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The Volleyball Attack: Training, Kinematics, and the Role of the Torso

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THE VOLLEYBALL ATTACK: TRAINING, KINEMATICS, AND THE ROLE OF THE TORSO

by

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ABSTRACT

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Volleyball is an explosive, dynamic sport popular around the globe. The volleyball attack is the predominant point-scoring avenue and the point of interest for many coaches and players. As this motion is repeated many times throughout the course of a match, it is linked to overuse injuries at the shoulder. The purpose of this dissertation is to investigate methodological approaches for research in this movement as well as establishing mechanisms for improving performance and the health of the volleyball players' shoulder.

For the first study, a systematic review of published literature was performed to ascertain training protocols beneficial to volleyball players' shoulders; findings suggested kinetic chain training protocols may influence stability during this movement. However, when reviewing the current research, it was clear an established methodology for calculating kinematic variables at the shoulder when performing the attack was missing in the literature. For the second study, twenty-two healthy, experienced volleyball players completed volleyball attacks off a stationary volleyball using marker-based 3D motion capture. Six rotation sequences commonly utilized to calculate shoulder kinematics were compared for anatomical understanding and accuracy. The YXY and XYZ sequences were found to be the most reliable and should be employed in future research. Following the establishment of the importance of rotation sequences in calculations, data collections were brought into the field to evaluate the influence of the kinetic chain on performance. For the final study, thirty experienced players were recruited to perform 14 attacks while wearing inertial measurements on a sand volleyball court. Sex was found to be the most

predictive variable of ball velocity in both the line and cross-court directions, with peak trunk rotational velocity as a second significant measure. These results suggest a greater reliance on trunk motion when performing the attack in the sand, as our results contrast with those reported in the literature on hard-court. Coaches and players should place an emphasis on increasing the velocity of their trunk rotation when attacking to improve ball velocity.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Volleyball is a widely popular, growing sport with participants around the globe. The primary offensive maneuver in volleyball is called the “attack”. This explosive action consists of a running approach, jump, and overhead movement with the intention of contacting the ball in such a way so the opposing team cannot return it. This motion is directly related to the success of a team (A. O. G. F. Oliveira et al., 2018). As such, the attack is the interest of many research studies concerning volleyball; this research analyzes the mechanics and kinematic profiles of the attack, relationships to injury, sex differences, the influence of setting (i.e., hard vs sand court) and participant characteristics.

1.2 An overview of research in volleyball

1.2.1 Kinematic Properties

Various kinematic properties of the volleyball attack have been evaluated through research. Evaluating kinematic properties that define a movement is important to provide normative values which can then be used in the recommendation for exercise regimens, rehabilitative procedures, and training for performance improvements. These kinematic parameters can also be used to identify risk factors for injury.

Studies focusing on the shoulder found volleyball players contact the ball during an attack with ~130° of shoulder abduction, possibly increasing risk for subacromial impingement or labrum tears (Mitchinson et al., 2013; Reeser, Fleisig, et al., 2010). Shoulder flexion range of motion during the attack averages ~160° (Wagner et al., 2014); differences in technique may reduce injury risk by inspiring smaller ranges of motion during the attack that do not push the limits of anatomical movement (Seminati et al., 2015). Some disparities exist in the literature regarding maximal shoulder external rotation (ER) angle and rotation velocities. Wagner et al. (2014) reported maximal ER angles of around 55°, whereas Reeser et al. (2010) reported a much higher average of 160°. Two studies found maximal internal rotation (IR) velocity to be around 2500 °/s (Reeser, Joy, et al., 2010; Serrien et al., 2016) with other researchers finding values around 4520 °/s (Wagner et al., 2014). These contrasting results could be due to different participant populations, or the rotation sequence utilized for three-dimensional kinematic calculations.

Trunk and pelvis kinematics have also been investigated. Peak pelvis rotation averages at about 370 degrees per second, with the trunk rotating faster at 640 degrees per second (Wagner et al., 2014). Proximal-to-distal sequencing has been noted in the volleyball attack in multiple studies (Serrien et al., 2018; Wagner et al., 2014). While exact normative values have yet to be fully elucidated in research, it is clear the shoulder moves through a large range of motion at a high velocity when performing the volleyball attack. With emerging research supporting the influence of the kinetic chain in performing this movement, it is imperative we assess the kinematic parameters that fall within this umbrella to create a better picture of the attack profile and how to mitigate loading of the shoulder at these high velocities.

1.2.2 The influence of direction

The attack has variations players employ to improve the success of the movement; one such modification is changing the direction of attack. Researchers have evaluated differences in kinematics and kinetics when performing attacks to different areas of the court (Brown et al., 2014; Mitchinson et al., 2013; Reeser, Fleisig, et al., 2010). Reeser et al. (2010) found no significant differences between attack direction in any kinetic or kinematic parameters. Mitchinson et al. (2015) found players were more rotated through the trunk and contacted the ball with their shoulders in a more flexed position when performing the cross-court attack. Range of shoulder rotation velocity was also greater in the cross-court direction (Mitchinson et al., 2013). Contrasting results regarding the influence of attack direction on ball velocity have been reported, with two studies finding no difference between directions (Mitchinson et al., 2013; Reeser, Fleisig, et al., 2010) and one study finding the cross-court attack resulted in significantly smaller ball velocities (Brown et al., 2014). Disparities between these results could be due to differences in study population (female collegiate vs elite male) or methodology (fixed ball vs. player-driven).

1.2.3 Sex Differences

Some sex differences in aspects of the volleyball attack have been reported, although they are not largely studied. A direct comparison of ball velocity between sexes has not been performed; however, based on reported means, men have tend to display greater ball velocity (19-27 m/s) and hand velocity at ball contact (19.2-21.9 m/s) when compared to women (15-20 m/s and 13.8-18.7 m/s, respectively) (Coleman et al., 1993; Mitchinson et al., 2013; L. dos S. Oliveira et al., 2020; Seminati et al., 2015). In terms of technique, men prefer the circular and low bow-and-arrow technique when compared to women (Giatsis et al., 2022); the snap and straight arm techniques were more predominant in women than men. No difference between sexes was found in the incidence of shoulder injury (Reeser, Joy, et al., 2010), suggesting these differences in technique are not indicative of shoulder injury. Elite male players also display significantly higher shoulder internal rotation velocity around the time of ball contact, as well as greater horizontal adduction in the follow through phase (Serrien et al., 2016).

1.2.4 Sand vs. Hard-Court

The sport of volleyball has many variants, including hard-court, sand, grass, sitting, and snow. For the purposes of this dissertation, a description of research comparing jumping and the attack between the two most prominent variations of volleyball, hard-court and sand, will be performed. Distinct differences have been revealed when comparing countermovement jump (CMJ) performance in the sand (Giatsis et al., 2018; Tilp et al., 2008). Volleyball players perform CMJs with a more upright torso in the sand, while producing shorter jump heights and decreased force production (Giatsis et al., 2018; Pavlov & Buzhinskiy, 2019; Tilp et al., 2008). The duration of countermovement and push-off phases of the jump is increased when compared to the hard-court (Tilp et al., 2008), and hip extension is exacerbated (Giatsis et al., 2018). When performing the attack specifically, the variability in jump height was three times higher in the sand condition (Pavlov & Buzhinskiy, 2019). Researchers postulate these differences are attributed to the shifting surface and subsequent adjustments required to maintain stability.

1.2.5 Injuries and Risk Factors

Researchers have postulated that the prevalence of shoulder overuse injury is due to the repetitive nature of the volleyball attack (Reeser, Joy, et al., 2010; Seminati & Minetti, 2013; Wang & Cochrane, 2001). Shoulder injuries are the third most common in volleyball (Kugler et al., 1996) and account for 8-20% of all reported injuries (Briner & Kacmar, 1997). Overuse injuries also incur about 7 weeks of play time lost (Verhagen et al., 2004). Many types of shoulder injuries fall under this umbrella of "overuse injury" in the literature, including shoulder impingement, scapular dyskinesis, and labral tears. Due to the generalizing of shoulder overuse injuries in this manner, risk factors for these specific injuries are not divulged and instead general factors are reported. Our current knowledge of risk factors for shoulder injury in volleyball is derived from research on other overhead motions such as the baseball pitch. Most overhead movements share similar attributes, yet there are intrinsic differences to each causing distinct kinematic and kinetic profiles (Wagner et al., 2014).

For these reasons, the exact risk factors and epidemiology of shoulder overuse injuries in volleyball is unknown; to estimate risk factors for injury, researchers connect morphological, strength, and technical measures with shoulder pain (Forthomme et al., 2013; Kugler et al., 1996; Mitchinson et al., 2013; Reeser, Joy, et al., 2010; Yi-Fen Shih & Yuan-Ching Wang, 2019). Players with shoulder pain present with a more forward slump of their shoulders (Forthomme et al., 2013), coracoid tightness (Reeser, Joy, et al., 2010), a lateralized scapula (Kugler et al., 1996), and indicators of scapular dyskinesis (Reeser, Joy, et al., 2010). Volleyball players also tend to display glenohumeral internal rotation deficit, which could be connected with shoulder overuse pain (Forthomme et al., 2013; Lajtai et al., 2009; Martelli et al., 2013; Reeser, Joy, et al., 2010; Saccol et al., 2016; Witvrouw et al., 2000). An imbalance of shoulder internal and external rotators is positively correlated with shoulder pain in volleyball players specifically (Wang & Cochrane, 2001), while low core strength is linked with shoulder pain in overhead athletes overall (Burkhart et al., 2003).

