types of swings. Similar mechanics should typically lead to similar end-point speeds, as seen here.
Although hand speeds are often lower during the OS type swing, the hand speed-time graph shapes that are created for each type of swing are very similar (Figure 5.16, Figure 5.17). Rather than having a different shape, the OS swing-related curves simply have lower peaks. This, potentially, indicates a position where smaller and less powerful muscles are used to accelerate the arm, but do so similarly.

Compared to other studies the hand speeds seen in this study are very similar. Hand speeds of approximately 17 m/s were seen in this study, whereas other studies have recorded speeds ranging from 13 m/s to more than 20 m/s (Chung et al., 1990; Coleman et al., 1993; Kugler et al., 1996). Again, these studies all analyzed SA type hits.

An important outcome of this study is that volleyball athletes at the elite level do not necessarily employ the same kinematics to attack a ball when using different attack swings. Not only was the variability between trials within subjects quite high but differences that were very obvious in one subject were often times either non-existent in other subjects or reversed. As such, it is recommended that each athlete at this level be treated as an independent case and dealt with separately with respect to training, injury prevention and rehabilitation.

Although some differences were lost when the subjects’ data were combined, a number of important similarities and differences between the three volleyball attack swings studied did become apparent. Not surprisingly, the OS swings differed from the SA and CB swings by requiring the shoulder to be less horizontally adducted. This presumably allowed the attacker to contact the ball at a position above and laterally to the hitting shoulder allowing it to be hit away from the midline of the body. It is expected that because this awkward position is potentially unstable, it may be responsible for the
decreased hand speed that is present during this type of swing. Few differences were measured between the SA and CB swing types.

Because of the similarities between the SA and CB swing types, it is possible that much of the kinematic differences that propel the ball in a different trajectory are due to either one or a combination of the following: the flexion of the wrist, which was found to differ between the two swing types; small minute differences in each joint that add up to a large overall kinematic difference of the arm as a whole; or from elsewhere in the body, such as the trunk. One possibility is that the trunk is rotated during flight so that the ball can be hit using the same basic kinematics for both swing types. This could possibly explain the similarities in hand speed as well. It is logical that if the same kinematics were used for both swings there would be little difference in the hand speeds and speed-time profiles. The question still remains as to whether the trunk is rotated before, during or after the player leaves the ground in the attack sequence.

It is important to reiterate that subjects were aware of the swing type before the commencement of each trial. So it is possible that the subjects were able to decrease differences between the CB and SA swing types by rotating their bodies during their take-off. In actual game situations this may not always be the case as the attackers may be forced to choose a swing while in the air, a choice based on how the opposing team’s block is set up. More differences may have been evident between the OS swing and the other two swings had the subjects been forced to ‘choose’ a swing type while in midair.

A concerning aspect of the results of the current study involves the large variations seen in a number of the measures. There are a number of possible sources for this. First, although every effort was made to eliminate any trials that were not associated with realistic marker motions, there is a chance some of these may have been missed, and
subsequently included in the analysis. The resulting trajectories were ‘smooth’ and appeared to recreate the actual motion of the subjects when visually inspected by the researchers, however, because software was used to ‘fill’ any gaps in marker trajectories, it is possible that these were not, in fact, representative of the actual movements of the upper limb of the subjects, and increased the variability. With the limited number of cameras used for such a dynamic motion in this study, it was very difficult to recreate a subject’s attack swing with no gaps in marker data. Every effort was made to reduce the amount of gaps, however, and it appears that more cameras would be needed to facilitate this.

Second, it is possible that the current study design did not employ either enough trials and/or subjects. It is possible that with additional subjects and/or trials, variability could have reduced due to any outlying data that was not eliminated from the study. As per the results of the power calculation done prior to the study, it was assumed that this number of trials would be sufficient, however, and the availability of athletes limited the number of subjects available. It is unknown how either of these would, in fact, affect the variability. Finally, it is possible that the volleyball swing is, in fact, extremely variable both between and within subjects, and some subjects are even more variable than others in their mechanics. This could account for some of the large variability seen in this study, especially when between subject data was combined.

As seen in Appendix F, both Cardan angles and Joint Coordinate System approaches were first used to try and calculate the angles of the shoulder, elbow and wrist. Both of these techniques were ineffective in calculating reasonable angles. As such, planar projections were used to calculate these angles. Although this technique gave much more reasonable results there is still some error involved with this method.
However, the angles calculated in this study and those previously published are quite similar. For those joint angles where no previous data has been published (elbow pronation, radial/ulnar deviation of the wrist), it is unknown how reasonable the calculations are. Future studies that also focus on these joint angles may shed more light on the accuracy of these measures.

Because time of ball contact was not known it was difficult to accurately describe the kinematics of the swing with respect to the phases of the swing. Also, because of this, it was not viable to discuss the temporal aspects of the swings. Based on previous academic knowledge, it was still possible to discuss the kinematics analyzed in this study with respect to phases, but only anecdotally. It is possible that certain differences may lie between swings based on when certain kinematic attributes happen with respect to the phases.

The necessity to suspend the ball to protect the cameras may have changed some of each swing’s kinematics. In a normal situation the ball is set and follows a trajectory that would put the ball past the attacker. The attacker must choose the appropriate time to strike the ball. In this study this decision was eliminated as the ball hung motionless above the court in its pre-selected hitting position. Although this may have reduced variability due to setting, it may also have reduced the differences between the swing types.

As mentioned previously, future studies should attempt to take into account the body as a whole when studying the volleyball swing. It is possible that there is too much full body involvement in the volleyball attack sequence for researchers to consider only a small portion of it. In other words, no single part of the body appears to be more crucial than all the others when it comes to generating different attack swings in the sport of
volleyball. With a full body approach it would be possible to discern where the differences between SA and CB swings come from, as it appears that few differences occur in the upper limb. It would also be extremely advantageous to the sport of volleyball for future studies to focus on the potential physiological effects that these swings may have on an elite volleyball player’s shoulder. More pathological knowledge could improve training, and reduce injuries as well as improve rehabilitation programs for volleyball players.
References


Canada: John Wiley & Sons, Inc.
CHAPTER 6 – GENERAL DISCUSSION

The three studies contained herein focused on developing an understanding of volleyball attack swings that have not been described in the scientific literature. Previous studies have focused solely on the straight ahead swing (SA) where the ball is hit above and slightly in front of the hitting shoulder and directed forward. The three studies above gathered new knowledge on swings that have yet to be studied scientifically.

Study #1, entitled An epidemiological analysis of the different arm swing types used in elite levels of men’s volleyball, it was discovered that four distinct swings are used at the elite level: straight ahead (SA); cross-body (CB); outside swing (OS); and outside swing with a net (OSN) (Chapter 3). In the CB swing the ball is hit across the body and directed to the side opposite the hitting arm rather than forward. In the two outside swings the ball is directed to the side of the hitting arm away from the midline of the body. During OS swings the net is not of direct concern to the attacking player and occurs when a right handed player hits from position 4 and when a left handed player hits from position 2. During OSN swings the net is of direct concern to the attacking player and occurs when a right handed player hits from position 2 and when a left handed player hits from position 4.

This first study found that the SA swing was, as expected, the most commonly used swing at the elite volleyball level. CB swings were used significantly more than either OS or OSN swings individually but not more than when the number of OS and OSN swings was combined. Therefore, the CB and ‘outside’ swings are used with approximately the same frequency in elite-level men’s volleyball matches. Due to the study’s limitations the results may not accurately represent the actual frequencies with
which these swings are used. However, the results demonstrate the existence of other swings and give an indication of their frequency. Little is known about the CB, OS and OSN swings and the next step was to determine the ball speeds attained using these different arm swings.

The second study, entitled *An analysis of the resulting velocities of balls struck using kinematically different volleyball attack swings*, accurately measured the ball velocities that elite-level male volleyball players were able to create during an attack using these four swings (Chapter 4). We suspected that upper body rotation and the large horizontal adductor muscles associated with the CB swing would help the CB swing produce the highest ball velocities. The SA and CB swings did produce the highest velocities but there was no difference between them. The large amount of forward rotational torque that can be created by the abdominals during the SA swing may offset the activity of the horizontal adductor muscles in the CB swing. The need to bring the arm across the body in the CB swing may reduce the forceful contraction of the abdominal flexors in favour of the longitudinal rotators. Also, the OS ball speed was faster than OSN which is likely because the player must consider the net with respect to the path of the arm. Since the velocities were different among the swings the next step was to analyze the kinematics of different swings and look for similarities and differences.

The third and final study, entitled *A kinematic analysis of various attack spike arm motions commonly utilized in the sport of volleyball*, examined the kinematic differences between three of the four swing types (SA, CB, and OS) (Chapter 5). A number of interesting differences and unexpected similarities were found. Specifically, the SA and CB swings were very similar regardless of their resulting ball trajectory. The only
difference between the CB and SA swings was that CB swings had a higher peak wrist flexion angle than SA swings. This suggests that these swings are kinematically similar while the previous study showed that the resulting ball speeds from these swings were similar as well. The difference in ball trajectory might be explained either by wrist flexion or by a difference that was not measured, such as trunk rotation. Regardless, because of the similarities between these two swings the results of the second study are understood; if the kinematics of the swings are similar, logically, the resulting ball velocities should be as well.

The biggest kinematic differences were found between the OS and both the CB and SA swings. During the OS swing the shoulder was less horizontally adducted than during the SA swing. This allowed the ball to be hit anterior and lateral to the hitting shoulder. The potential instability and lack of strength in this awkward position is most likely responsible for the low ball speed seen in Study #2. More research would need to be done to test this. Additionally, CB swings were associated with more external rotation than OS swings. This is thought to be a result of the extra trunk rotation needed to hit a ball across one’s body while using the same kinematics as the SA swing. This increased maximum external rotation seen during CB swings could have some pathological consequences.

Although only a few differences were found between the SA, CB and OS swing types, it is possible that with a larger subject pool more differences between these swings could become apparent. This is largely due to the fact that individually, differences were often found between the swings, but when all of the data was combined, the variation between the swings was too large. However, as shown in Chapter 2, there is a large amount of kinematic variability of the upper arm in high level players during the
acceleration phase of the swing. It is possible that this variability is substantial enough to make finding differences between athletes/swings difficult.

It is also likely that some measurement errors such as visually selecting marker data based on the smoothness of it’s trajectory may have led to some of the large variability seen in this study. Also, future studies should analyze the body as a whole when comparing the three arm swings. The findings of this project demonstrate that no single part of the body is entirely responsible for an attack at the elite level.
APPENDIX A

Study #1 – Statistical Analysis Results

NPar Tests

Mann-Whitney Test

Ranks

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Test Statistics\(^b\)

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\(^a\) Not corrected for ties.

\(^b\) Grouping Variable: type

NPar Tests

Mann-Whitney Test

Test Statistics\(^b\)

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\(^a\) Not corrected for ties.

\(^b\) Grouping Variable: type

NPar Tests
Mann-Whitney Test

Ranks

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\(^a\) Not corrected for ties.
\(^b\) Grouping Variable: type

NPar Tests

Mann-Whitney Test

Ranks

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<sup>a</sup> Not corrected for ties.

<sup>b</sup> Grouping Variable: type

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### NPar Tests

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#### Mann-Whitney Test

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<sup>a</sup> Not corrected for ties.

<sup>b</sup> Grouping Variable: type
### Ranks

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\(^a\) Not corrected for ties.  
\(^b\) Grouping Variable: type
APPENDIX B

Study #2 - Letter of Information and Consent

Letter of Information & Consent Form

An analysis of the resulting velocities and accelerations of balls struck using kinematically different volleyball attack swings

Dear ______________________________

You are being invited to participate in a research study that involves elite volleyball players and attempts to determine differences in ball velocity between four separate spiking motions. These include the straight ahead, cross-body, outside without net interference and outside with net interference attacks. They are common motions used in the sport of volleyball. Participants can drop out at any time without any risk of penalties, and all participant information will be kept in strict confidence. You are asked to review this consent form with the researcher, so that he can explain all of the procedures in full detail. Please feel free to ask questions at any time.