1.3 Gap in Knowledge

With the prevalence of shoulder overuse injuries in the sport, it is important to determine the mechanisms behind shoulder injuries, preventative measures, and effective treatment protocols to ameliorate the impact on player health. Because the shoulder is made of many moving parts, including the trunk, upper arm, and scapula, it is possible training modalities not specifically aimed at shoulder musculature may positively impact the health of this joint (Chang et al., 2022). The first article in this dissertation examines interventions for the improvement of volleyball players' shoulder strength, pain, flexibility, and kinematics in the attack.

Kinematics are often calculated using three-dimensional motion capture technology. Motion capture technologies allow researchers and clinicians to characterize complex movements, analyze mechanisms behind injuries, improve movement patterns, and inform surgical interventions (Garcia et al., 2022; Mitchinson et al., 2013; Zaheri et al., 2022; Zahradnik et al., 2018). Despite its popularity in analyzing three-dimensional sport movements, motion capture has seldom been used to analyze upper extremity biomechanics in volleyball players. One likely cause of the hesitancy to introduce motion capture to this explosive upper extremity task is the difficulty in resolving these movements into three-dimensional space via a cardan rotation sequence.

Calculating three-dimensional kinematics at the shoulder can present with problems due to the large range of motion at this joint (Bonnefoy-Mazure et al., 2010; Šenk & Chèze, 2006). The ISB recommends utilizing the Euler rotation sequence YXY for kinematic calculations at the shoulder to account for these issues (Wu et al., 2005); however, previous research suggested this sequence is not ideal for all overhand movements (Bonnefoy-Mazure et al., 2010; Šenk & Chèze, 2006). Before performing research into kinematics leading to injury, one must first establish the proper protocol for the calculation of parameters characterizing the attack. The second article in this dissertation evaluates the efficacy of several commonly implemented rotation sequences used to calculate shoulder kinematics when performing this explosive movement. This paper aims to establish proper protocol and provide insight into the underlying mathematics required to work with motion-capture based movement analyses of the upper extremity.

Lab-based motion-capture measurements provide crucial insight into movement characteristics and are the current gold standard for three-dimensional movement analysis. However, performance in lab-based environments can be vastly different than performance in the actual environment (Friesen et al., 2020). To fully replicate volleyball motions, labs would need high ceilings, enough room for a volleyball court, and the necessary equipment (net, antennae, sand, etc.). Thus, some ecological validity is yielded in a lab setting due to location constraints and to control for confounding variables that may influence results. Yet, analyzing movement in the performance environment, where the participant is most comfortable and likely performing naturally, is crucial to understand how people move within their typical setting. Furthermore, there is a paucity of research regarding the kinematic analysis of the kinetic chain's influence on performance when performing the attack in the sand. The aim of the third study is to use small wearable inertial measurement units (IMUs) to investigate the influence of trunk and pelvis motions on upper arm velocity and attack success when performing the attack in a sand volleyball facility.

1.4 Specific Aims and Hypotheses

Paper 1

Aim 1.1: Consolidate all information regarding the efficacy of interventions aimed towards improving the health of the volleyball player's shoulder.

> Hypothesis 1.1: Interventions including exercises that improve strength and flexibility of the shoulder and torso musculature will reduce shoulder pain and injury incidence in volleyball players.

Paper 2

Aim 2.1: Establish an ideal and coherent methodology for the calculation of shoulder kinematics when performing the volleyball attack.

Hypothesis 2.1: The XZY and YXY sequences will prove the most coherent when calculating shoulder kinematics during the attack.

Paper 3

Aim 3.1: Evaluate the influence of the kinetic chain on ball velocity when performing a volleyball attack on the sand with small wearable devices.

Hypothesis 3.1: Increased trunk and pelvis rotation during the attack will result in higher ball velocity.

Hypothesis 3.2: Hip-to-shoulder separation angle with significantly and positively predict ball velocity.

Hypothesis 3.3: There will be a significant influence of sex, with males displaying greater ball velocities.

CHAPTER 2

INTERVENTIONS TO IMPROVE SHOULDER HEALTH IN VOLLEYBALL PLAYERS: A SYSTEMATIC REVIEW

2.1 Abstract

Volleyball is a widely popular sport in which there are many overuse injuries at the shoulder. OBJECTIVE: To synthesize evidence on interventions geared towards improving the strength, mobility, and overall health of the shoulder in volleyball players. DESIGN: Guided by the PRISMA framework, the researchers designed an a priori systematic review of the published literature. Databases, reference lists, and journals were searched for pertinent information; articles were evaluated for level of evidence and bias. Evidence was compiled to identify suggestions for effective training protocols or interventions to promote beneficial adaptations at the shoulder in volleyball players. RESULTS: 683 articles were found via the systematic search. After title and abstract screening followed by full text review, eleven articles were selected for synthesis. Low to moderate evidence exists suggesting stretching programs improve flexibility of the shoulder in volleyball players. Moderate evidence supports the inclusion of shoulder-specific resistance training programs into regular exercise training to enhance the health of shoulder musculature. Weak evidence supports the efficacy of specific training instruments, including gyroscopic devices and weighted jump ropes, in their influence on shoulder health. CONCLUSION: Volleyball players should incorporate shoulder-specific stretches and exercise protocols into their training programs to mitigate injury risk and promote shoulder health.

2.2 Introduction

Volleyball is an explosive, dynamic sport that is popular around the world. As with any sport, participation in volleyball comes with inherent risk of injury. Acute injuries due to participation typically occur at the knee and ankle while overuse injuries present at the low-back and shoulder (Bahr et al., 2003; Briner & Kacmar, 1997; Seminati & Minetti, 2013; Verhagen et al., 2004). Shoulder pain is common in volleyball players, with afflictions at this joint making up 8-20 percent of all injuries. Furthermore, shoulder pain or injury results in long periods of removal from gameplay or practice (Seminati & Minetti, 2013; Verhagen et al., 2004). In volleyball, the most common cause of overuse injury at the shoulder is the overhead attack. This movement is the leading cause of point scoring, the primary offensive movement in the sport, and associated with the success of the team (A. O. G. F. Oliveira et al., 2018). With its importance to the sport of volleyball, the attack proves an essential skill for players to perfect. Depending on position, players can execute this movement 20-40 times per match (Wolfe et al., 2019). Shoulder pain and injury that impacts a player's ability to perform this movement can have severe repercussions for a player's success and time on the court.

Because of the prevalence of shoulder pain in volleyball players resulting from repetitive practice and performance of the volleyball attack, prior research has attempted to identify risk factors for shoulder injuries. Volleyball players commonly present with glenohumeral internal rotation deficit (GIRD), thought to be indicative of posterior capsule tightness in the shoulder and a possible mechanism for injury (Briner & Kacmar, 1997). One study suggested greater shoulder rotator muscle eccentric maximal strength could be protective against shoulder pain (Forthomme et al., 2013). For those already presenting with shoulder pain, other interventions have been put forward to mitigate pain. Briner and Kacmar (1997) suggested the implementation of exercises that improve the stabilization of the scapula could lessen pain due to rotator cuff tendinitis. Stretching programs have also been suggested to relieve tightness. The prevalence of shoulder pain in volleyball players inspires the need for preventative and rehabilitative care. While many sports require overhand movements, the demands of each are distinct. Therefore, the purpose of this systematic review is to compile evidence regarding effective training interventions for volleyball players that improve shoulder muscular strength, flexibility, and stability and reduce pain.

2.3 Methods

2.3.1 Approaches. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRSMA) framework was employed in the development of the research methodology for this study. The search terms were chosen based on the population, intervention, comparison, outcome (PICO) structure (Schardt et al., 2007). Table 1 contains the search terms and Boolean operators inputted into the databases for article retrieval.

Table 1. Search Terms

Category	Search Terms
Population	"volleyball" OR "volleyball player*" OR "volleyball athlete*"
Interventions	"strength train*" or "resistance train*" or "weight train*" OR "rehab*" OR “train*”
Outcome	"shoulder health" OR "shoulder pain" OR "shoulder injury" OR "shoulder strength" OR "playing time" OR "shoulder mobility"

The databases searched were as follows: SportDiscus, CINHAL, PubMed, Sports Medicine and Education Index, Cochrane, and Medline. Searches were further refined via the use of “English” and “peer-reviewed” filters. All results were imported into an electronic citation manager. Duplicates were removed, then all titles and abstracts were screened for inclusion. Following title and abstract screening, full articles were retrieved and evaluated for quality and bias. For all information regarding article retrieval see Figure 1.

2.3.2 Inclusion and Exclusion Criteria.

Articles were included if it was written in English, published in a peer-reviewed journal, volleyball players were a part of the subject population, and a training or exercise intervention was implemented at the shoulder. Levels I-IV were included in this systematic review, evaluated using the guidelines set forth by Cook et al., (1995) and Sackett, (1989) (Table 2):

Table 2. Level of Research Study

Level I	Systematic reviews, meta-analyses, randomized controlled trials
Level II	Two groups, non-randomized (e.g., cohort, control groups)
Level III	One group, non-randomized (e.g., time-analysis: pre-test and post-test)
Level IV	Descriptive studies
Level V	Case Reports and expert opinions

Articles were excluded if they did not meet the above guidelines.