Purpose and Aims of the Study:
This study is being conducted as part of a biomechanics master’s thesis. Because little is known about the spiking motion, this study will attempt to examine the differences, if any, between resulting ball velocity and four different spiking motions (explained above). To do this, participants will be asked to spike standard size and weight men’s volleyballs to specific areas of the court at predetermined approach angles. This will facilitate participants in using the proper attack motion being analyzed. The findings of this study will increase our knowledge of varying arm swings, and will then be used in a future study looking at the kinematics of each of the four different types of spike motions. The purposes of this study are as follows:

1. To further our current knowledge of the sport of volleyball and, more specifically, differences between varying arm swings.
2. To determine the differences in resulting ball velocity when various spiking motions are employed.

Procedures during Testing
A full sized volleyball court with the net set at the men’s height will be used throughout this study. Official CIS approved volleyballs will be used in all trials. A volleyball setting machine will be used which will allow the volleyballs to be ‘set’ identically each time. This will
remove setting variability and allow proper timing by the subjects in each of the trials. Subject trials will be filmed using a high speed digital video camera.

Subjects will have a full warm-up prior to any of the trials. Trials will be grouped into types, with five trials for each of the cross-body, straight ahead, outside without net, and outside with net swings. This will result in a total of 20 trials per subject. Because the camera and lighting equipment must be rearranged to accurately capture each swing type, swing types, not trials, will be randomized. All trials within that group will be done consecutively and then subjects will move onto the next randomized trial type. Subjects will be asked to hit balls to specific areas using predetermined approaches at a near maximal attack power. Predetermined approaches and targets will allow the camera to remain perpendicular to the plane in which the ball travels. Therefore, each trial will require the subject to approach in a predetermined direction, spike a ball over a standard sized net at near maximum velocity, and attempt to hit a target on the opposite side of the net, while not coming in contact with the net. Balls will be set by a volleyball setting machine that can replicate ball trajectory for each set. This will reduce the variability of the sets compared to a human setter. If the subject fails to hit the ball to the desired area, or comes in contact with the net the trial will not be used and the subject will be asked to attempt the trial again. Once all trials within a type are complete the camera and lighting will be moved to the designated area for the next trial type. Subjects will be given as much time as necessary between trials to ensure they do not fatigue.

The entire data collection process should take about an hour and a half.

Risks of Participation

As with all athletic-type movements requiring strength and coordination there are inherent risks associated with any study requiring these types of forceful movements. Due to the volleyball-related level of the athletes participating in this study, the risks should be no greater than those encountered in a regular set of practice or game spikes. Although subjects will be asked to spike the ball with maximal force, they will be given as much warm-up and rest as needed so that they do not fatigue or increase the chances of injury. Furthermore, it is not expected that subjects will have to spike the ball more than about 40 times in total, which accounts for hitting errors. Finally, participants are encouraged to stop at any time if any pains or aches emerge, or in the case of dizziness or nausea.

Participants may have a stiff back, abdominals or shoulders the next day due to muscle fatigue caused by lactic acid build-up, depending on their level of conditioning. This pain or stiffness should disappear within two days. If this pain or stiffness does not disappear, please contact the principal investigator immediately.

Benefits of Participation:

Participants of this study will have the benefit of contributing to the academic knowledge concerning the sport of volleyball. This could lead to improved training and increased skill level of future athletes in this sport. Additionally, participation will give the subjects a chance to learn about data collection, and the scientific process themselves.

Exclusion Criteria:

To minimize the risk of injury during this study, we are excluding anyone who currently has any shoulder, back or abdominal pain, or anyone that has had shoulder, back or abdominal pains in the last 6 months. Additionally, anyone that has had shoulder surgery on their dominant volleyball shoulder will also be excused from this study. Finally, due to the inherent differences that have been found between the kinematics of males and females, only males will be included in this study.

Confidentiality:
As the principal investigator, I will maintain confidentiality of all information collected. Your data will be collected and stored by a subject number. All files will be stored without names on secure password-protected computers and your data will be destroyed immediately on completion of the study.

**Voluntary Nature of the Study:**
Your participation in this study is completely voluntary and is not a required part of your student status. Please be aware that investigators will be providing encouragement for you to give a maximal effort when needed. However, stopping the testing protocol is still under your control. You may withdraw from this study at any time without penalty or coercion. Your data will be removed if you wish it withdrawn. Decisions to withdraw will have no effect on your current academic standings as a student.

**Liability:**
By signing the consent form, you do NOT waive your legal rights nor release the investigator(s) from their legal and professional responsibilities.

**Subject Statement and Signature:**
As a volunteer participant, I have read and understand the consent form for this study. The purposes, procedures and technical language have been explained to me. I have been given sufficient time to consider the above information and understand that I may withdraw if I choose to do so. I have had the opportunity to ask questions which have been answered to my satisfaction. I understand that my participation is in confidence to the investigators of this study only. I am voluntarily signing this consent form below. I will receive a copy of this consent form for future reference.

If I am dissatisfied with any aspect of the study, or have questions, concerns or adverse events, I have been encouraged to contact the principal investigator Marek Plawinski at (613) 583-0969 (9mpp1@qlink.queensu.ca), Dr. Pat Costigan at (613) 533-6603 (pat.costigan@queensu.ca); or the General Research Ethics Board at (613) 533-6081. (fridl@post.queensu.ca).

By signing this consent form, I am indicating that I agree to participate in this volleyball-based research study.

Signature of Subject      Date

By signing this consent form, I confirm that I have carefully explained the nature of the above research study to the subject. I certify that, to the best of my knowledge, the subject understands clearly the nature of the study and the demands, benefits, and risks involved to participants in this study.

Signature of Witness      Date
APPENDIX C

RADAR Gun Accuracy Test

To test the accuracy of the RADAR gun used in the study entitled An analysis of the resulting velocities of balls struck using kinematically different volleyball attack swings, the RADAR gun was used simultaneously with a high-speed digital video camera to measure (RADAR gun) and calculated (high-speed digital video camera) the velocities of struck balls. A researcher with the RADAR gun stood behind a mesh netting through which readings could easily be made by the RADAR gun, but which protected both the researcher and equipment. A researcher who was a former elite-level volleyball player hit balls while standing on the ground at the target area in front of the RADAR gun, while a high speed digital video camera was stationed perpendicular to the plane of the ball trajectory at a known distance. A calibration frame was positioned in the plane of the ball flight, so that video data could be later calibrated with a high level of accuracy. After each hit, the measured ball velocity was recorded, and the flight of the ball was digitally stored on a computer. Ten trails were measured by the RADAR gun and recorded on video. Spike effort was chosen so that a wide range of speeds could be tested. Also, two hits were chosen to test how much error was involved with ball trajectories that did not closely coincide with the RADAR gun’s ‘sweet spot’. These balls were hit about five feet to either side of the target area.

Once all 10 trials were complete, video data was analyzed on a digital motion analysis program, and linear displacements were calculated. The resulting data was then used to calculate the velocity of the ball during mid-flight. These velocities were then compared to the measured ball velocities gathered from the RADAR gun (Table C1). A difference of only 1.2 km/h (2.2 %) was present between the two methods of measuring ball speed. Also, as expected, the two hits that were directed away from the RADAR gun target area (trials number 6 and 8) had a greater video data to RADAR data difference associated with them than most of the other trials. This finding necessitated balls to be hit relatively close to the target area during the study so that accuracy of the measuring equipment could remain high.
Table C1 – Ball velocity data measured using the RADAR gun and calculated using a high speed digital video camera. Ball spike intensity was chosen so that a full range of ball velocities could be tested. Also, trials number 6 and 8 were hit approximately five feet to the left and right of the target area (directly in front of the RADAR gun) respectively.

<table>
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<th>TRIAL</th>
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<th>Video (km/h)</th>
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AVERAGE: 1.2 2.2

With such a small difference between these two sources, it was deemed that the RADAR gun was easier to use and just as accurate as using the high speed digital video camera. As such it was used in all trials throughout Study #2.
APPENDIX D

Study #2 – Statistical Analysis Results

Velocity Data

General Linear Model

Within-Subjects Factors

Measure: MEASURE_1

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Descriptive Statistics

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a. Exact statistic

b. Design: Intercept
   Within Subjects Design: factor1
Mauchly's Test of Sphericity

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Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

- a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.
- b. Design: Intercept
  Within Subjects Design: factor1

Tests of Within-Subjects Effects

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Tests of Between-Subjects Effects

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Estimated Marginal Means

factor1

Estimates

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Pairwise Comparisons

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<td>1.217</td>
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Based on estimated marginal means

^{*}: The mean difference is significant at the .05 level.

^{a}: Adjustment for multiple comparisons: Bonferroni.
Multivariate Tests

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<th>Value</th>
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</table>

Each F tests the multivariate effect of factor1. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

- a. Exact statistic

Normalized Data

General Linear Model

Within-Subjects Factors

Measure: MEASURE_1

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Descriptive Statistics

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Multivariate Tests

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- a. Exact statistic
- b.

- Design: Intercept
- Within Subjects Design: factor1

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**Mauchly's Test of Sphericity**

<table>
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<tr>
<th>Within Subjects Effect</th>
<th>Mauchly's W</th>
<th>Approx. Chi-Square</th>
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Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept
   Within Subjects Design: factor1

**Tests of Within-Subjects Effects**

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**Tests of Between-Subjects Effects**

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Estimated Marginal Means

factor1

Estimates

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Pairwise Comparisons

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Based on estimated marginal means

* The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.
### Multivariate Tests

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<td>.000</td>
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</tbody>
</table>

Each F tests the multivariate effect of factor 1. These tests are based on the linearly independent pairwise comparisons among the estimated marginal means.

a. Exact statistic
APPENDIX E

Study #3 – Power Calculation

To calculate the minimum number of subjects needed for the third study, a power calculation was done using the ball speed results from the second study. Using the average speeds and standard deviations for all four swings, F-scores and effect sizes were calculated comparing each of the means (Table D1). These values were then used to determine appropriate N values for Study #3 using tables (Stevens, 1999). With a confidence level of 90% and an $\alpha$ of 0.05, it was determined that difference should be seen in the third study between all swings except CB and SA using approximately 5 subjects.

Table D1 – Calculated F-scores and effect sizes comparing each of the four swings using the mean speeds and standard deviations from Study #2. These values were then used to determine appropriate N values for Study #3. CB – cross body, SA – straight ahead, OS – outside swing with no net, OSN – outside swing with net.

<table>
<thead>
<tr>
<th></th>
<th>CB-SA</th>
<th>SA-OS</th>
<th>OS-OSN</th>
<th>CB-OSN</th>
<th>CB-OS</th>
<th>SA-OSN</th>
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<td>36.9</td>
<td>128</td>
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<tr>
<td>Effect Size ($f$)</td>
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<td>1.81</td>
<td>1.15</td>
<td>2.59</td>
<td>1.43</td>
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</table>

APPENDIX F

Study #3 - Letter of Information and Consent

Letter of Information & Consent Form

A kinematic analysis of various attack spike arm motions commonly utilized in the sport of volleyball

Dear ________________________________

You are being invited to participate in a research study that involves elite volleyball players and attempts to analyze different spiking motions often utilized in the sport of volleyball. These motions include the straight ahead, cross-body, outside without net interference and outside with net interference attacks. You can drop out of this study at any time without any risk of penalties, and all participant information will be kept in strict confidence. You are asked to review this consent form with the researcher, so that he can explain all of the procedures in full detail. Please feel free to ask questions at any time.

Purpose and Aims of the Study:

This study is being conducted as part of a biomechanics master’s thesis. Because little is known about the spiking motion, this study will attempt to examine the kinematic differences between four different spiking motions (explained above). To do this, you will be asked to spike standard size and weight men’s volleyballs to specific areas of the court at predetermined approach angles. This will facilitate you in using the proper attack motion being analyzed. The findings of this study will increase our knowledge of varying arm swings which have been shown to be commonly used in the sport. The purposes of this study are as follows:

3. To further current knowledge of the sport of volleyball and, more specifically, differences between various arm swings.
4. To develop a spiking motion model that will take into account the full range of shoulder spiking positions employed by elite level volleyball players.
5. To develop a phase definition system so that future researchers in this area will be able to properly identify certain phases of the spiking motion.
6. To possibly link certain volleyball-related pathologies to specific spiking motions utilized by volleyball players.