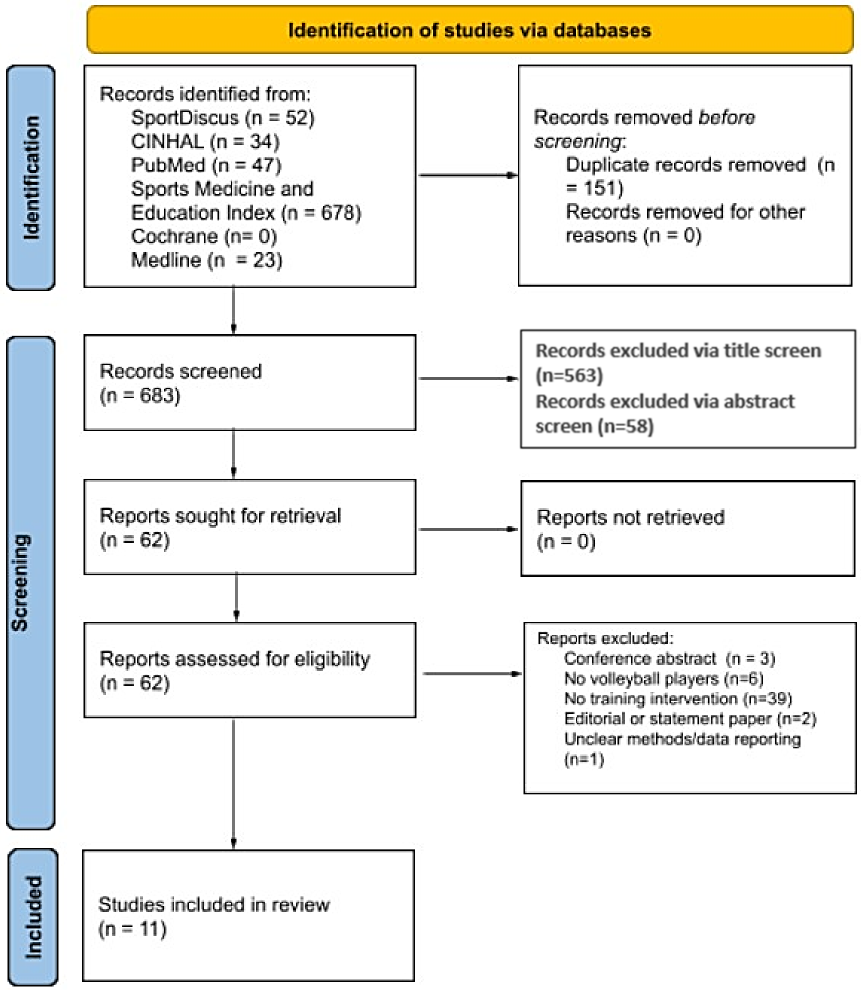
2.3.3 Data Extraction and Appraisal.

Following the removal of duplicates, the primary author screened the titles and abstracts for inclusion in the full review process. If an article was chosen for full review, its information was inserted into an evidence table (Table 3). This information included type of study, level of evidence, population description, interventions employed, outcome variables assessed, and results. The risk of bias for each article was assessed using the template risk of bias table from Higgins et al., (2011)Higgins et al. (2011) (Table 4). Strength of evidence was determined according to guidelines outlined in Berkman et al., (2015). After all articles were screened, catalogued, and assessed for bias, synthesis of evidence began. Suggestions for intervention strategies on improving the health and mobility of the shoulder were then reported based on the strength of evidence reported in the articles revealed by the systematic review.

2.4 Results

The search of databases returned 834 results. Following the removal of duplicates, 683 articles remained. Titles and abstracts were screened for inclusion, resulting in 62 articles for full text review. Fifty articles were excluded as they were a conference abstract, editorial or statement paper, contained no volleyball players, contained no training intervention employed, and/or were unclear reporting of the training intervention and shoulder health outcomes (Figure 1). Eleven articles were included in the final analysis: eight articles were Level I randomized control trials and three articles were Level III single group intervention studies. The results from the selected articles were divided into three categories based on the training intervention implemented: stretching, specialized programming, and equipment.

Figure 1. PRISMA Flowchart



From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: http://www.prisma-statement.org/

Table 3. Evidence Table

Author/Year	Level of Evidence/ Study Design/ Participant Characteristics	Intervention and Control Groups	Outcome Measures	Results
Babaei-Mobarakeh et al. (2017)	Level 1/RCT/45 male volleyball players	Shoulder impingement intervention group, tennis elbow intervention group, control group; intervention groups received gyroscopic training	Internal and external concentric & eccentric shoulder strength, grip strength, wrist extension strength, shoulder & wrist proprioception	Significant difference from pre-test to post-test in both intervention groups for all measures. Significant difference between both intervention groups and the control group for all measures.
Chang et al. (2022)	Level 1/RCT/40 volleyball players with scapular dyskinesis and chronic shoulder pain	Kinetic chain training vs conventional shoulder training groups	Self-reported shoulder pain, scapular dyskinesis, attack kinematics, & muscle activation	Significant time effect on pain, scapular upward rotation, and upper trunk side-bending. No effect on muscle activation. Group by time effect on upper trunk rotation at ball contact: kinetic chain group increased contralateral rotation.
Chepeha et al. (2018)	Level 1/RCT/37 college overhand athletes	Sleeper stretch and control groups	Shoulder IR and horizontal adduction ROM	Significant increases in IR and horizontal adduction in the training group
Duzgun et al. (2010)	Level 1/RCT/24 13-16 year old volleyball players	Weighted jump rope, unweighted jump rope, & control group	Shoulder IR/ER and shoulder elevator isokinetic strength	Total eccentric work during shoulder elevation improved in the weighted and control groups. There were no differences in the thumbs down shoulder elevation movement. Peak torque and total work decreased in IR isokinetic testing at all speeds. ER peak torque and total work increased at 60°/s for the weighted group,

				and total work for unweighted group improved for ER at 60°/s. IR peak torque and total work at 180°/s decreased significantly for the unweighted jump rope and control groups
Eshghi et al. (2022)	Level 1/RCT/32 male youth Iranian volleyball players	Control and experimental group. Experimental group performed the "FIFA 11 + Shoulder" (11+S) program for 8 weeks	Isokinetic strength of the shoulder: IR/ER eccentric and concentric strength at 60 deg/s and 180 deg/s, ab/adduction concentric strength at 60 deg/s, and flex/ext concentric strength at 60 deg/s; FDR at 60 deg/s and 180 deg/s	No significant interaction in isokinetic shoulder strength. Significant Time x Group interaction on FDR at 180 deg/s with the intervention group showing significant improvement over time. No interaction effect at 60 deg/s.
Gharisia et al. (2021)	Level 1/RCT/42 physically active athletes (20 males and 22 females)	Sleeper stretch vs. novel stretch	Shoulder pain and IR ROM	Significant effect of time for both groups in shoulder IR ROM; IR ROM increased from baseline to week 4. A significant group by time interaction was found for shoulder pain: those in the novel group showed a significant reduction in pain intensity over time.
Merolla et al. (2010)a infraspinatus strength	Level 3/non-randomized pre and post-test/31 athletes (22 men 9 women mean age 22 rotator cuff tears)	Rehabilitation program; no control group	Isokinetic strength test and ROM assessment	Significant increase in isokinetic strength and a significant increase in IR ROM of the glenohumeral joint following rehabilitation program.
Merolla et al. (2010)b	Level 3/non-randomized pre and post test/29 subjects 8 tennis 18	Rehabilitation program; no control group	Supraspinatus and infraspinatus isometric	Significant increase in IR ROM and significant decrease in pain following intervention. No

supraspinatus weakness	volleyball (18 male 11female)		strength, shoulder IR ROM	significant differences between tennis and volleyball players found.
Moradi et al. (2020)	Level 1/RCT/60 university male volleyball players	8-week TheraBand throwing intervention group and control group	Infraspinatus, Supraspinatus, and Deltoid activation, IR ROM, Rotator cuff isokinetic strength, Joint position sense	Intervention group showed significant delay in muscle activation of evaluated muscles reduced muscle activation, improved IR ROM, shoulder eccentric strength, shoulder concentric strength, and JPS.
Schwartz et al. (2021)	Level 3/Non-randomized pre- and post-test/20 male handball or volleyball athletes with GIRD and horizontal adduction deficit	Stretching program consisting of the sleeper stretch and cross-body arm stretch; no control group	Self-reported pain, shoulder tightness, passive IR and ER, indicators of impingement syndrome and rotator cuff lesions, ER and IR rotator strength	Significant decrease in pain and tightness, increase in internal passive mobility, reduction in positive tests for impingement syndrome and rotator cuff lesion following stretching intervention with no changes in isokinetic strength. Greater posterior tilt of the scapula was found in the symptomatic group at rest following the intervention.
Zarei et al. (2021)	Level 1/RCT/32 young male volleyball players	Control and experimental group; experimental group performed the "FIFA 11 + Shoulder" (11+S) program for 8 weeks	Shoulder JPS, TTDPM, and UQYBT performance	Improvement on UQYBT performance in the FIFA 11+S group. Significant effect of time for JPS of IR at 45 degrees, JPS of ER at 75 degrees, and TTDPM of ER at 75 degrees for both groups with no difference between groups.
RCT: randomized control trial; JPS: joint position sense; IR: internal rotation; ER: external rotation; ROM: range of motion TTDPM: threshold to detect passive motion, UQYBT: upper quarter Y balance test				

Table 4. Risk of Bias Table

	Selection Bias		Performance Bias	Detection Bias		Attrition Bias	Reporting Bias
Citation	Random Sequence Generation	Allocation Concealment	Blinding of Participants and Personnel	Blinding of Outcome Assessment: Self-reported outcomes	Blinding of Outcome Assessment: Objective Outcomes	Incomplete Outcome Data	Selective Reporting
Babaei-Mobarakeh et al. (2017)	+	+	+	(?)	+	+	+
Chang et al. (2017)	+	(?)	-	(?)	-	+	+
Chepeha et al. (2018)	+	(?)	-	+	+	+	+
Duzgun et al. (2010)	+	(?)	(?)	(?)	(?)	+	+
Esghi et al. (2022)	+	(?)	(?)	(?)	-	+	(?)
Gharisia et al. (2021)	+	+	-(participants) +(personnel)	+	+	+	-
Merolla et al. (2010)a infraspinatus strength	-	(?)	(?)	-	-	+	(?)
Merolla et al. (2010)b supraspinatus weakness	-	(?)	(?)	-	-	+	+
Mordai et al. (2020)	+	(?)	-(participants) +(personnel)	(?)	+	+	+
Schwartz et al. (2021)	-	(?)	(?)	(?)	(?)	+	(?)