Procedures during Testing

A full sized volleyball court with the net set at the men’s height will be used throughout this study. Official CIS approved volleyballs will be used in all trials. A volleyball setting
machine will be used which will allow the volleyballs to be ‘set’ identically each time. This will remove setting variability and make it easier for you to have proper timing in each of the trials. So that real-time positional data can be attained of certain parts of the body, a digital motion tracking system will be used. This system will record the positions of reflective markers placed on a number of locations on your body throughout each of the trials. These markers are non-invasive and require only a small amount of adhesive to remain attached to their specific point after which they can be easily removed. An additional digital video camera will be used as a recording device so that arm swing types can be monitored.

In addition to this, you may be asked to be fitted with surface electromyographic (EMG) electrodes for the duration of the study so that muscle activity information may be gathered throughout the hitting trials. This will only serve as supplementary information, and is not the primary focus of the study. Surface electrode EMG will be collected from the following seven (7) muscles: anterior and posterior deltoids, trapezius, pectoralis major, infraspinatus, latissimus dorsi and triceps brachii. Using surface electrodes means that this system will be non-invasive and extremely safe.

You will be allowed to have a full warm-up prior to any of the trials. There will be five trials per type of attack (cross body, straight ahead, outside swing with no net, outside swing with net) making 20 hitting trials, all of which will be randomized. You will be asked to hit volleyballs at near maximal attack power to specific areas using predetermined approaches. Predetermined approaches will allow the researchers to monitor the swing types you perform more effectively. Therefore, each trial will require you to approach in a predetermined direction, spike a ball over a standard sized net at near maximum velocity, and attempt to hit a target on the opposite side of the net, while not coming in contact with the net. Balls will be set by a volleyball setting machine that can replicate ball trajectory for each set. This will reduce the variability of the sets compared to a human setter. If you fail to hit the ball to the desired area or to use the desired swing type, that trial will not be counted and you will be asked to attempt the trail again. You will be given as much time as necessary so that you do not fatigue throughout the trials.

The entire data collection process should take about 2 hours.

Risks of Participation

As with all athletic-type movements requiring strength and coordination there are inherent risks associated with any study requiring these types of forceful movements. Due to the volleyball-related level of the athletes participating in this study, the risks should be no greater than those encountered in a regular set of practice or game spikes, and in fact, should be lower. Although you will be asked to spike the ball with maximal force, you will be given as much warm-up and rest as needed so that you do not fatigue or increase the chances of injury.

The reflective markers being used in this study will not affect your movements in any way, and therefore, there is no risk of injury as a result of their use. The electromyographic (EMG) system that may be used in this study will require sticky electrodes to be placed on seven muscles in and around your dominant shoulder. It is rare that the gel used to adhere the electrodes to your skin may cause irritation, however, if this problem does occur, it is commonly very slight and should pass within a few days. The EMG system does require wires to trail behind you throughout the trials. These wires are, however, very long and should pose no risk of restricted movement or injury during successive trials.

It is not expected that subjects will have to spike the ball more than about 40 times in total, which accounts for hitting errors. This is less than the number of times you are often required to hit in a regular set of practices or games. Finally, you are encouraged to stop at any time if any pains or aches emerge, or in the case of dizziness or nausea.

You may have a stiff back, abdominals or shoulders the next day due to muscle fatigue caused by lactic acid build-up, depending on their level of conditioning. This pain or stiffness
should disappear within two days. If this pain or stiffness does not disappear, please contact the principal investigator immediately.

**Benefits of Participation:**
There are no direct benefits to participating in this study.

**Exclusion Criteria:**
To minimize the risk of injury during this study, we are excluding anyone who currently has any shoulder, back or abdominal pain, or anyone that has had shoulder, back or abdominal pains in the last 6 months. Additionally, anyone that has had shoulder surgery on their dominant volleyball shoulder will also be excused from this study. Finally, due to the inherent differences that have been found between the kinematics of males and females, only males will be included in this study.

**Confidentiality:**
As the principal investigator, I will maintain confidentiality of all information collected. Your data will be collected and stored by a subject number. All files will be stored without names on secure password-protected computers and your data will be destroyed immediately on completion of the study.

**Voluntary Nature of the Study:**
Your participation in this study is completely voluntary and is not a required part of your student status. Please be aware that investigators will be providing encouragement for you to give a maximal effort when needed, however, stopping the testing protocol is still under your control. You may withdraw from this study at any time without penalty or coercion. Your data will be removed if you wish it withdrawn. Decisions to withdraw will have no effect on your current academic standings as a student or your current status as an athlete.

**Liability:**
By signing the consent form, you do NOT waive your legal rights nor release the investigator(s) from their legal and professional responsibilities.

**Subject Statement and Signature:**
As a volunteer participant, I have read and understand the consent form for this study. The purposes, procedures and technical language have been explained to me. I have been given sufficient time to consider the above information and understand that I may withdraw if I choose to do so. I have had the opportunity to ask questions which have been answered to my satisfaction. I understand that my participation is in confidence to the investigators of this study only. I am voluntarily signing this consent form below. I will receive a copy of this consent form for future reference.

If I am dissatisfied with any aspect of the study, or have questions, concerns or adverse events, I have been encouraged to contact the principal investigator Marek Plawinski at (613) 583-0969 (9mpp1@qlink.queensu.ca), Dr. Pat Costigan at (613) 533-6603 (pat.costigan@queensu.ca); or the director of the School of Kinesiology and Health Studies, Dr. Jean Cote, at (613) 533-6601 (jc46@post.queensu.ca). Finally, if you have any concerns about your rights as a research subject, please contact Dr. Albert Clark, Chair of the Queen’s University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board at (613) 533-6081.
By signing this consent form, I am indicating that I agree to participate in this volleyball-based research study.

________________________  __________________________
Signature of Subject       Date

By signing this consent form, I confirm that I have carefully explained the nature of the above research study to the subject. I certify that, to the best of my knowledge, the subject understands clearly the nature of the study and the demands, benefits, and risks involved to participants in this study.

________________________  __________________________
Signature of Witness       Date
APPENDIX

Study #3 – Planar Projection MatLab Code

UpperLimbModel.m

function [alpha_shoulder, beta_shoulder, alpha_elbow, beta_elbow, gamma_elbow, alpha_wrist, beta_wrist, gamma_wrist] ... = UpperLimbModel;

% Create 'parameter' matrix containing all required parameters for each subject
parameter = XLSread('study3.xls');

% Create 'filtfreq' matrix containing all required filter frequencies attained with a residual analysis (Residual_UL.m)
% Each row represents a subject (S01, S02, etc.) and each column represents a calculated angle (alpha_shoulder, beta_shoulder, etc.)
filtfreq = XLSread('residual.xls');

% Loop for each of the 126 data files
for i = 1:126
    disp('');
    % Extract and create reference, file, and endfile names as well as handedness of subject
    refname = [num2str(parameter(i,1)) '.txt'];
    filename = [num2str(parameter(i,2)) '.txt'];
    filenum = parameter(i,2);
    endfilename = [num2str(0) num2str(parameter(i,2)) '.xls'];
    filestart = parameter(i,3);
    fileend = parameter(i,5);
    handed = parameter(i,6);
    disp(filename);

    % Calibration procedure
    disp('Starting calibration procedure')
    [RTM_trunk, RTM_upperarm, RTM_lowerarm, RTM_hand] = Calibrate_CS(refname);
    disp('Calibration procedure complete')

    % Read data and separate
    disp('Starting read-data procedure')
    [p1_trunk, p2_trunk, p3_trunk, p1_upperarm, p2_upperarm, p3_upperarm, p1_lowerarm, p2_lowerarm, p3_lowerarm, ...
    p1_hand, p2_hand, p3_hand] = Read_ULdata(filename, filestart, fileend);
    disp('Read-data procedure complete')

    % Calculate instantaneous speed and acceleration of most distal marker (p2_hand)
    disp('Starting hand speed and acceleration calculation')
    [speed, axel] = Speed_UL(filenum, p2_hand);
    disp('Speed_Ul calculation complete')

    % Write maxspeed for each subject to single file
    maxspeed(1,i) = speed(1,1);
    maxspeed(2,i) = speed(1,2);

    disp('');
disp('Hand speed and acceleration calculation complete')

% Joint angle calculation using planar projections
disp('Starting planar projection procedure')
[beta_shoulder, gamma_shoulder, alpha_shoulder, beta_elbow, alpha_elbow, beta_wrist, alpha_wrist] ...
= Planar_UL(RTM_trunk, RTM_upperarm, RTM_lowerarm, RTM_hand, p1_trunk, p2_trunk, ...
p3_trunk, p1_upperarm, ...
p2_upperarm, p3_upperarm, p1_lowerarm, p2_lowerarm, p3_lowerarm, p1_hand, p2_hand, p3_hand, ...
filename, handed);
disp('Planar projection procedure complete')

% Conduct residual analysis on each calculated angle for all swings per subject
%disp('Starting residual analysis')
%Residual_UL(axel);
%disp('Residual analysis complete')

% Filter calculated angles using frequencies attained from residual analysis
disp('Starting filtering procedure')
[beta_shoulder, gamma_shoulder, alpha_shoulder, beta_elbow, alpha_elbow, beta_wrist, alpha_wrist] ...  
= Filter_UL(beta_shoulder, gamma_shoulder, alpha_shoulder, beta_elbow, alpha_elbow, beta_wrist, ...
alpha_wrist, i, filtfreq);
disp('Filter procedure complete')

% Determine maximum/minimums for certain calculated anlges
disp('Starting max/min procedure')
[mmas, mmbhs, mmgs, mmae, mmbw, mmbw] = Maxmin_UL(beta_shoulder, gamma_shoulder, ...
alpha_shoulder, ...
beta_elbow, alpha_elbow, beta_wrist, alpha_wrist, i, filenum);
if (filenum > 1.1 & filenum < 1.2) | (filenum > 2.1 & filenum < 2.2) | (filenum > 3.1 & filenum < 3.2) | ...
  (filenum > 4.1 & filenum < 4.2) | (filenum > 5.1 & filenum < 5.2) | (filenum > 6.1 & filenum < 6.2)
mmaalpha_shoulder(1:4,i) = mmas; mmbeta_shoulder(1:4,i) = mmbhs; mmgamma_shoulder(1:4,i) = mmgs;
mmaalpha_shoulder(1:4,i) = mmas;
mmbeta_shoulder(1:4,i) = mmbhs; mmgamma_shoulder(1:4,i) = mmgs;
mmaalpha_shoulder(6:9,i-7) = mmas; mmbeta_shoulder(6:9,i-7) = mmbhs; mmgamma_shoulder(6:9,i-7) = mmgs;
mmbeta_shoulder(6:9,i-7) = mmbhs; mmaalpha_shoulder(6:9,i-7) = mmas;
mmbeta_shoulder(6:9,i-7) = mmbhs; mmgamma_shoulder(6:9,i-7) = mmgs;
mmbeta_shoulder(6:9,i-7) = mmbhs; mmaalpha_shoulder(6:9,i-7) = mmas;
mmbeta_shoulder(6:9,i-7) = mmbhs; mmgamma_shoulder(6:9,i-7) = mmgs;
mmbeta_shoulder(6:9,i-7) = mmbhs; mmaalpha_shoulder(6:9,i-7) = mmas;
mmbeta_shoulder(6:9,i-7) = mmbhs; mmgamma_shoulder(6:9,i-7) = mmgs;
mmbeta_shoulder(6:9,i-7) = mmbhs; mmaalpha_shoulder(6:9,i-7) = mmas;
mmbeta_shoulder(6:9,i-7) = mmbhs; mmgamma_shoulder(6:9,i-7) = mmgs;
mmaalpha_shoulder(11:14,i-14) = mmas; mmbeta_shoulder(11:14,i-14) = mmbhs;
mmaalpha_shoulder(11:14,i-14) = mmas; mmbeta_shoulder(11:14,i-14) = mmbhs;
mmaalpha_shoulder(11:14,i-14) = mmas; mmbeta_shoulder(11:14,i-14) = mmbhs;
mmaalpha_shoulder(11:14,i-14) = mmas; mmbeta_shoulder(11:14,i-14) = mmbhs;
mmbeta_shoulder(11:14,i-14) = mmbhs;
mmaalpha_shoulder(11:14,i-14) = mmas; mmbeta_shoulder(11:14,i-14) = mmbhs;
mmbeta_shoulder(11:14,i-14) = mmbhs;
mmbeta_shoulder(11:14,i-14) = mmbhs;
mmbeta_shoulder(11:14,i-14) = mmbhs;
end
disp('Max/min procedure complete')