Zarei et al. (2021)	+	(?)	+ (participants) - (personnel)	(?)	(?)	+	(?)

Note. Categories for risk of bias are as follows: Low risk of bias (+), unclear risk of bias (?), high risk of bias (-).

2.4.1 Stretching Interventions

Three studies (Chepeha et al., 2018; Gharisia et al., 2021; Schwartz et al., 2021) investigated the effects of specific shoulder stretches on shoulder mobility, pain, and indicators of health concerns. The stretching intervention in all these studies included the sleeper stretch (Figure 2), but the methods differ in number of repetitions, duration, and the inclusion of other stretches in the protocol. These studies provide moderate levels of evidence supporting the inclusion of a stretching protocol into training programs for volleyball players.

Figure 2. Sleeper Stretch

Chepeha et al. (2018) performed a Level I randomized control trial in which they asked participants in the intervention group to perform the sleeper stretch every day for 5 repetitions. Those in the control group performed their regular training exercises with no inclusion of posterior shoulder stretches. Participants were only included if they presented with posterior shoulder tightness, defined as a reduction in internal rotation range of motion greater than 15° in the dominant limb. Improvements in shoulder ranges of motion were significant following the eight-week intervention program (Chepeha et al., 2018). Moreover, after only four weeks of the intervention, athletes reported better shoulder functioning. However, certain aspects should be considered when generalizing the success of this stretching program to volleyball players. For instance, while volleyball athletes made up the majority of participants in this study (24 out of 37), other overhand athletes were included in the program. Furthermore, the athletes in this study already presented with posterior shoulder tightness. It is possible that the benefits of performing the sleeper stretch would not be found in those without deficits in posterior shoulder range of motion.

Gharisia et al. (2021) (Level I) compared the sleeper stretch to a novel, modified sleeper stretch (Figure 3) and their efficacy in improving pain and IR ROM. No significant group by time interaction was found for IR ROM, but both groups significantly improved in their ROM over time. No distinction between asymptomatic and symptomatic individuals were made for the ROM evaluation. For pain assessment, participants were split up into asymptomatic and symptomatic groups within the overall experimental groups. Asymptomatic participants showed no change in pain levels over time. Symptomatic members of the novel stretching group displayed a significant reduction in pain over time with no decrease in pain for the sleeper stretch group. This supports the replacement of the standard sleeper stretch with the novel stretch in those presenting with shoulder pain (Gharisia et al., 2021).

The findings of Schwartz et al. (2021) (Level III) support the sleeper stretch as a positive intervention that can improve the health of the shoulder. They included symptomatic (presenting with shoulder pain) and asymptomatic (no shoulder pain in their dominant limb) overhand athletes and asked the athletes to perform a stretching program which included the sleeper stretch and cross-body stretch. These athletes competed in either handball or volleyball and presented with GIRD and horizontal adduction deficit. The cross-body arm stretch is performed by standing against a wall to stabilize the scapula, raising the arm 90 degrees, and maximally horizontally adducting the shoulder. The major findings of the study included a reduction in pain in the symptomatic group and improvements in both groups in shoulder tightness (Schwartz et al., 2021). Most importantly, indicators of impingement syndrome and rotator cuff lesion were significantly reduced in the symptomatic group following this stretching protocol.

A significant limitation of Schwartz et al. (2021) and Gharisia et al. (2021) in their application to volleyball players specifically is the ambiguity on the number of volleyball players in the participant population. In both studies, the authors clearly state the inclusion of volleyball players in their pool; however, the exact number is unknown. It is possible most of the participants participated in other overhead sports with only a select few playing volleyball. Overhand athletes perform similar movements and are therefore often grouped together, yet the demands of these movements are distinct for each sport. As such, these findings should be accepted warily regarding the specific population of this systematic review.

2.4.2 Specialized Programming

There is moderate evidence supporting the use of specialized training programs as a means of improving shoulder health. Three Level I studies investigated the impact of two different training programs on varying aspects of shoulder wellbeing, with contrasting results. Zarei et al. (2021) and Eshghi et al. (2022) investigated the efficacy of the FIFA 11+S program on characteristics of shoulder health in young male volleyball players. The FIFA 11 + S injury prevention program was originally developed to reduce risk factors of shoulder injuries in goalkeepers in soccer (Eshghi et al., 2022; Zarei et al., 2021); however, the program includes shoulder strengthening exercises thought to have an impact on the health of other overhead athletes. This program includes three parts: a warmup, core strengthening, and strength and balance training for the upper limb; a full description is elucidated in Ejnisman et al., (2016).

According to Zarei et al. (2021), no effect on muscle proprioception was found.

However, participants significantly improved in dynamic stability. Isokinetic strength of the shoulder was not found to differ between the intervention and control groups, but a significant time x group interaction was found when evaluating the functional deceleration ratio (FDR) at 180 °/s (Eshghi et al., 2022). The intervention group increased their FDR by 20% following the FIFA 11 + S training program. FDR has been defined as the ratio between eccentric ER strength and concentric IR strength (Berckmans et al., 2017), but the exact calculation of FDR by Eshghi et al. was not outlined in the article. Therefore, cross-study comparisons cannot be made, as one can only infer how this variable was calculated based on previous research.

Another Level I study investigated the effect of a kinetic chain exercise program on attack performance and shoulder pain in volleyball players (Chang et al., 2022). Participants included 40 volleyball players with scapular dyskinesis and chronic shoulder pain. Researchers split participants into a kinetic chain intervention group and a control group performing a typical shoulder strengthening program. Both groups displayed significantly reduced shoulder pain following the training interventions, lending credence to incorporating these modalities into training protocols for volleyball players (Chang et al., 2022). Contrary to their hypothesis, no differences existed between groups in pain reduction, attack kinematics, or scapular activation.

In addition to the three Level I studies mentioned above, two Level III studies investigated the impact of a specialized program designed to restore scapular muscle control (Merolla, De Santis, Campi, et al., 2010; Merolla, De Santis, Sperling, et al., 2010). In Merolla et al. (2010b), 31 professional volleyball players with scapular dyskinesis took part in a six-month rehabilitation program that included exercises targeting the trapezius, rhomboids, and serratus anterior. Participants significantly improved in the infraspinatus strength test and in pain levels following this rehabilitation protocol. Similar improvements in strength, ROM, and pain were seen in Merolla et al. (2010a) in a population of volleyball and tennis players. IR ROM, supraspinatus strength, and pain levels improved following the rehabilitation protocol with no differences between the tennis and volleyball players.

2.4.3 Instrumented Interventions

Evidence supporting the efficacy of therapeutic instruments to improve shoulder health is emerging in the literature. There are many kinds of instruments employed; therefore, it is difficult to group their results together to evaluate overall efficacy. Three Level I RCTs (Babaei-Mobarakeh et al., 2018; Duzgun et al., 2010; Moradi et al., 2020) are included in this subcategory. Each of these studies examined the incorporation of an external tool, instrument, or accessory in their intervention protocols.

In adolescent male volleyball players, external rotation strength was shown to improve following training with a weighted jump rope compared to an unweighted condition (Duzgun et al., 2010). Participants in this study were randomly assigned to one of three groups: a control with no jump rope training, an unweighted jump rope group, and a weighted jump rope group. Those with scapular dyskinesis or shoulder pain were excluded from the study. 12 weeks of regular volleyball training and jump rope training were completed and measures of strength were evaluated. The only significant improvement between the control, weighted, and unweighted groups was in the external rotation strength.

Another instrument investigated was a gyroscopic device. These vibrating devices can be easily incorporated into exercise to provide oscillatory perturbations and increase intensity. Players with shoulder impingements or tennis elbow were recruited to participate in eight weeks of training with a gyroscopic device (Babaei-Mobarakeh et al., 2018). In this Level I study, participants were split into three groups (two intervention and one control) and performed 8 weeks of training. The two intervention groups were split by health concern: one group consisted of those with shoulder impingement syndrome and the other with tennis elbow. The control group did not perform any targeted resistance training but received self-care recommendations for pain and patient education. Researchers found significant improvements in shoulder, wrist, and grip strength, shoulder and wrist proprioception, and dynamic stability in the intervention groups. Despite these promising results, the lack of comparison to a regular resistance training protocol makes it unclear whether improvements in strength were a result of the unique gyroscopic device.