% Write calculated data
disp('Writing planar projection data')
[UL_data] = Write_ULdata(beta_shoulder, gamma_shoulder, alpha_shoulder, beta_elbow, alpha_elbow, ...
beta_wrist, alpha_wrist, handed, endfilename, filenum, speed, axel);
disp('Writing planar projection data complete')

% Determine mean angles throughout swing
disp('Starting mean angle procedure')
tempUL = UL_data(:,4:length(UL_data));
meanangles(:,i) = mean(tempUL,2);
disp('Mean angle procedure complete')

end

disp(' ')

% Write other data
disp('Writing other data')
DLMwrite('MaxSpeed.xls', maxspeed, '	');
DLMwrite('mmalpha_shoulder.xls', mmalpha_shoulder, '	');
DLMwrite('mmbeta_shoulder.xls', mmbeta_shoulder, '	');
DLMwrite('mmgamma_shoulder.xls', mmgamma_shoulder, '	');
DLMwrite('mmalpha_elbow.xls', mmalpha_elbow, '	');
DLMwrite('mmbeta_elbow.xls', mmbeta_elbow, '	');
DLMwrite('mmalpha_wrist.xls', mmalpha_wrist, '	');
DLMwrite('mmbeta_wrist.xls', mmbeta_wrist, '	');
DLMwrite('meanangles.xls', meanangles, '	');
disp('Writing other data complete')

disp(' ')

Calibrate_CS.m

function [RTM_trunk, RTM_upperarm, RTM_lowerarm, RTM_hand] = Calibrate_CS(refname);

% Read ASCII files for coordinate data ignoring first line (DLM is (0,0) based so (1,0) is second row, first
% column)
% Can be .txt or .dat extensions
CalData = DLMread(refname,'\t',1,2);

% Separate out coordinate system for each segment array marker and calculate mean
% (trunk(p1,p2,p3), upperarm(p1,p2,p3), lowerarm(p1,p2,p3), hand(p1,p2,p3)
% p3_lowerarm = p1_hand
% Trunk
  p1_trunk = mean(CalData(:,1:3),1); p2_trunk = mean(CalData(:,31:33),1); p3_trunk =
  mean(CalData(:,7:9),1);
% Upper Arm
  p1_upperarm = mean(CalData(:,19:21),1); p2_upperarm = mean(CalData(:,22:24),1); p3_upperarm =
  mean(CalData(:,10:12),1);
% Lower Arm
  p1_lowerarm = mean(CalData(:,16:18),1); p2_lowerarm = mean(CalData(:,25:27),1); p3_lowerarm =
  mean(CalData(:,28:30),1);
% Hand
  p1_hand = mean(CalData(:,28:30),1); p2_hand = mean(CalData(:,13:15),1); p3_hand =
  mean(CalData(:,4:6),1);
Calculate unit vectors for each array (trunk, upperarm, lowerarm, hand) in calibration frame

(i=mediolateral axis, j=anteroposterior axis, k=longitudinal axis)

% Adapted from 'Research Methods in Biomechanics', (2004), pg. 42-44.

% Trunk
\[ i_{\text{trunk}} = \frac{\text{cross}(p_3_{\text{trunk}}-p_1_{\text{trunk}}, p_2_{\text{trunk}}-p_1_{\text{trunk}})}{\text{norm}(\text{cross}(p_3_{\text{trunk}}-p_1_{\text{trunk}}, p_2_{\text{trunk}}-p_1_{\text{trunk}}))}; \]
\[ k_{\text{trunk}} = \frac{p_1_{\text{trunk}}-p_2_{\text{trunk}}}{\text{norm}(p_1_{\text{trunk}}-p_2_{\text{trunk}})}; \]
\[ j_{\text{trunk}} = \text{cross}(k_{\text{trunk}}, i_{\text{trunk}}); \]

% Upper Arm
\[ i_{\text{upperarm}} = \frac{\text{cross}(p_2_{\text{upperarm}}-p_1_{\text{upperarm}}, p_3_{\text{upperarm}}-p_1_{\text{upperarm}})}{\text{norm}(\text{cross}(p_2_{\text{upperarm}}-p_1_{\text{upperarm}}, p_3_{\text{upperarm}}-p_1_{\text{upperarm}}))}; \]
\[ k_{\text{upperarm}} = \frac{p_2_{\text{upperarm}}-p_1_{\text{upperarm}}}{\text{norm}(p_2_{\text{upperarm}}-p_1_{\text{upperarm}})}; \]
\[ j_{\text{upperarm}} = \text{cross}(k_{\text{upperarm}}, i_{\text{upperarm}}); \]

% Lower Arm
\[ i_{\text{lowerarm}} = \frac{p_2_{\text{lowerarm}}-p_1_{\text{lowerarm}}}{\text{norm}(p_2_{\text{lowerarm}}-p_1_{\text{lowerarm}})}; \]
\[ k_{\text{lowerarm}} = \frac{p_3_{\text{lowerarm}}-p_1_{\text{lowerarm}}}{\text{norm}(p_3_{\text{lowerarm}}-p_1_{\text{lowerarm}})}; \]
\[ i_{\text{lowerarm}} = \frac{\text{cross}(k_{\text{lowerarm}}, i_{\text{lowerarm}})}{\text{norm}(\text{cross}(k_{\text{lowerarm}}, i_{\text{lowerarm}}))}; \]
\[ j_{\text{lowerarm}} = \text{cross}(k_{\text{lowerarm}}, i_{\text{lowerarm}}); \]

% Hand
\[ i_{\text{hand}} = \frac{\text{cross}(p_1_{\text{hand}}-p_3_{\text{hand}}, p_1_{\text{hand}}-p_2_{\text{hand}})}{\text{norm}(\text{cross}(p_1_{\text{hand}}-p_3_{\text{hand}}, p_1_{\text{hand}}-p_2_{\text{hand}}))}; \]
\[ j_{\text{hand}} = \frac{p_3_{\text{hand}}-p_1_{\text{hand}}}{\text{norm}(p_3_{\text{hand}}-p_1_{\text{hand}})}; \]
\[ k_{\text{hand}} = \frac{\text{cross}(i_{\text{hand}}, j_{\text{hand}})}{\text{norm}(\text{cross}(i_{\text{hand}}, j_{\text{hand}}))}; \]

Calculate reference coordinate system for each segment

% Trunk
\[ \text{RefCS}_{\text{trunk}} = [-i_{\text{trunk}}(1,2) -j_{\text{trunk}}(1,2) -k_{\text{trunk}}(1,2); i_{\text{trunk}}(1,1) j_{\text{trunk}}(1,1) k_{\text{trunk}}(1,1); i_{\text{trunk}}(1,3) j_{\text{trunk}}(1,3) k_{\text{trunk}}(1,3)]; \]

% Upper Arm
\[ \text{RefCS}_{\text{upperarm}} = [-i_{\text{upperarm}}(1,2) -j_{\text{upperarm}}(1,2) -k_{\text{upperarm}}(1,2); i_{\text{upperarm}}(1,1) j_{\text{upperarm}}(1,1) k_{\text{upperarm}}(1,1); i_{\text{upperarm}}(1,3) j_{\text{upperarm}}(1,3) k_{\text{upperarm}}(1,3)]; \]

% Lower Arm
\[ \text{RefCS}_{\text{lowerarm}} = [-i_{\text{lowerarm}}(1,2) -j_{\text{lowerarm}}(1,2) -k_{\text{lowerarm}}(1,2); i_{\text{lowerarm}}(1,1) j_{\text{lowerarm}}(1,1) k_{\text{lowerarm}}(1,1); i_{\text{lowerarm}}(1,3) j_{\text{lowerarm}}(1,3) k_{\text{lowerarm}}(1,3)]; \]

% Hand
\[ \text{RefCS}_{\text{hand}} = [-i_{\text{hand}}(1,2) -j_{\text{hand}}(1,2) -k_{\text{hand}}(1,2); i_{\text{hand}}(1,1) j_{\text{hand}}(1,1) k_{\text{hand}}(1,1); i_{\text{hand}}(1,3) j_{\text{hand}}(1,3) k_{\text{hand}}(1,3)]; \]

Calculate rotation matrix for RefCS for each segment

% Trunk
\[ \text{RTM}_{\text{trunk}} = \text{inv} (\text{RefCS}_{\text{trunk}}); \]

% Upper Arm
\[ \text{RTM}_{\text{upperarm}} = \text{inv} (\text{RefCS}_{\text{upperarm}}); \]
% Lower Arm
RTM_lowerarm = inv(RefCS_lowerarm);

% Hand
RTM_hand = inv(RefCS_hand);

Read_ULdata.m

function [p1_trunk, p2_trunk, p3_trunk, p1_upperarm, p2_upperarm, p3_upperarm, p1_lowerarm, p2_lowerarm, p3_lowerarm, ... p1_hand, p2_hand, p3_hand] = ReadUL_data(filename, filestart, fileend);

% Read ASCII files for coordinate data ignoring first two lines
SubData = dlmread(filename,'\t',[filestart 2 fileend 34]);

% Separate out coordinate system for each segment array marker (trunk(p1,p2,p3), upperarm(p1,p2,p3), lowerarm(p1,p2,p3), hand(p1,p2,p3)
% Trunk
p1_trunk = SubData(:,1:3); p2_trunk = SubData(:,31:33); p3_trunk = SubData(:,7:9);
% Upper Arm
p1_upperarm = SubData(:,19:21); p2_upperarm = SubData(:,22:24); p3_upperarm = SubData(:,10:12);
% Lower Arm
p1_lowerarm = SubData(:,16:18); p2_lowerarm = SubData(:,25:27); p3_lowerarm = SubData(:,28:30);
% Hand
p1_hand = SubData(:,28:30); p2_hand = SubData(:,13:15); p3_hand = SubData(:,4:6);

Speed_UL.m

function [speed, axel] = Speed_UL(filenum, p2_hand);

% Calculate instantaneous speed of most distal marker
for i = 1:length(p2_hand)-1
    a = p2_hand(i,:);
    b = p2_hand(i+1,:);
    speed(1,i+4) = norm((b-a)/0.0083)/100;
end

% Filter speed calculations at 19.5Hz (calculated using residual analysis)
[B, A] = butter(2, (19.5/60));
filtdata = speed(1,5:length(speed));
speed(1,5:length(speed)) = filtfilt(B, A, filtdata);
speed(1,2) = max(speed(1,:));
speed(1,1) = filenum;

% Calculate instantaneous acceleration of most distal marker
for i = 1:length(speed)-6
    a = speed(1,i+5);
    b = speed(1,i+6);
    axel(1,i+6) = (b-a)/0.0083;
end
Planar_UL.m

function [beta_shoulder, gamma_shoulder, alpha_shoulder, beta_elbow, alpha_elbow, beta_wrist, alpha_wrist] = Planar_UL(RTM_trunk, RTM_upperarm, RTM_lowerarm, RTM_hand, p1_trunk, p2_trunk, p3_trunk, p1_upperarm, p2_upperarm, p3_upperarm, p1_lowerarm, p2_lowerarm, p3_lowerarm, p1_hand, p2_hand, p3_hand, filename, handed);

% Calculate provisional and segment coordinate systems for each instant in time
% using unit vectors for each array (trunk, upperarm, lowerarm, hand)
% (i = mediolateral axis, j = anteroposterior axis, k = longitudinal axis)
% Calculate angles using planar projections
% (alpha = abduction/adduction, beta = horizontal abduction/adduction, gamma = external/internal rotation)
% Adapted from Feltner and Nelson, 1996, and Christopher, 2001

for i=1:length(p1_trunk)

% Trunk
i_trunk = (cross((p3_trunk(i,:)-p1_trunk(i,:)),(p2_trunk(i,:)-p1_trunk(i,:))))/ ... (norm(cross((p3_trunk(i,:)-p1_trunk(i,:)),(p2_trunk(i,:)-p1_trunk(i,:)))));
k_trunk = (p1_trunk(i,:)-p2_trunk(i,:))/(norm(p1_trunk(i,:)-p2_trunk(i,:)));
j_trunk = cross(k_trunk,i_trunk);

PCS_trunk = [-i_trunk(1,2) -j_trunk(1,2) -k_trunk(1,2);
             i_trunk(1,1) j_trunk(1,1) k_trunk(1,1);
             i_trunk(1,3) j_trunk(1,3) k_trunk(1,3)];

%PCS_trunk = PCS_trunk'

SCS_trunk = PCS_trunk * RTM_trunk;

% Upper Arm
i_upperarm = (cross((p2_upperarm(i,:)-p1_upperarm(i,:)),(p3_upperarm(i,:)-p1_upperarm(i,:))))/ ... (norm(cross((p2_upperarm(i,:)-p1_upperarm(i,:)),(p3_upperarm(i,:)-p1_upperarm(i,:)))));
k_upperarm = (p2_upperarm(i,:)-p1_upperarm(i,:))/(norm(p2_upperarm(i,:)-p1_upperarm(i,:)));
j_upperarm = cross(k_upperarm,i_upperarm);

PCS_upperarm = [-i_upperarm(1,2) -j_upperarm(1,2) -k_upperarm(1,2);
                 i_upperarm(1,1) j_upperarm(1,1) k_upperarm(1,1);
                 i_upperarm(1,3) j_upperarm(1,3) k_upperarm(1,3)];

%PCS_upperarm = PCS_upperarm'

SCS_upperarm = PCS_upperarm * RTM_upperarm;

% Lower Arm
tempi = (p2_lowerarm(i,:)-p1_lowerarm(i,:))/(norm(p2_lowerarm(i,:)-p1_lowerarm(i,:)));
k_lowerarm = (p3_lowerarm(i,:)-p1_lowerarm(i,:))/(norm(p3_lowerarm(i,:)-p1_lowerarm(i,:)));
i_lowerarm = cross(k_lowerarm,tempi)/(norm(cross(k_lowerarm,tempi)));
j_lowerarm = cross(k_lowerarm,i_lowerarm);
PCS_lowerarm = [-i_lowerarm(1,2) -j_lowerarm(1,2) -k_lowerarm(1,2);
               i_lowerarm(1,1)  j_lowerarm(1,1)  k_lowerarm(1,1);
               i_lowerarm(1,3)  j_lowerarm(1,3)  k_lowerarm(1,3)];

%PCS_lowerarm = PCS_lowerarm'

SCS_lowerarm = PCS_lowerarm * RTM_lowerarm;

% Hand
i_hand = (cross((p1_hand(i,:)-p3_hand(i,:)),(p1_hand(i,:)-p2_hand(i,:)))) ... 
        / (norm(cross((p1_hand(i,:)-p3_hand(i,:)),(p1_hand(i,:)-p2_hand(i,:))));
tempj = (p3_hand(i,:)-p1_hand(i,:))/(norm(p3_hand(i,:)-p1_hand(i,:)));
k_hand = cross(i_hand,tempj)/(norm(cross(i_hand,tempj)));
j_hand = cross(k_hand,i_hand);

PCS_hand = [-i_hand(1,2) -j_hand(1,2) -k_hand(1,2);
               i_hand(1,1)  j_hand(1,1)  k_hand(1,1);
               i_hand(1,3)  j_hand(1,3)  k_hand(1,3)];

%SCS_hand = SCS_hand'

SCS_hand = PCS_hand * RTM_hand;

% Determine joint angles using planar projections
% Unit vectors u1 and u2 are defined to coincide with the long axes of the upperarm and lowerarm, respectively
u1 = SCS_upperarm(:,3);
u2 = SCS_lowerarm(:,3);

% Shoulder abduction/adduction angle (alpha_shoulder)
% Calculated as the angle between vectors u3 and k_trunk, where u3 is the projection of u1 onto the plane formed by i_trunk and k_trunk
% Viewed from the front, abduction ranges from 0 degrees with the body in the reference position to approximately 180 degrees with the arm fully abducted
u3 = (u1-dot(u1,SCS_trunk(:,2))*SCS_trunk(:,2))/(norm(u1-dot(u1,SCS_trunk(:,2))*SCS_trunk(:,2)));
alpha_shoulder(1,i+3) = acos(dot(u3,SCS_trunk(:,3)));

% Shoulder horizontal abduction/adduction angle (beta_shoulder)
% Calculated as the angle between the vectors u4 and j_trunk where u4 is the projection of u1 onto the plane formed by i_trunk and j_trunk
% Viewed from directly overhead, counterclockwise positions of u4 relative to i_trunk are considered positive angles (horizontal adduction) and clockwise positions were negative angles (horizontal abduction)
if handed == 1
    u4 = (u1-dot(u1,SCS_trunk(:,3))*SCS_trunk(:,3))/(norm(u1-dot(u1,SCS_trunk(:,3))*SCS_trunk(:,3))); 
    beta_shoulder(1,i+3) = acos(dot(u4,-SCS_trunk(:,2)))
else
    u4 = (u1-dot(u1,SCS_trunk(:,3))*SCS_trunk(:,3))/(norm(u1-dot(u1,SCS_trunk(:,3))*SCS_trunk(:,3))); 
    beta_shoulder(1,i+3) = acos(dot(u4,-SCS_trunk(:,2)))
end

% Shoulder internal/external rotation angle (gamma_shoulder)
% Calculated as the angle between vectors u5 and u6, where u5 and u6 are the projections of \( k_{trunk} \) and \( i_{lowerarm} \), respectively, onto the plane formed by \( j_{upperarm} \) and \( i_{upperarm} \).
% Viewed from the side, rotation angles range approximately -90 degrees with the shoulder in max internal rotation to approximately 180 degrees with the shoulder in max external rotation

if handed == 1
    u5 = (SCS_trunk(:,3)-dot(SCS_trunk(:,3),SCS_upperarm(:,3))*SCS_upperarm(:,3))/ ... 
        (norm(SCS_trunk(:,3)-dot(SCS_trunk(:,3),SCS_upperarm(:,3))*SCS_upperarm(:,3)));
    u6 = (SCS_lowerarm(:,1)-dot(SCS_lowerarm(:,1),SCS_upperarm(:,3))*SCS_upperarm(:,3))/... 
        (norm(SCS_lowerarm(:,1)-dot(SCS_lowerarm(:,1),SCS_upperarm(:,3))*SCS_upperarm(:,3)));
    gamma_shoulder(1,i+3) = acos(dot(u5,u6));
else
    u5 = (SCS_trunk(:,3)-dot(SCS_trunk(:,3),SCS_upperarm(:,3))*SCS_upperarm(:,3))/ ... 
        (norm(SCS_trunk(:,3)-dot(SCS_trunk(:,3),SCS_upperarm(:,3))*SCS_upperarm(:,3)));
    u6 = (-SCS_lowerarm(:,1)+dot(SCS_lowerarm(:,1),SCS_upperarm(:,3))*SCS_upperarm(:,3))/ ... 
        (norm(SCS_lowerarm(:,1)-dot(SCS_lowerarm(:,1),SCS_upperarm(:,3))*SCS_upperarm(:,3)));
    gamma_shoulder(1,i+3) = acos(dot(u6,u5));
end

% Elbow flexion/extension angle (alpha_elbow)
% Calculated as the angle between \( -u1 \) and \( u2 \)
% Elbow flexion/extension angles range from approximately 180 degrees when fully extended to approximately 40 degrees
% when fully flexed
alpha_elbow(1,i+3) = acos(dot(-u1,u2));

% Elbow pronation/supination angle (beta_elbow)
% Calculated as the angle between vectors u7 and \( j_{lowerarm} \), where u7 is the projection of \( j_{hand} \)
% onto the plane defined by \( i_{lowerarm} \) and \( j_{lowerarm} \)
% Full supination at 0 degrees with positive angles representing pronation
u7 = (SCS_hand(:,2)-dot(SCS_hand(:,2),SCS_lowerarm(:,3))*SCS_lowerarm(:,3))/ ... 
    (norm(SCS_hand(:,2)-dot(SCS_hand(:,2),SCS_lowerarm(:,3))*SCS_lowerarm(:,3)));
beta_elbow(1,i+3) = acos(dot(u7,SCS_lowerarm(:,2)));

% Wrist flexion/extension angle (alpha_wrist)
% Calculated as the angle between vectors u8 and \( j_{hand} \), where u8 is the projection of u2
% onto the plane defined by \( j_{hand} \) and \( k_{hand} \)
% Negative angles represent wrist flexion while positive angles represent wrist extension
u8 = (u2-dot(u2,SCS_hand(:,1))*SCS_hand(:,1))/(norm(u2-dot(u2,SCS_hand(:,1))*SCS_hand(:,1)));
alpha_wrist(1,i+3) = acos(dot(u8,SCS_hand(:,2)))-(pi/2);

% Wrist radial/ulnar deviation angle (beta_wrist)
% Calculated as the angle between vectors u9 and \( i_{hand} \), where u9 is the projection of u2
% onto the plane defined by \( i_{hand} \) and \( k_{hand} \)
% Positive angles represent ulnar deviation while negative angles represent radial deviation
u9 = (u2-dot(u2,SCS_hand(:,2))*SCS_hand(:,2))/(norm(u2-dot(u2,SCS_hand(:,2))*SCS_hand(:,2)));
beta_wrist(1,i+3) = acos(dot(u9,SCS_hand(:,1)))-(pi/2);
end

Residual_UL.m

function Residual_UL1(angle1);

% Conducts a residual analysis on the data based on a 2nd order butterworth filter at 1, 2, 3, ..., 59 Hz
% Uses the 'butter' function to calculate 'A' and 'B' which are used by the function 'filter' to filter the raw data
% The filtered data is then compared to the unfiltered data to perform a residual analysis and find the most appropriate cutoff frequency
% Adapted from Winter, 1990

for i = 1:59
    data = angle1(1,4:length(angle1)); % row of column in this line is the angle that's being analyzed
    [B, A] = butter(2, (i/60));
    fdata = filtfilt(B, A, data);
    Freq(1,i) = i;
    diff = fdata - data; % calculate the differences, faster than looping
    diff_sqr = diff .^2; % square all elements of diff using a vectorize operation (^) rather than just (^)
    diff_mean = mean(diff_sqr); % compute the mean
    RMS(1,i) = sqrt(diff_mean); % the root of the mean of the squared differences
end

hold on;
plot(Freq, RMS, 'k');

Filter_UL.m

function [beta_shoulder, gamma_shoulder, alpha_shoulder, beta_elbow, alpha_elbow, beta_wrist, ...
    alpha_wrist] = Filter_UL(beta_shoulder, gamma_shoulder, alpha_shoulder, beta_elbow, ...
    alpha_elbow, beta_wrist, alpha_wrist, i, filtfreq);

    % Filters calculated angles for each subject based on residual analysis done (Residual_UL)