The final intervention to be evaluated is the use of a TheraBand in conjunction with various throwing exercises (Moradi et al., 2020). 60 male volleyball players with GIRD completed an eight-week training protocol and were evaluated based on IR ROM, glenohumeral joint position sense, and muscular activity of the infraspinatus, supraspinatus, and all three sections of the deltoid. Participants in both groups performed variations of the sleeper stretch for the training period, while members of the intervention group performed additional throwing exercises with the TheraBand. Researchers found significant differences between groups following the training period in muscle activation, onset of muscle activation, IR ROM, shoulder strength, and joint position sense. The intervention group showed significant improvement in IR Rom, joint position sense, and strength. Additionally, they displayed delayed onset of the middle deltoid, supraspinatus, and infraspinatus muscles when throwing, and decreased activation of the overall deltoid, supraspinatus, and infraspinatus. GIRD is thought to affect the timing of muscle activation (Moradi et al., 2020); however, it is unclear whether the differences in timing found in this study are improvements or regressions.

2.5 Discussion

Evidence regarding varying interventions aimed towards improving shoulder health in volleyball athletes is presented in this systematic review. Volleyball players are at risk for shoulder pain and injury due to the nature of their sport (Bahr et al., 2003; Briner & Kacmar, 1997; Verhagen et al., 2004; Zarei et al., 2021). It is paramount that athletes take precautions to limit the incidence of these health issues.

Current literature suggests shoulder tightness as the cause of shoulder pain, range of motion deficits, and impingements (Chepeha et al., 2018). Research suggests these phenomena could be improved by completing a stretching program (Briner & Kacmar, 1997). Three articles reported findings supporting the implementation of a stretching program that includes the sleeper stretch in volleyball players (Chepeha et al., 2018; Gharisia et al., 2021; Schwartz et al., 2021) . The sleeper stretch is designed to relieve posterior shoulder tightness by targeting the posterior rotator cuff and the posterior capsule of the shoulder. As GIRD is regularly seen in volleyball players and other overhead athletes (Briner & Kacmar, 1997; Chepeha et al., 2018; Mizoguchi et al., 2022; Schwartz et al., 2021), it is warranted to suggest the prescription of the sleeper stretch to this population. Furthermore, a modification of the sleeper stretch, as investigated by Gharisia et al. (2022), could be beneficial for those presenting with shoulder pain.

The benefits of the sleeper stretch and its impacts on GIRD are supported in the literature in volleyball players. However, these studies reported conflicting results on the improvement of shoulder pain following stretching programs. It is possible that the disparities in results between the three studies are a result of slightly different programs, as Schwartz et al. (2021) included the cross-body stretch in their program and Gharisia et al. (2022) simply compared two versions of the sleeper stretch. Shoulder stretching and resistance training may be beneficial in reducing pain levels in those who already present with shoulder pain (Babaei-Mobarakeh et al., 2018; Chang et al., 2022; Schwartz et al., 2021), but an analysis of a healthy population was not performed. Typically, it is easier to improve pain and mobility if there are already deficits present in a population.

Specialized training programs have been suggested to improve shoulder health, with varying degrees of success. The incorporation of a shoulder-specific training program into regular practice had some positive effects on components of shoulder health (Eshghi et al., 2022; Zarei et al., 2021). This program, while originally developed for soccer goalkeepers (Ejnisman et al., 2016), was found to improve FDR at 180 °/s, performance on the Upper Quarter Y-Balance Test, and joint position sense in adolescent male volleyball players. While improvement in FDR has implications for a reduction in stress on passive stabilizers of the shoulder (Rokito et al., 1998), it is important to note the authors of Eshghi et al. (2022) did not report the exact calculation of this variable. Thus, cross-study comparisons are limited. Despite this limitation, the results of Zarei et al. (2021) support the prescription of this training protocol for improvements in shoulder dynamic stability and proprioception.

Training modalities specifically designed to target shoulder musculature are the most commonly prescribed; yet, other research has suggested targeting the entire kinetic chain to improve shoulder and scapular health (Chu et al., 2016). As the volleyball attack is not simply a shoulder movement, it would follow that training the full body or those segments most involved kinetic chain of the movement (ex. pelvis, trunk) would impact performance. In contrast to this theory, no difference between conventional shoulder training and kinetic chain training were found (Chang et al., 2022).

Modifications to training devices and the inclusion of additional equipment have also been put forth as possible avenues for improving shoulder health. Volleyball players displayed minimal differences in shoulder strength between weighted and unweighted jump rope training (Duzgun et al., 2010), quelling the suggestion to include this type of exercise as a possible mode of improvement for the shoulder. The use of a gyroscopic vibrating device was found to significantly improve shoulder strength (Babaei-Mobarakeh et al., 2018). The incorporation of TheraBand throwing exercises was found to strengthen the shoulder, expand IR ROM, enhance muscle proprioception, and impact muscular activation (Moradi et al., 2020). However, these two studies presented with some distinct limitations (Babaei-Mobarakeh et al., 2018; Moradi et al., 2020). While the improvements in strength and shoulder functioning were evident following training with the gyroscopic device (Babaei-Mobarakeh et al., 2018), it is difficult to say if it should be recommended above other options for the reduction of shoulder pain and improvement in shoulder health due to the lack of a comparison to a regular exercise protocol. Similarly, in Moradi et al. (2020), the control group performed stretching exercises rather than all exercises without the TheraBand. It is then impossible to determine if the improvements in the intervention group were due to the TheraBand rather than the incorporation of additional exercises.

2.6 Limitations

The literature reviewed in this study was limited in its size, population, study design, and outcome measures. There were a small number of studies that fit the criteria of this review with varying approaches to improving shoulder health. Furthermore, the population of each of these studies was varied. Volleyball players were included in each study; however, other overhand athletes also made up a decent proportion of the participants. Sport specificity is a known phenomenon (Reilly et al., 2009); therefore, it is hard to generalize the findings of all overhead athletes to volleyball players specifically. Additionally, many of these interventions were performed by those already presenting with deficits. A more robust analysis would include a healthy population along with control group(s). With regards to study methodology, most of the included articles did not blind the personnel administering the outcome measures. This diminishes the strength of the results, as unblinded personnel may influence the performance of the participants if they believe one group should outperform the other. However, the biggest limitation of the current review is the variability and ambiguity of the outcome measures evaluated in these studies. Many of these studies investigate changes in range of motion; yet it is unclear whether a larger range of motion is beneficial or just an indicator of greater instability.

2.7 Implications for Future Research

There are a few recommendations based on the findings of this systematic review:

- While all studies incorporated some participants classified as volleyball players (ex. a group of overhead athletes), few included solely volleyball players as their subject population. Due to sport specificity, it is imperative future research investigate this specific population for the most applicable findings.
- Few studies meeting the criteria for this review included a healthy population of volleyball players, instead focusing on those with upper extremity pathologies. While improving the health of an injured population is incredibly important, findings should be generalized to volleyball players as a whole in order to support the mitigation of injury risk for all players. Future studies should investigate these interventions in healthy populations to determine if the effects are similar.

- More research is needed on the relationship between the variables assessed in these studies (ex. Range of motion, pain, shoulder strength) and injury incidence. If the purpose of training interventions is to reduce injury risk, outcome measures should be derived from variables indicative of injury.
- Research regarding the effect of these interventions and others over long periods of time should be performed. Interventions lasted around 8-12 weeks and further muscular adaptations could be present with prolonged training interventions.

2.8 Implications for Training Interventions

Including exercises that enhance shoulder musculature strength and flexibility in regular training is purported to improve the health of this joint in volleyball players. Based on the findings of this review, the incorporation of a stretching program with a sleeper or modified sleeper stretch into regular practice is beneficial for volleyball players (Chepeha et al., 2018; Gharisia et al., 2021; Schwartz et al., 2021). Shoulder strength is also significantly impacted by shoulder-specific, kinetic chain, and TheraBand exercises (Chang et al., 2022; Moradi et al., 2020; Zarei et al., 2021). As such, volleyball coaches and trainers should include these protocols in their workout sessions to assist in the prevention of injuries. There is limited evidence on the efficacy of the use of a gyroscopic device or weighted jump roping, however no negative effects were reported (Babaei-Mobarakeh et al., 2018; Duzgun et al., 2010). If individual players find these accessories to be beneficial, then the inclusion of them is supported.

2.9 Conclusion

To our knowledge, this is the first review to date to synthesize evidence regarding the efficacy of training interventions for the shoulder health of volleyball players. The findings of this systematic review suggest the implementation of stretching and shoulder strengthening exercises in training protocols to induce muscular adaptations that could be beneficial for the shoulder of volleyball players. Advancements in flexibility of the shoulder musculature could lead to a reduction in tightness, improving quality of life in those who experience pain as a result of tension in this area. Significant improvement in shoulder functioning could have implications for gameplay enhancements and the reduction of injury risk in volleyball players.

CHAPTER 3.

ROTATION SEQUENCES FOR THE CALCULATION OF SHOULDER KINEMATICS IN THE VOLLEYBALL ATTACK

Barrett KB, Parrish, K., & Bennett, H. J. Rotation sequences for the calculation of shoulder kinematics of the volleyball attack. *Journal of Biomechanics*, 2024.162: 111906.