    % S01
    if i <= 21
        [B, A] = butter(2, (filtfreq(1,1)/60));
        filtdata = alpha_shoulder(1,4:length(alpha_shoulder));
        alpha_shoulder(1,4:length(alpha_shoulder)) = filtfilt(B, A, filtdata);
        [B, A] = butter(2, (filtfreq(1,2)/60));
        filtdata = beta_shoulder(1,4:length(beta_shoulder));
        beta_shoulder(1,4:length(beta_shoulder)) = filtfilt(B, A, filtdata);
        [B, A] = butter(2, (filtfreq(1,3)/60));
        filtdata = gamma_shoulder(1,4:length(gamma_shoulder));
        gamma_shoulder(1,4:length(gamma_shoulder)) = filtfilt(B, A, filtdata);
        [B, A] = butter(2, (filtfreq(1,4)/60));
        filtdata = alpha_elbow(1,4:length(alpha_elbow));
        alpha_elbow(1,4:length(alpha_elbow)) = filtfilt(B, A, filtdata);
        [B, A] = butter(2, (filtfreq(1,5)/60));
        filtdata = beta_elbow(1,4:length(beta_elbow));
        beta_elbow(1,4:length(beta_elbow)) = filtfilt(B, A, filtdata);
        [B, A] = butter(2, (filtfreq(1,6)/60));
        filtdata = alpha_wrist(1,4:length(alpha_wrist));
        alpha_wrist(1,4:length(alpha_wrist)) = filtfilt(B, A, filtdata);
        [B, A] = butter(2, (filtfreq(1,7)/60));
        filtdata = beta_wrist(1,4:length(beta_wrist));
        beta_wrist(1,4:length(beta_wrist)) = filtfilt(B, A, filtdata);

    % S02
    elseif i > 21 & i <= 42

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[B, A] = butter(2, (filtfreq(2,1)/60));
filtdata = alpha_shoulder(1,4:length(alpha_shoulder));
alpha_shoulder(1,4:length(alpha_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(2,2)/60));
filtdata = beta_shoulder(1,4:length(beta_shoulder));
beta_shoulder(1,4:length(beta_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(2,3)/60));
filtdata = gamma_shoulder(1,4:length(gamma_shoulder));
gamma_shoulder(1,4:length(gamma_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(2,4)/60));
filtdata = alpha_elbow(1,4:length(alpha_elbow));
alpha_elbow(1,4:length(alpha_elbow)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(2,5)/60));
filtdata = beta_elbow(1,4:length(beta_elbow));
beta_elbow(1,4:length(beta_elbow)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(2,6)/60));
filtdata = alpha_wrist(1,4:length(alpha_wrist));
alpha_wrist(1,4:length(alpha_wrist)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(2,7)/60));
filtdata = beta_wrist(1,4:length(beta_wrist));
beta_wrist(1,4:length(beta_wrist)) = filtfilt(B, A, filtdata);

elseif i > 42 & i <= 63
[B, A] = butter(2, (filtfreq(3,1)/60));
filtdata = alpha_shoulder(1,4:length(alpha_shoulder));
alpha_shoulder(1,4:length(alpha_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(3,2)/60));
filtdata = beta_shoulder(1,4:length(beta_shoulder));
beta_shoulder(1,4:length(beta_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(3,3)/60));
filtdata = gamma_shoulder(1,4:length(gamma_shoulder));
gamma_shoulder(1,4:length(gamma_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(3,4)/60));
filtdata = alpha_elbow(1,4:length(alpha_elbow));
alpha_elbow(1,4:length(alpha_elbow)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(3,5)/60));
filtdata = beta_elbow(1,4:length(beta_elbow));
beta_elbow(1,4:length(beta_elbow)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(3,6)/60));
filtdata = alpha_wrist(1,4:length(alpha_wrist));
alpha_wrist(1,4:length(alpha_wrist)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(3,7)/60));
filtdata = beta_wrist(1,4:length(beta_wrist));
beta_wrist(1,4:length(beta_wrist)) = filtfilt(B, A, filtdata);

elseif i > 63 & i <= 84
[B, A] = butter(2, (filtfreq(4,1)/60));
filtdata = alpha_shoulder(1,4:length(alpha_shoulder));
alpha_shoulder(1,4:length(alpha_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(4,2)/60));
filtdata = beta_shoulder(1,4:length(beta_shoulder));
beta_shoulder(1,4:length(beta_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(4,3)/60));
filtdata = gamma_shoulder(1,4:length(gamma_shoulder));
gamma_shoulder(1,4:length(gamma_shoulder)) = filtfilt(B, A, filtdata);
gamma_shoulder(1,4:length(gamma_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(4,4)/60));
filtdata = alpha_elbow(1,4:length(alpha_elbow));
alpha_elbow(1,4:length(alpha_elbow)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(4,5)/60));
filtdata = beta_elbow(1,4:length(beta_elbow));
beta_elbow(1,4:length(beta_elbow)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(4,6)/60));
filtdata = alpha_wrist(1,4:length(alpha_wrist));
alpha_wrist(1,4:length(alpha_wrist)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(4,7)/60));

elseif i > 84 & i <= 105
[B, A] = butter(2, (filtfreq(5,1)/60));
filtdata = alpha_shoulder(1,4:length(alpha_shoulder));
alpha_shoulder(1,4:length(alpha_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(5,2)/60));
filtdata = beta_shoulder(1,4:length(beta_shoulder));
beta_shoulder(1,4:length(beta_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(5,3)/60));
filtdata = gamma_shoulder(1,4:length(gamma_shoulder));
gamma_shoulder(1,4:length(gamma_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(5,4)/60));
filtdata = alpha_elbow(1,4:length(alpha_elbow));
alpha_elbow(1,4:length(alpha_elbow)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(5,5)/60));
filtdata = beta_elbow(1,4:length(beta_elbow));
beta_elbow(1,4:length(beta_elbow)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(5,6)/60));
filtdata = alpha_wrist(1,4:length(alpha_wrist));
alpha_wrist(1,4:length(alpha_wrist)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(5,7)/60));
filtdata = beta_wrist(1,4:length(beta_wrist));
beta_wrist(1,4:length(beta_wrist)) = filtfilt(B, A, filtdata);

elseif i > 105 & i <= 126
[B, A] = butter(2, (filtfreq(6,1)/60));
filtdata = alpha_shoulder(1,4:length(alpha_shoulder));
alpha_shoulder(1,4:length(alpha_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(6,2)/60));
filtdata = beta_shoulder(1,4:length(beta_shoulder));
beta_shoulder(1,4:length(beta_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(6,3)/60));
filtdata = gamma_shoulder(1,4:length(gamma_shoulder));
gamma_shoulder(1,4:length(gamma_shoulder)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(6,4)/60));
filtdata = alpha_elbow(1,4:length(alpha_elbow));
alpha_elbow(1,4:length(alpha_elbow)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(6,5)/60));
filtdata = beta_elbow(1,4:length(beta_elbow));
beta_elbow(1,4:length(beta_elbow)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(6,6)/60));

else

end
filtdata = alpha_wrist(1,4:length(alpha_wrist));
alpha_wrist(1,4:length(alpha_wrist)) = filtfilt(B, A, filtdata);
[B, A] = butter(2, (filtfreq(6,7)/60));
filtdata = beta_wrist(1,4:length(beta_wrist));
beta_wrist(1,4:length(beta_wrist)) = filtfilt(B, A, filtdata);
end

Maxmin_UL.m

function [mmas, mmbs, mmgs, mmae, mmbe, mmaw, mmbw] = Maxmin_UL(beta_shoulder, gamma_shoulder, alpha_shoulder, ...
  beta_elbow, alpha_elbow, beta_wrist, alpha_wrist, i, filenum);

% alpha_shoulder
mmas(1,1) = filenum;
mmas(2,1) = max(alpha_shoulder(1,4:length(alpha_shoulder))) * 180 / pi;
mmas(3,1) = min(alpha_shoulder(1,4:length(alpha_shoulder))) * 180 / pi;
mmas(4,1) = mmas(2,1) - mmas(3,1);

% beta_shoulder
mmbs(1,1) = filenum;
mmbs(2,1) = max(beta_shoulder(1,4:length(beta_shoulder))) * 180 / pi;
mmbs(3,1) = min(beta_shoulder(1,4:length(beta_shoulder))) * 180 / pi;
mmbs(4,1) = mmbs(2,1) - mmbs(3,1);

% gamma_shoulder
mmgs(1,1) = filenum;
mmgs(2,1) = max(gamma_shoulder(1,4:length(gamma_shoulder))) * 180 / pi;
mmgs(3,1) = min(gamma_shoulder(1,4:length(gamma_shoulder))) * 180 / pi;
mmgs(4,1) = mmgs(2,1) - mmgs(3,1);

% alpha_elbow
mmae(1,1) = filenum;
mmae(2,1) = max(alpha_elbow(1,4:length(alpha_elbow))) * 180 / pi;
mmae(3,1) = min(alpha_elbow(1,4:length(alpha_elbow))) * 180 / pi;
mmae(4,1) = mmae(2,1) - mmae(3,1);

% beta_elbow
mmbe(1,1) = filenum;
mmbe(2,1) = max(beta_elbow(1,4:length(beta_elbow))) * 180 / pi;
mmbe(3,1) = min(beta_elbow(1,4:length(beta_elbow))) * 180 / pi;
mmbe(4,1) = mmbe(2,1) - mmbe(3,1);

% alpha_wrist
mmaw(1,1) = filenum;
mmaw(2,1) = max(alpha_wrist(1,4:length(alpha_wrist))) * 180 / pi;
mmaw(3,1) = min(alpha_wrist(1,4:length(alpha_wrist))) * 180 / pi;
mmaw(4,1) = mmaw(2,1) - mmaw(3,1);

% beta_wrist
mmbw(1,1) = filenum;
mmbw(2,1) = max(beta_wrist(1,4:length(beta_wrist))) * 180 / pi;
mmbw(3,1) = min(beta_wrist(1,4:length(beta_wrist))) * 180 / pi;
mmbw(4,1) = mmbw(2,1) - mmbw(3,1);

Write_ULdata.m
function [UL_data] = Write_ULdata(beta_shoulder, gamma_shoulder, alpha_shoulder, beta_elbow, alpha_elbow, ...  
  beta_wrist, alpha_wrist, handed, endfilename, filenum, speed, axel);

% Write to UL_data matrix and multiply shoulder angles by -1, as well multiply internal/external rotation and
% adduction/abduction angles by -1 for left handed subjects (S02 and S03) using handed parameter.
% Files are written using a 0 at the start to indicate that it has been processed.
UL_data(1,:) = alpha_shoulder;
UL_data(2,:) = beta_shoulder;
UL_data(3,:) = gamma_shoulder;
UL_data(4,:) = alpha_elbow;
UL_data(5,:) = beta_elbow;
UL_data(6,:) = alpha_wrist;
UL_data(7,:) = beta_wrist;
UL_data(8,:) = zeros;
UL_data(9,:) = speed;
UL_data(10,:) = axel;

% Convert data from radians to degrees
UL_data(1:7,:) = UL_data(1:7,:) * 180 / pi;

% Set first column as subject number (A), swing type (B) and swing number (C) (A.BC)
UL_data(1,1) = filenum;
UL_data(2,1) = filenum;
UL_data(3,1) = filenum;
UL_data(4,1) = filenum;
UL_data(5,1) = filenum;
UL_data(6,1) = filenum;
UL_data(7,1) = filenum;
UL_data(1:7,1) = UL_data(1:7,1) * 180 / pi;

% Set second column as angle (A = alpha, B = beta, C = shoulder)
UL_data(1,2) = 1;
UL_data(2,2) = 1;
UL_data(3,2) = 1;
UL_data(4,2) = 2;
UL_data(5,2) = 2;
UL_data(6,2) = 3;
UL_data(7,2) = 3;

% Set third column as joint (S = shoulder, E = elbow, W = wrist)
UL_data(1,3) = 1;
UL_data(2,3) = 2;
UL_data(3,3) = 3;
UL_data(4,3) = 1;
UL_data(5,3) = 2;
UL_data(6,3) = 1;
UL_data(7,3) = 2;

DLMwrite(endfilename, UL_data, 'w');
function [beta_shoulder, gamma_shoulder, alpha_shoulder, beta_elbow, gamma_elbow, alpha_elbow,
beta_wrist, gamma_wrist, alpha_wrist] = Cardan_UL(RTM_trunk, RTM_upperarm, RTM_lowerarm, RTM_hand, p1_trunk, p2_trunk,
p3_trunk, p1_upperarm, ...
p2_upperarm, p3_upperarm, p1_lowerarm, p2_lowerarm, p3_lowerarm, p1_hand, p2_hand, p3_hand,
filename);

% Calculate provisional and segment coordinate systems for each instant in time
% using unit vectors for each array (trunk, upperarm, lowerarm, hand)
% (i = mediolateral axis, j = anteroposterior axis, k = longitudinal axis)
% Calculate angles using cardan sequence
% (alpha = flexion/extension, beta = abduction/adduction, gamma = external/internal rotation)
for i=1:length(p1_trunk)
    % Trunk
    j_trunk = (cross((p3_trunk(i,:)-p1_trunk(i,:)),(p2_trunk(i,:)-p1_trunk(i,:))))/ ...
              (norm(cross((p3_trunk(i,:)-p1_trunk(i,:)),(p2_trunk(i,:)-p1_trunk(i,:)))))
    k_trunk = (p1_trunk(i,:)-p2_trunk(i,:))/(norm(p1_trunk(i,:)-p2_trunk(i,:)));
    i_trunk = cross(j_trunk,k_trunk);
    PCS_trunk = [-i_trunk(1,2) -j_trunk(1,2) -k_trunk(1,2);
                   i_trunk(1,1) j_trunk(1,1) k_trunk(1,1);
                   i_trunk(1,3) j_trunk(1,3) k_trunk(1,3)];

    %PCS_trunk = PCS_trunk'
    SCS_trunk = PCS_trunk * RTM_trunk;

    % Upper Arm
    j_upperarm = (cross((p3_upperarm(i,:)-p1_upperarm(i,:)),(p2_upperarm(i,:)-p1_upperarm(i,:))))/ ...
                  (norm(cross((p3_upperarm(i,:)-p1_upperarm(i,:)),(p2_upperarm(i,:)-p1_upperarm(i,:)))))
    k_upperarm = (p2_upperarm(i,:)-p1_upperarm(i,:))/(norm(p2_upperarm(i,:)-p1_upperarm(i,:)));
    i_upperarm = cross(j_upperarm,k_upperarm);
    PCS_upperarm = [-i_upperarm(1,2) -j_upperarm(1,2) -k_upperarm(1,2);
                    i_upperarm(1,1) j_upperarm(1,1) k_upperarm(1,1);
                    i_upperarm(1,3) j_upperarm(1,3) k_upperarm(1,3)];

    %PCS_upperarm = PCS_upperarm'
    SCS_upperarm = PCS_upperarm * RTM_upperarm;

    % Lower Arm
    tempi = (p2_lowerarm(i,:)-p1_lowerarm(i,:))/(norm(p2_lowerarm(i,:)-p1_lowerarm(i,:)));
    k_lowerarm = (p3_lowerarm(i,:)-p1_lowerarm(i,:))/(norm(p3_lowerarm(i,:)-p1_lowerarm(i,:)));
    j_lowerarm = cross(k_lowerarm,tempi)/(norm(cross(k_lowerarm,tempi)));
    i_lowerarm = cross(j_lowerarm,k_lowerarm);
PCS_lowerarm = [-i_lowerarm(1,2) -j_lowerarm(1,2) -k_lowerarm(1,2); 
  i_lowerarm(1,1) j_lowerarm(1,1) k_lowerarm(1,1); 
  i_lowerarm(1,3) j_lowerarm(1,3) k_lowerarm(1,3)];

%PCS_lowerarm = PCS_lowerarm'

SCS_lowerarm = PCS_lowerarm * RTM_lowerarm;

% Hand
i_hand = (cross((p1_hand(i,:)-p3_hand(i,:)),(p1_hand(i,:)-p2_hand(i,:)))) ... 
  / (norm(cross((p1_hand(i,:)-p3_hand(i,:)),(p1_hand(i,:)-p2_hand(i,:)))));

tempj = (p3_hand(i,:)-p1_hand(i,:))/(norm(p3_hand(i,:)-p1_hand(i,:)));

k_hand = cross(i_hand,tempj)/(norm(cross(i_hand,tempj)));

j_hand = cross(k_hand,i_hand);

PCS_hand = [-i_hand(1,2) -j_hand(1,2) -k_hand(1,2); 
  i_hand(1,1) j_hand(1,1) k_hand(1,1); 
  i_hand(1,3) j_hand(1,3) k_hand(1,3)];

%PCS_hand = PCS_hand'

SCS_hand = PCS_hand * RTM_hand;

% Calculate rotation matrix for each joint (C=A*inv(B))
% Shoulder
A = SCS_trunk;
B = SCS_upperarm;
C_shoulder = B\A;

% Elbow
A = SCS_upperarm;
B = SCS_lowerarm;
C_elbow = B\A;

% Wrist
A = SCS_lowerarm;
B = SCS_hand;
C_wrist = B\A;

% Calculate alpha, beta, and gamma for each joint
% Also adapted from Tupling and Pierrynowski, 1987

% Shoulder
beta_shoulder(1,i+3) = asin(C_shoulder(3,1));

R32CosB = -C_shoulder(3,2) / cos(beta_shoulder(1,i+3));
if (R32CosB >= 0)
  alpha_shoulder(1,i+3) = asin(R32CosB);
if (R32CosB > pi)
  %alpha_shoulder(1,i+3) = alpha_shoulder(1,i+3) - (2*pi);
  alpha_shoulder(1,i+3) = alpha_shoulder(1,i+3) - (pi);
elseif (R32CosB > 0)
  %alpha_shoulder(1,i+3) = pi - alpha_shoulder(1,i+3);
end
elseif (R32CosB < 0)
    alpha_shoulder(1,i+3) = asin(-R32CosB);
    if (-R32CosB > pi)
        %alpha_shoulder(1,i+3) = alpha_shoulder(1,i+3) - (2*pi);
        alpha_shoulder(1,i+3) = alpha_shoulder(1,i+3) - (pi);
    elseif (-R32CosB > 0)
        %alpha_shoulder(1,i+3) = pi - alpha_shoulder(1,i+3);
    end
    alpha_shoulder(1,i+3) = -alpha_shoulder(1,i+3);
end

R21CosB = -C_shoulder(2,1) / cos(beta_shoulder(1,i+3));
if (R21CosB >= 0)
    gamma_shoulder(1,i+3) = asin(R21CosB);
    if (R21CosB > pi)
        %gamma_shoulder(1,i+3) = gamma_shoulder(1,i+3) - (2*pi);
        gamma_shoulder(1,i+3) = gamma_shoulder(1,i+3) - (pi);
    elseif (R21CosB > 0)
        %gamma_shoulder(1,i+3) = pi - gamma_shoulder(1,i+3);
    end
    elseif (R21CosB < 0)
        gamma_shoulder(1,i+3) = asin(-R21CosB);
        if (-R21CosB > pi)
            %gamma_shoulder(1,i+3) = gamma_shoulder(1,i+3) - (2*pi);
            gamma_shoulder(1,i+3) = gamma_shoulder(1,i+3) - (pi);
        elseif (-R21CosB > 0)
            %gamma_shoulder(1,i+3) = pi - gamma_shoulder(1,i+3);
        end
    gamma_shoulder(1,i+3) = -gamma_shoulder(1,i+3);
end

% Elbow
beta_elbow(1,i+3) = asin(C_elbow(3,1));

R32CosB = -C_elbow(3,2) / cos(beta_elbow(1,i+3));
if (R32CosB >= 0)
    alpha_elbow(1,i+3) = asin(R32CosB);
    if (R32CosB > pi)
        %alpha_elbow(1,i+3) = alpha_elbow(1,i+3) - (2*pi);
        alpha_elbow(1,i+3) = alpha_elbow(1,i+3) - (pi);
    elseif (R32CosB > 0)
        %alpha_elbow(1,i+3) = pi - alpha_elbow(1,i+3);
    end
    elseif (R32CosB < 0)
        alpha_elbow(1,i+3) = asin(-R32CosB);
        if (-R32CosB > pi)
            %alpha_elbow(1,i+3) = alpha_elbow(1,i+3) - (2*pi);
            alpha_elbow(1,i+3) = alpha_elbow(1,i+3) - (pi);
        elseif (-R32CosB > 0)
            %alpha_elbow(1,i+3) = pi - alpha_elbow(1,i+3);
        end
    alpha_elbow(1,i+3) = -alpha_elbow(1,i+3);
end

R21CosB = -C_elbow(2,1) / cos(beta_elbow(1,i+3));
if (R21CosB >= 0)
gamma_elbow(1,i+3) = asin(R21CosB);
if (R21CosB > pi)
    gamma_elbow(1,i+3) = gamma_elbow(1,i+3) - (2*pi);
    gamma_elbow(1,i+3) = gamma_elbow(1,i+3) - (pi);
elseif (R21CosB > 0)
    gamma_elbow(1,i+3) = pi - gamma_elbow(1,i+3);
end
elseif (R21CosB < 0)
    gamma_elbow(1,i+3) = asin(-R21CosB);
    if (-R21CosB > pi)
        gamma_elbow(1,i+3) = gamma_elbow(1,i+3) - (2*pi);
        gamma_elbow(1,i+3) = gamma_elbow(1,i+3) - (pi);
    elseif (-R21CosB > 0)
        gamma_elbow(1,i+3) = pi - gamma_elbow(1,i+3);
    end
    gamma_elbow(1,i+3) = -gamma_elbow(1,i+3);
end

% Wrist
beta_wrist(1,i+3) = asin(C_wrist(3,1));

R32CosB = -C_wrist(3,2) / cos(beta_wrist(1,i+3));
if (R32CosB >= 0)
    alpha_wrist(1,i+3) = asin(R32CosB);
    if (R32CosB > pi)
        alpha_wrist(1,i+3) = alpha_wrist(1,i+3) - (2*pi);
        alpha_wrist(1,i+3) = alpha_wrist(1,i+3) - (pi);
    elseif (R32CosB > 0)
        alpha_wrist(1,i+3) = pi - alpha_wrist(1,i+3);
    end
    alpha_wrist(1,i+3) = -alpha_wrist(1,i+3);
end
elseif (R32CosB < 0)
    alpha_wrist(1,i+3) = asin(-R32CosB);
    if (-R32CosB > pi)
        alpha_wrist(1,i+3) = alpha_wrist(1,i+3) - (2*pi);
        alpha_wrist(1,i+3) = alpha_wrist(1,i+3) - (pi);
    elseif (-R32CosB > 0)
        alpha_wrist(1,i+3) = pi - alpha_wrist(1,i+3);
    end
    alpha_wrist(1,i+3) = -alpha_wrist(1,i+3);
end

R21CosB = -C_wrist(2,1) / cos(beta_wrist(1,i+3));
if (R21CosB >= 0)
    gamma_wrist(1,i+3) = asin(R21CosB);
    if (R21CosB > pi)
        gamma_wrist(1,i+3) = gamma_wrist(1,i+3) - (2*pi);
        gamma_wrist(1,i+3) = gamma_wrist(1,i+3) - (pi);
    elseif (R21CosB > 0)
        gamma_wrist(1,i+3) = pi - gamma_wrist(1,i+3);
    end
else if (R21CosB < 0)
    gamma_wrist(1,i+3) = asin(-R21CosB);
    if (-R21CosB > pi)
        gamma_wrist(1,i+3) = gamma_wrist(1,i+3) - (2*pi);
        gamma_wrist(1,i+3) = gamma_wrist(1,i+3) - (pi);
    elseif (-R21CosB > 0)
%gamma_wrist(1,i+3) = pi - gamma_wrist(1,i+3);
end
gamma_wrist(1,i+3) = -gamma_wrist(1,i+3);
end
end

JCS_UL.m

function [beta_shoulder, gamma_shoulder, alpha_shoulder, beta_elbow, gamma_elbow, alpha_elbow, beta_wrist, gamma_wrist, alpha_wrist] = JCS_UL(RTM_trunk, RTM_upperarm, RTM_lowerarm, RTM_hand, p1_trunk, p2_trunk, p3_trunk, p1_upperarm, p2_upperarm, p3_upperarm, p1_lowerarm, p2_lowerarm, p3_lowerarm, p1_hand, p2_hand, p3_hand);