3.1 Abstract

Calculating upper extremity kinematics during overhead movements presents with problems typically not seen for the lower extremity due to the large range of motion. Due to these unique issues, different rotation sequences have been suggested to circumvent challenges due to gimbal lock (GL) and angle coherence (AC). The purpose of this study is to determine the most appropriate rotation sequence for shoulder angle calculation during a volleyball attack. METHODS: 15 healthy experienced volleyball players (women = 8) performed 5 attacks off a stationary ball. A 12-camera 3D motion capture system was utilized to record trunk and arm kinematics to compare joint angles calculated using the YXY, ZXY, XZY, YXZ, ZYX, and XYZ rotation sequences. Instances of GL and AC inconsistences were marked for each trial. The last 3 trials were used for analysis. RESULTS: The YXY and XYZ sequences presented with the least total number of errors (12 and 5, respectively). 5 instances of GL were present in the XYZ sequence while none were recorded for the YXY sequence. All other sequences returned incoherent angles that greatly exceeded known ranges of motion. CONCLUSION: When performing kinematic analyses during a volleyball attack, researchers should adhere to ISB recommendations and employ the Eulerian YXY sequence for calculations. If greater anatomical understanding is desired, the XYZ sequence may be utilized for most subjects.

3.2 Introduction

Made up of the torso, humerus, scapula, and clavicle, the shoulder is a complex joint capable of a large range of motion (ROM). Calculation of three-dimensional joint kinematics occurs using the Tait-Bryan ZXY (Z: mediolateral, X: anteroposterior, Y: vertical axes) rotation sequence due to ease of understanding and a history of lower extremity research in gait (Baker, 2001; Lees et al., 2010; Wren & Mitiguy, 2007). Furthermore, the ZXY sequence is preprogrammed into many commercial gait analysis software packages (e.g., Vicon Clinical Manager: Oxford Metrics, UK, Coda: Charnwood Dynamics, UK, Elite: BTS, Italy, Motus 2000: Peak Performance Technologies, USA) since it is most common for gait analysis (Baker, 2001). However, this rotation sequence can present with problems in amplitude coherence (AC) (Bonnefoy-Mazure et al., 2010; Šenk & Chèze, 2006) and gimbal lock (GL) (Bonnefoy-Mazure et al., 2010; Šenk & Chèze, 2006) when examining upper extremity kinematics. The International Society of Biomechanics recommends employing the Eulerian-YXY rotation sequence to minimize the occurrence of GL for shoulder kinematics (Wu et al., 2005). Nonetheless, other sequences have proven to be more reliable and understandable in terms of anatomical position (Bonnefoy-Mazure et al., 2010; López-Pascual et al., 2016; Šenk & Chèze, 2006). A single ideal method has not been suggested for all movements. Thus, it is important to determine a comprehensible rotation sequence resolution presenting with the least amount of gimbal locks and angle incoherence for each overhand movement.

Volleyball is a popular sport played in over 200 countries around the globe according to its governing body, the Fédération Internationale de Volleyball (Fédération Internationale de Volleyball, n.d.). This sport consists of many explosive movements, the most common offensive action being the “attack”. The volleyball attack (Figure 1) consists of a high-velocity overhead movement crucial to the overall success of a team (A. O. G. F. Oliveira et al., 2018). The attack has been predominantly linked to shoulder overuse injuries leading to the evaluation of attack mechanics within the field of biomechanics (Briner & Kacmar, 1997). Previous research has reported kinematic variables of the overhand attack (Brown et al., 2014; Ferris et al., 1995; Jurkojć et al., 2017; Mitchinson et al., 2013), but have not clearly defined the rotation sequence used to perform these calculations. The 3D rotation sequence is extremely important in the calculation of shoulder angles; both results and interpretations of the angle can change based on rotation sequence rather than the movement itself (Bonnefoy-Mazure et al., 2010; Creveaux et al., 2018). As such, researchers and clinicians alike continue to face many challenges when compiling findings across the literature given the ambiguity of the rotation sequence methodology.

Figure 3. Depiction of a Volleyball Attack

Therefore, the purpose of this study is to evaluate shoulder angles calculated from six rotation sequences (YXY, ZXY, XZY, YXZ, ZYX, and XYZ) during volleyball attacks. The YXY, ZXY, and XZY sequences have been previously analyzed in the tennis serve, with the recommendation to employ XZY when calculating shoulder angle (Bonnefoy-Mazure et al., 2010). In our analysis, these three sequences were included in addition to YXZ, ZYX, and XYZ. Evaluating six sequences provides a more robust analysis than any previous investigation and supplies additional information on the efficacy of a variety of methods for kinematic calculations. We hypothesize the XZY and YXY sequences will present with the smallest number of instances of gimbal lock and angle incoherence (Bonnefoy-Mazure et al., 2010; Creveaux et al., 2018).

3.3 Methods

3.3.1 Participants.

To participate in this study, participants were required to be between 18-35 years of age, competing at the AA level or above, have no current shoulder pain, and had no major orthopedic surgery in the last six months. The AA level is described as highly competitive players, college athletes, or professionals (*Leagues*, n.d.). Participants were excluded if they had current shoulder pain, a major orthopedic surgery in the last six months and/or did not meet inclusion criteria. 15 healthy volleyball players (women=8) that competed at the AA level or above volunteered to participate in this study. Participant characteristics are reported in Table 1.

Table 5. Participant Characteristics reported as Mean (SD)

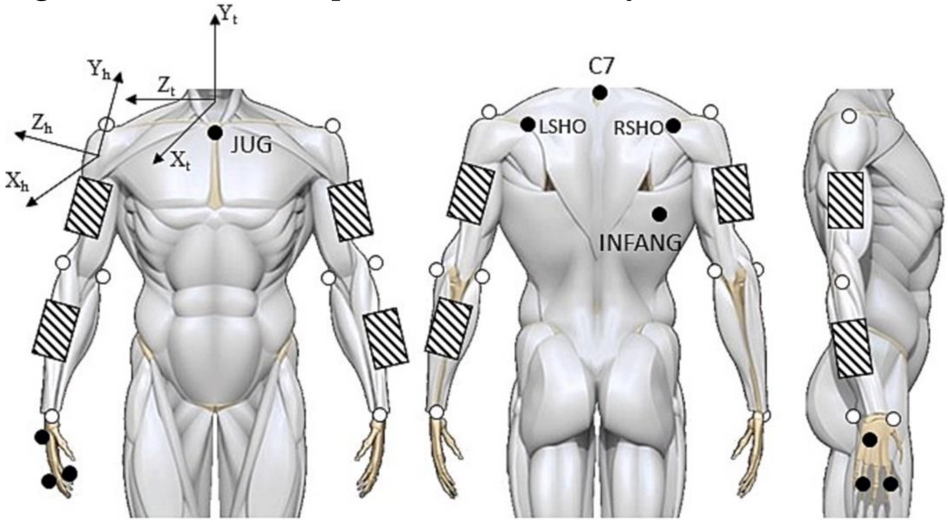
	Overall	Males	Females
Age (yrs)	26.20 (3.59)	26.29 (4.19)	26.13 (3.27)
Height (m)	1.82 (0.07)	1.84 (0.07)	1.81 (0.06)
Mass (kg)	79.01 (16.10)	82.53 (18.94)	75.94 (13.72)
Years of Experience	11.17 (3.70)	9.64 (3.20)	12.50 (3.78)

3.3.2 Testing Protocol.

Following signing of the informed consent, participants completed a medical history questionnaire to determine eligibility for inclusion. If all inclusion criteria were met, data collection proceeded. A 12-camera three-dimensional motion capture system was used to record trunk and upper extremity kinematics at 250Hz. Marker placements are depicted in Figure 2.

Participants were instructed to perform their regular approach and jump, followed by hitting a stationary volleyball held at a comfortable height straight ahead, and complete the movement with their arm swing across their body with their dominant hand near the contralateral hip. The last 3 three successful trials were used for analyses.

Figure 4. Marker set implemented in the study.



Note: Depiction of anatomical markers (white), tracking markers (black), tracking clusters (striped rectangles), and segmental coordinate systems (left).

3.3.3 Data Processing.

Data were processed using Visual3d (version 6; C-Motion, Inc.). A kinematic model using an upper arm cluster to track the humerus and the left shoulder, right shoulder, C7, inferior angle, and jugular markers to track the trunk was created. Segmental coordinate systems were defined according to ISB recommendations for the humerus, forearm, and hand (Wu et al., 2005). Due to participant apparel, a marker was placed on the inferior angle of the dominant limb as indicated by (Haneline et al., 2008) in place of the T8 marker recommended by the ISB. The shoulder joint center was calculated as an offset of the distance between the left and right acromion markers (Rab et al., 2002).

A priori analyses indicated the optimal cutoff frequency was 15Hz; data were filtered using a 4th order zero-lag Butterworth filter. Shoulder angles were calculated as the rotations of the humerus relative to the thorax using six rotation sequences: ZXY, YXY, XZY, YXZ, ZYX, and XYZ. ISB axis nomenclature is different from that of Visual3D. For example, the mediolateral axis is “X” in Visual3D but "Z" according to the ISB. Regardless of nomenclature, any cardan rotation sequence can be easily implemented in Visual3d using the imbedded “Compute Model Based” function, whereby the user selects type of computation (e.g., joint angle via segment selection) along with additional specifiers, such as cardan sequence, via drop down menus. Readers are directed to the Visual3d wiki page (managed by C-Motion, www.c-motion.com/v3dwiki) or to reach out to C-Motion directly for additional information. For ease of reporting and conversion with current literature, the ISB nomenclature is reported herein.