% Calculate provisional and segment coordinate systems for each instant in time
% using unit vectors for each array (trunk, upperarm, lowerarm, hand)
% (i = mediolateral axis, j = anteroposterior axis, k = longitudinal axis)
% Calculate angles using joint coordinate system (JCS) (floating axis)
% (alpha = flexion/extension, beta = abduction/adduction, gamma = external/internal rotation)
% Adapted from 'Research Methods in Biomechanics', (2004), pg. 49-50.

for i=1:length(p1_trunk)

% Trunk
j_trunk = (cross((p3_trunk(i,:)-p1_trunk(i,:)),(p2_trunk(i,:)-p1_trunk(i,:))))/ ...
(norm(cross((p3_trunk(i,:)-p1_trunk(i,:)),(p2_trunk(i,:)-p1_trunk(i,:)))));

k_trunk = (p1_trunk(i,:)-p2_trunk(i,:))/(norm(p1_trunk(i,:)-p2_trunk(i,:)));
i_trunk = cross(j_trunk,k_trunk);

PCS_trunk = [-i_trunk(1,2) -j_trunk(1,2) -k_trunk(1,2);
              i_trunk(1,1) j_trunk(1,1) k_trunk(1,1);
              i_trunk(1,3) j_trunk(1,3) k_trunk(1,3)];

%PCS_trunk = PCS_trunk'

SCS_trunk = PCS_trunk * RTM_trunk;

% Upper Arm
j_upperarm = (cross((p3_upperarm(i,:)-p1_upperarm(i,:)),(p2_upperarm(i,:)-p1_upperarm(i,:))))/ ...
(norm(cross((p3_upperarm(i,:)-p1_upperarm(i,:)),(p2_upperarm(i,:)-p1_upperarm(i,:)))));

k_upperarm = (p2_upperarm(i,:)-p1_upperarm(i,:))/(norm(p2_upperarm(i,:)-p1_upperarm(i,:)));
i_upperarm = cross(j_upperarm,k_upperarm);

PCS_upperarm = [-i_upperarm(1,2) -j_upperarm(1,2) -k_upperarm(1,2);
                 i_upperarm(1,1) j_upperarm(1,1) k_upperarm(1,1);
                 i_upperarm(1,3) j_upperarm(1,3) k_upperarm(1,3)];

%PCS_upperarm = PCS_upperarm'

SCS_upperarm = PCS_upperarm * RTM_upperarm;

% Lower Arm

tempi = (p2_lowerarm(i,:)-p1_lowerarm(i,:))/(norm(p2_lowerarm(i,:)-p1_lowerarm(i,:)));
k_lowerarm = (p3_lowerarm(i,:)-p1_lowerarm(i,:))/(norm(p3_lowerarm(i,:)-p1_lowerarm(i,:)));
j_lowerarm = cross(k_lowerarm,tempi)/(norm(cross(k_lowerarm,tempi)));
i_lowerarm = cross(j_lowerarm,k_lowerarm);
PCS_lowerarm = [-i_lowerarm(1,2) -j_lowerarm(1,2) -k_lowerarm(1,2); 
   i_lowerarm(1,1) j_lowerarm(1,1) k_lowerarm(1,1); 
   i_lowerarm(1,3) j_lowerarm(1,3) k_lowerarm(1,3)];

%PCS_lowerarm = PCS_lowerarm'

SCS_lowerarm = PCS_lowerarm * RTM_lowerarm;

% Hand
i_hand = (cross((p1_hand(i,:)-p3_hand(i,:)),(p1_hand(i,:)-p2_hand(i,:))))./ 
   (norm(cross((p1_hand(i,:)-p3_hand(i,:)),(p1_hand(i,:)-p2_hand(i,:))));
tempj = (p3_hand(i,:)-p1_hand(i,:))/(norm(p3_hand(i,:)-p1_hand(i,:)));
k_hand = cross(i_hand,tempj)/((norm(cross(i_hand,tempj))));
j_hand = cross(k_hand,i_hand);

PCS_hand = [-i_hand(1,2) -j_hand(1,2) -k_hand(1,2); 
   i_hand(1,1) j_hand(1,1) k_hand(1,1); 
   i_hand(1,3) j_hand(1,3) k_hand(1,3)];

%PCS_hand = PCS_hand'

SCS_hand = PCS_hand * RTM_hand;

% Calculate floating axis (FA) for each joint.
% Shoulder
FA_shoulder = cross(k_upperarm, i_trunk) / norm(cross(k_upperarm, i_trunk));

% Elbow
FA_elbow = cross(k_lowerarm, i_upperarm) / norm(cross(k_lowerarm, i_upperarm));

% Wrist
FA_wrist = cross(k_hand, i_lowerarm) / norm(cross(k_hand, i_lowerarm));

% Calculate alpha, beta, and gamma for each joint
% (alpha = flexion/extension, beta = abduction/adduction, gamma = external/internal rotation)
% Shoulder
alpha_shoulder(1,i+3) = (0.5*pi) - acos(dot(k_trunk, FA_shoulder));
beta_shoulder(1,i+3) = (-0.5*pi) - acos(dot(k_upperarm, i_trunk));
gamma_shoulder(1,i+3) = (0.5*pi) - acos(dot(i_upperarm, FA_shoulder));

% Elbow
alpha_elbow(1,i+3) = (0.5*pi) - acos(dot(k_upperarm, FA_elbow));
beta_elbow(1,i+3) = (-0.5*pi) - acos(dot(k_lowerarm, i_upperarm));
gamma_elbow(1,i+3) = (0.5*pi) - acos(dot(i_lowerarm, FA_elbow));

% Wrist
alpha_wrist(1,i+3) = (0.5*pi) - acos(dot(k_lowerarm, FA_wrist));
beta_wrist(1,i+3) = (-0.5*pi) - acos(dot(k_hand, i_lowerarm));
gamma_wrist(1,i+3) = (0.5*pi) - acos(dot(i_hand, FA_wrist));
end
A residual analysis was conducted on each calculated angle (shoulder abduction/adduction, horizontal abduction/adduction, internal/external rotation; elbow flexion/extension, pronation; wrist flexion/extension, radial/ulnar deviation) for each of the six subjects using all three swing types studied (SA, CB, OS). Thus, a total of 42 separate analyses were done. This was done using MatLab code, to create a graph of the residuals of all of the usable swings. Using the method described by Winter, a line was drawn manually along the semi-horizontal straight to the y-axis (Winter, 1990). This line was then extended horizontally back into the graph, and where it touched the average point of all lines was drawn vertically downwards. Where this line finally crossed the x-axis was determined the best trade-off between smoothing and loss of information. A digital representation of this procedure can be seen in Figure 1.
Figure G1 – A digital representation of the method used to conduct a residual analysis on each angle calculated for each subject, as described by Winter (Winter, 1990). A line was drawn manually along the semi-horizontal axis towards the y-axis (light grey line). The line was then extended back into the graph horizontally to the approximate average point of all lines (dark grey line). It was then extended vertically down (black line), and where it crossed the x-axis was the frequency (13 Hz in this example) used to filter that angle data for that subject.

APPENDIX J

Study #3 – Statistical Analysis Results

Note: The statistical results provided below are associated with the mean maximal abduction angles of the shoulder calculated in the third study (Table 5.4). Other results were not included as a measure to save space.

Oneway

Descriptives

<table>
<thead>
<tr>
<th>angle</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error</th>
<th>95% Confidence Interval for Mean</th>
<th>Minimum</th>
<th>Maximum</th>
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<td>159.6430</td>
<td>165.5110</td>
<td>150.39</td>
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ANOVA

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<th>F</th>
<th>Sig.</th>
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Post Hoc Tests
Multiple Comparisons

Dependent Variable: angle
Tukey HSD

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<tr>
<th>(I) type</th>
<th>(J) type</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig.</th>
<th>95% Confidence Interval Lower Bound</th>
<th>Upper Bound</th>
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<tbody>
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<td>2.90651</td>
<td>3.47558</td>
<td>.687</td>
<td>-6.0616</td>
<td>11.8747</td>
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<tr>
<td>OS</td>
<td>SA</td>
<td>-2.90651</td>
<td>3.47558</td>
<td>.687</td>
<td>-11.8747</td>
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<tr>
<td>OS</td>
<td>CB</td>
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Homogeneous Subsets

angle
Tukey HSDa,b

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Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 6.300.
b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Oneway

Descriptives

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<tr>
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<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error</th>
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ANOVA

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<th>Mean Square</th>
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**Post Hoc Tests**

**Multiple Comparisons**

Dependent Variable: angle
Tukey HSD

<table>
<thead>
<tr>
<th>(I) type</th>
<th>(J) type</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig.</th>
<th>95% Confidence Interval</th>
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<td>SA</td>
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<td>-21.73450</td>
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<td>.671</td>
<td>-86.8280 to 43.3590</td>
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<td>-55.6304 to 79.4711</td>
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<tr>
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<td>.398</td>
<td>-31.4387 to 98.7484</td>
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**Homogeneous Subsets**

angle

Tukey HSD\(^a,b\)

<table>
<thead>
<tr>
<th>type</th>
<th>N</th>
<th>Subset for alpha = .05</th>
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<tr>
<td>CB</td>
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<td>66.4931</td>
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Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 6.300.
b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Oneway
### Descriptives

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### Post Hoc Tests

#### Multiple Comparisons

Dependent Variable: angle
Tukey HSD

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### Homogeneous Subsets
### angle

Tukey HSD\(^{a,b}\)

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Means for groups in homogeneous subsets are displayed.

- b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

### Oneway

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#### Post Hoc Tests
Multiple Comparisons

Dependent Variable: angle
Tukey HSD

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Homogeneous Subsets

angle
Tukey HSD<sup>a,b</sup>

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Means for groups in homogeneous subsets are displayed.


b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Oneway

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Post Hoc Tests

Multiple Comparisons

Dependent Variable: angle
Tukey HSD

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Homogeneous Subsets

angle
Tukey HSD\(^{a,b}\)

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Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 6.300.

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Oneway
Descriptives

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Post Hoc Tests

Multiple Comparisons

Dependent Variable: angle
Tukey HSD

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* The mean difference is significant at the .05 level.

Homogeneous Subsets

227
Means for groups in homogeneous subsets are displayed.


b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Oneway

Descriptives

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ANOVA

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Post Hoc Tests
Multiple Comparisons

Dependent Variable: angle
Tukey HSD

<table>
<thead>
<tr>
<th>(I) type</th>
<th>(J) type</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig.</th>
<th>95% Confidence Interval</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA</td>
<td>CB</td>
<td>6.34107</td>
<td>7.27212</td>
<td>.659</td>
<td>-10.9281</td>
<td>23.6103</td>
<td></td>
</tr>
<tr>
<td>OS</td>
<td>SA</td>
<td>1.50429</td>
<td>7.31449</td>
<td>.977</td>
<td>18.8741</td>
<td>15.8656</td>
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</tr>
<tr>
<td>CB</td>
<td>SA</td>
<td>-6.34107</td>
<td>7.27212</td>
<td>.659</td>
<td>-23.6103</td>
<td>10.9281</td>
<td></td>
</tr>
<tr>
<td>OS</td>
<td>CB</td>
<td>7.84535</td>
<td>7.07586</td>
<td>.511</td>
<td>-24.6485</td>
<td>8.9578</td>
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Homogeneous Subsets

angle
Tukey HSD\(^{a,b}\)

<table>
<thead>
<tr>
<th>type</th>
<th>N</th>
<th>Subset for alpha = .05</th>
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<tbody>
<tr>
<td>CB</td>
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<td>119.3449</td>
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<td>SA</td>
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<td>125.6860</td>
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<tr>
<td>OS</td>
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<td>127.1903</td>
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<tr>
<td>Sig.</td>
<td>.524</td>
<td>1</td>
</tr>
</tbody>
</table>

Means for groups in homogeneous subsets are displayed.

\(^{a}\) Uses Harmonic Mean Sample Size = 38.876.

\(^{b}\) The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.