Rotation sequences were compared using AC and GL. AC was assessed using reported ranges of motion of the shoulder: clinical coherence (abduction: 185°, adduction: 55°, extension: 65°, flexion: 185°, external rotation (ER): 95°, internal rotation (IR): 95°) and an expanded internal/external ROM measured during passive trials in volleyball players (IR: 83°, ER: 129°; (Telles et al., 2021)). If a calculated angle fell outside of these ranges, the sequence was marked for incoherence in that trial. Values for total ROM of the shoulder in each plane were also assessed for violations. Instances of GL were recorded when the second rotation of the sequence fell within a conservative range of +/- 5 of 90° (Šenk & Chèze, 2006). Counts of violations were totaled across all participants.

3.4 Results

Peak angles for each rotation sequence across participants are reported in Table 2. AC issues and occurrences of GL are reported in Table 3. The ZXY and YXY sequences did not result in any instances of GL; however, the ZXY sequence frequently returned incoherent angles vastly exceeding known ranges of motion, particularly in IR/ER (Tables 2 & 3). In many instances when utilizing the XZY, ZYX, and YXZ sequences, angles did not return to anatomical position despite the neutral orientation of the participant (see Figure 3). The YXY and XYZ sequences presented with the least number of errors across all variables for each participant. A graphical example of shoulder angle calculations is provided in Figure 3.

Table 6. Maximum and minimum calculated angle per rotation sequence.

	Z		X		Y	
	Min	Max	Min	Max	Min	Max
XYZ	-37.47	152.99	-150.58	28.07	-89.56	67.62
YXY*	-107.14	138.60	-152.70	9.87	-107.04	53.53
XZY	-37.23	89.35	-399.76	414.34	-361.73	470.20
ZYX	-351.89	461.37	-374.78	398.89	-17.30	87.36
ZXY	-44.13	229.61	-84.65	40.83	-19.19	199.85
YXZ	-353.77	416.42	-87.02	15.57	-353.36	445.28

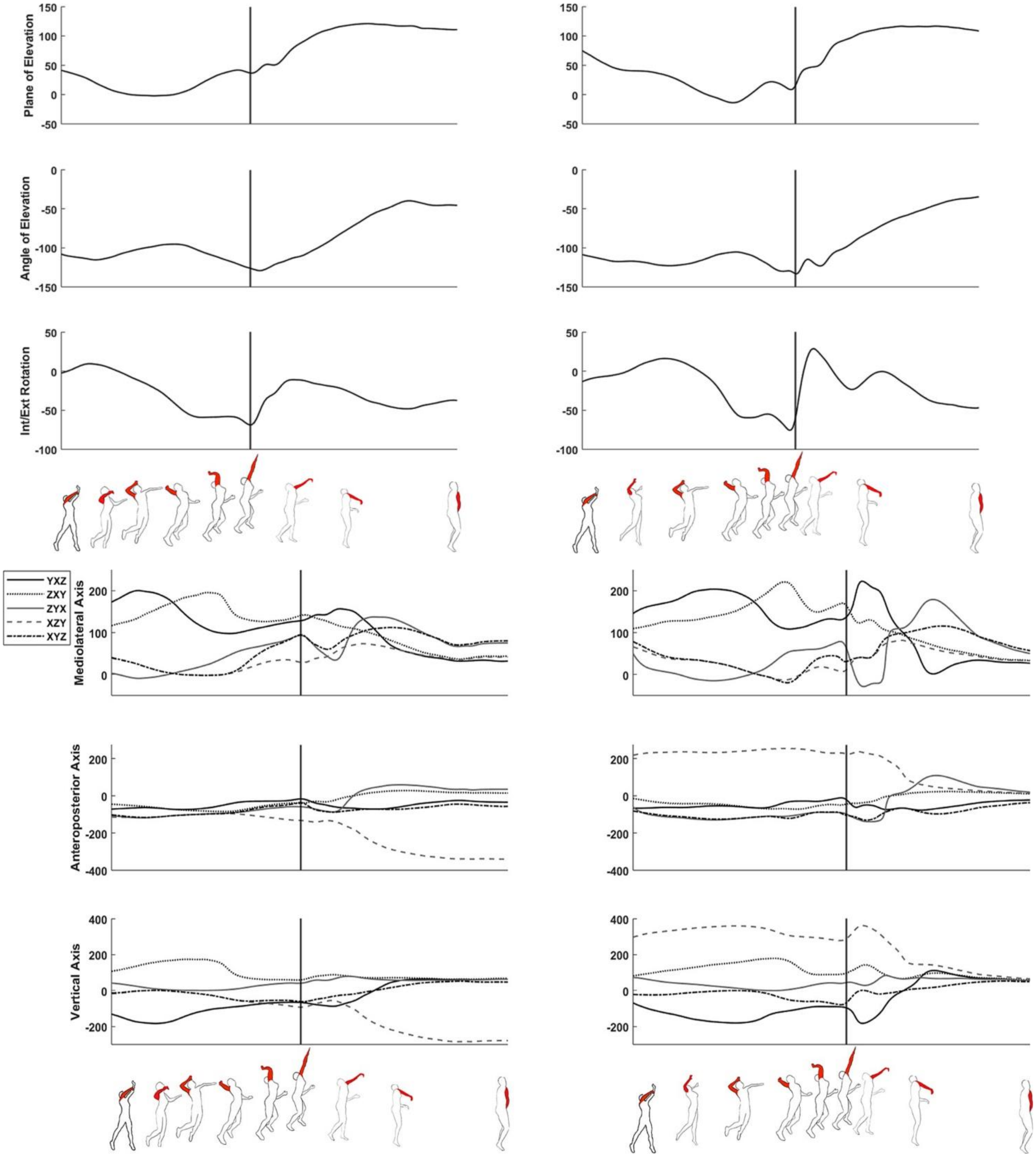
Note: *For the Eulerian YXY sequence, Z is the first rotation about the Y axis, X is the first rotation about the X axis, and Y is the second rotation about the Y axis

Table 7. Instances of Calculation Errors

	AC (VB)	ROM Coherence (VB)	AC (Clinical)	ROM Coherence (Clinical)	GL
XYZ	0	0	0	0	5
YXY	0	0	12	0	0
XZY	33	15	36	24	14
ZYX	20	0	12	3	2
ZXY	30	0	45	2	0
YXZ	25	22	45	27	3

Note: AC (VB): Angle coherence according to passive range of motion of volleyball players; ROM: Range of motion; GL: Gimbal Lock; AC (Clinical): Angle coherence according to clinical ranges of motion

Figure 5. Sample shoulder angle data from two representative participants.



Note: XYZ (top) and YXY (bottom) sequences measured in degrees for two participants (separate columns). Graphs depict angles from takeoff to follow-through. A detailed description of the rotations is provided in the Discussion section.

3.5 Discussion

The purpose of this research is to determine the ideal rotation sequence for use in the calculation of shoulder kinematics during the volleyball attack. Utilizing different rotation sequences drastically affects the resulting joint angles (Aliaj et al., 2021; Phadke et al., 2011). Current literature rarely reports the exact rotation sequence employed for calculations, or it is buried under many citations (Reeser et al., 2010). The lack of clarity makes cross-study comparisons extremely difficult or impossible to perform. Establishing a rotation sequence ideal for the volleyball attack allows for a clearer methodological process for future research.

Our hypothesis was partially supported: the ZXY and YXY rotation sequences did not present with any instances of gimbal lock; however, the XYZ sequence returned the least number of total errors. The XYZ sequence presented with no errors in ROM or AC, but resulted in 5 total instances of GL. While the total number of errors using the XYZ sequence was lower than YXY, the consequence of GL errors outweighs minor angle amplitude noncompliance. Although GL is a brief issue that may only span a few frames, it is unable to be rectified resulting in a loss of data. By contrast, minor instances of angle incoherence may be explained by a disparity in ROM values. The 12 angle incoherence errors seen using the YXY were flagged when comparing results to passive ROM (95° ER/IR). Because the passive ROM may not accurately reflect dynamic ROM or that of a population that repeatedly performs a movement in which the limits of the joint are tested (e.g., volleyball attack), we also evaluated each sequence using active ROM reported in volleyball players. Angle calculations using YXY were within the bounds of the active ROM (Table 3).

The results of this study are consistent with current ISB recommendations in that the Euler YXY sequence is a viable option for analyzing the attack (Wu et al., 2005). A cardan sequence is typically employed to improve comprehension of the movement and ensure repeatability of future/comparative work. Although the YXY sequence was without error in the current study, previous reports suggest the atypical, non-anthropological, and ambiguous terminology associated with this rotation sequence may limit understanding and application to clinicians and researchers (Phadke et al., 2011). These characteristics should be considered when selecting the best possible sequence for overhand movement.

Our findings contrast with previous literature suggesting the use of the XZY sequence for shoulder kinematics instead of the YXY (Bonnefoy-Mazure et al., 2010; Phadke et al., 2011) in the evaluation of tennis serves and clinical motions. The volleyball attack and tennis serve both require movement through a large ROM at the shoulder, suggesting it is possible the same rotation sequence would be ideal for both actions. However, our results of a greater number of AC and GL errors using the XZY sequence conflict with previous findings (Bonnefoy-Mazure et al., 2010). This contradiction supports the recommendation to determine the best rotation sequence for each upper extremity sport/movement, since each action has specific demands (Bonnefoy-Mazure et al., 2010; Šenk & Chèze, 2006). The current study also builds upon previous literature by including a greater number of rotation sequences in our analysis as well as evaluating AC via both total ROM and peak angles (Bonnefoy-Mazure et al., 2010; Creveaux et al., 2018; Šenk & Chèze, 2006). The inclusion of peak angles in our assessment allowed testing for errors that may go unnoticed via the typical ROM method. For example, there were 165 instances where the total ROM did not result in an error, but the actual computed angle was outside of known ranges of motion.

Caution should be employed when translating angles generated by the YXY sequence into anatomical terms. The first rotation in this sequence is considered the plane of elevation, the second the angle of elevation, and the third internal/external rotations. Based on the plane of elevation, the angle in the second rotation can correspond to typical anatomical terms such as flexion or abduction; however, this only occurs when the first rotation is at 90° or 0°. Utilizing a cardan sequence, rather than an Eulerian with repeated rotations about the same axis, allows researchers and readers like to interpret results more easily. In this vein, the employment of the XYZ sequence may be more suitable for comprehensibility. The XYZ sequence had minimal occurrences of gimbal lock and the angles can be interpreted in typical anatomical terms. For example, when evaluating angle calculations at hand contact for participant 7, the XYZ sequence shows 36° of abduction, then 60° of external rotation followed by 94° of flexion. In contrast, when using the YXY sequence, the shoulder is at 36° in the plane of elevation which does not correspond to any commonly referenced anatomical motions. This makes the second rotation a blend of flexion and abduction with an angle of -125° followed by external rotation of 68°. Both calculations are correct, however the understandability by researchers and clinicians is easier with a cardan rotation sequence such as XYZ.

This study was not without limitations. The kinematic model employed relates the movement of the humerus to the upper trunk, leaving out the influence of scapula motion. The use of surface reflective markers for scapula tracking may be unreliable due to the deep movements of the scapula in relation to the skin. Therefore, it is common to relate the motion of the humerus to the thorax when performing shoulder kinematic calculations (Aliaj et al., 2021; Bonnefoy-Mazure et al., 2010; Reeser et al., 2010; Seminati et al., 2015). An alternative study suggested moving the position of the surface markers to be dependent upon arm positions (de Groot et al., 1998); however, this may not be feasible during the volleyball attack as the arm moves rapidly through the movement. Consequently, the decision to relate the humerus to the thorax was made based on the previously reported methodologies (Aliaj et al., 2021; Bonnefoy-Mazure et al., 2010; Reeser et al., 2010; Seminati et al., 2015).

The significance of the attack in volleyball lends to the importance of this movement's analysis in research. Proper methodology should be established to promote reproducibility and cross-study comparisons. Based on our findings, the YXY rotation sequence should be employed by those investigating the volleyball attack following takeoff. If greater comprehensibility is desired, the XYZ sequence could be a suitable alternative. Future research should investigate the ideal sequence for other overhand sport movements to ensure reliable outputs.

3.6 Conflict of Interest Statement

We confirm that there were no conflict-of-interest statements during this study.

CHAPTER 4.

USING INERTIAL MEASUREMENT UNITS TO INVESTIGATE THE KINETIC CHAIN IN THE VOLLEYBALL ATTACK

4.1 Abstract

The volleyball attack is an explosive overhand movement and primary point-scoring maneuver in the sport; due to its importance in team success, mechanisms driving high-performance in this movement should be determined. Additionally, Sand volleyball is a popular form of the sport and remains largely unexplored in the current literature. PURPOSE: The purpose of this study is twofold: (1) to evaluate the contribution of the kinetic chain to performance in the attack on the sand and (2) to examine the influence of sex on ball velocity. METHODS: 30 participants were recruited to perform 14 attacks on a sand volleyball court while wearing inertial measurement units. Peak trunk rotation velocity in the vertical axis, peak pelvis rotation velocity in the vertical axis, hip-to-shoulder separation angle, upper arm velocity at contact, and sex were inputted into a hierarchical linear regression to determine their influence on ball velocity. RESULTS: Trunk rotation velocity (β =0.265, p=.041) and sex (β = -0.683, p<.001) were the largest contributors to ball velocity, with the overall model predicting around 74.8% of the variance down the line. In the cross-court, sex was the only significant predictor (β = -0.644, p<.001), with the overall model accounting for 78.5% of the variance. CONCLUSION: Males hit the ball significantly harder than females in both directions. It is possible players are more reliant on trunk rotation when performing attacks down the line, and therefore training protocols should focus on improving this variable. Future research should investigate other factors that may influence performance on the sand, as well as kinematic differences between

sexes that may lead to gameplay improvements.

4.2 Introduction

Volleyball is an Olympic level sport performed in over 200 countries (Fédération Internationale de Volleyball, n.d.). Characterized by a running approach, countermovement jump, then high velocity rotational overhand motion, the volleyball attack dominates the game as the primary point-scoring movement. Researchers, coaches, and players alike strive to determine mechanisms to improve success in this movement, along with reducing injury incidence due to its high velocity and repetitive nature. One suggested avenue for improving performance is the training and streamlining of the kinetic chain.

The kinetic chain has been researched in other high-velocity overhand sports such as baseball (Agresta et al., 2022) with mild success. Pitch velocity was found to be positively related to hip-to-shoulder separation (HTS), peak trunk rotation velocity, and peak pelvis rotation velocity (Agresta et al., 2022). This concept of proximal-to-distal sequencing, previously described in terms of throwing or kicking (Putnam, 1993), could also be applied to the volleyball attack. Indeed, research suggests volleyball players perform the attack with the timing of maximal angular velocities of various segments following this framework (Wagner et al., 2014).

However, little research investigating the influence of the kinetic chain on performance or injury exists in volleyball. Peak trunk and pelvis rotation velocity were found to have a positive correlation, but did not significantly predict, ball velocity in female collegiate players (Brown et al., 2014). When researching training modalities focusing on the pelvis and trunk, a kinetic chain focused training protocol resulted in greater scapular consistency and reduced pain when performing the attack in players with scapular dyskinesis (Chang et al., 2022). The kinetic chain training program was also more effective than a conventional training program in increasing trunk rotation at ball contact.

When comparing injured and uninjured players, no differences were found in trunk kinematics throughout the attack (Mitchinson et al., 2013); however, a significant effect of attack direction was revealed. Players were more rotated through the trunk at the instant of ball contact when performing attacks aimed cross-court when compared to attacks aimed straight ahead (Mitchinson et al., 2013). The direction of attack has also been shown to influence other kinematic variables in the attack: HTS significantly predicted ball velocity in the cross-court attack, but not in straight-ahead attacks (Brown et al., 2014).

Typically, participant populations in these research studies are comprised of only males (Coleman et al., 1993; Dal Bello et al., 2020; Giatsis et al., 2018; Marques et al., 2015; Mitchinson et al., 2013; Pavlov & Buzhinskiy, 2019; Tilp et al., 2008; Wagner et al., 2014), with few including females (Brown et al., 2014; Reeser, Fleisig, et al., 2010) or mixed populations (Seminati et al., 2015). To this end, significant differences have been found between boys and girls in the timing of peak velocities during the attack, which could be due to developmental disparities between sexes present at a young age (Serrien et al., 2018). In addition, Brown et al. (2014) listed average ball velocities from various research studies, whereby a difference in velocity trend can be seen, with males displaying higher ball velocities (25-28m/s vs. 15-19 m/s). A direct statistical comparison of sex has not been made, however, and to accurately prescribe specific training protocols, sex must be considered in research.

Much of current research in volleyball is performed with players on hard court (Brown et al., 2014; Coleman et al., 1993; Mitchinson et al., 2013; Reeser, Fleisig, et al., 2010). There is, however, a variation of hard-court volleyball growing in popularity yet lacking in research: sand volleyball. Sand volleyball is a widespread Olympic sport and presents with marked differences from its indoor counterpart. Volleyball players in the sand have smaller jump heights (Giatsis et al., 2018), slower approach speed (Pavlov & Buzhinskiy, 2019), greater back swing motion (Pavlov & Buzhinskiy, 2019), longer knee extension times (Tilp et al., 2008), and smaller stride length (Tilp et al., 2008). With these distinct differences between these volleyball variants, it is important to ensure research evaluates performance in both settings.

The gold standard for motion capture is a system utilizing retro-reflective markers and infrared cameras. Yet, participants can feel encumbered by these markers and have shown to move differently due to the setup (Friesen et al., 2020). Inertial measurement units (IMUs) are an emerging methodology for motion capture with small, lightweight devices that collect linear acceleration, angular velocity, and magnetometer data. Given the success of tracking high-velocity baseball pitching with IMUs (Agresta et al., 2022), it is reasonable IMUs would be a viable methodology to capture movement in the volleyball attack, providing ecological validity not seen before in volleyball research.

The purpose of this study is to evaluate the influence of the kinetic chain on ball velocity and success in the volleyball attack using IMUs in a sand volleyball setting. Our hypothesis is trifold: (1) increased trunk and pelvis rotation velocity will significantly predict ball velocity, (2) HTS will significantly and positively predict ball velocity, and (3) there will be a significant influence of sex, with males displaying greater ball velocities.

4.3 Methods

4.3.1 Participants.

33 participants were recruited to participate in this study. Due to data corruption, 30 were

included in the analysis. Participants were recruited from members of the Tidewater Volleyball Association and the Association of Volleyball Professionals via social media. Participants were included if they were between 18-35 years of age, competed at the AA level or above, had no current shoulder pain preventing them from full gameplay, and had no major orthopedic surgery in the last six months. The AA level is defined as those who are "highly competitive players, college athletes, or professionals" (*Leagues*, n.d.). Participant characteristics can be found in Table 8.

Table 8. Participant Characteristics

	Age (yrs)	Height (m)	Weight (kg)	Experience (yrs)
Male	26 (4)	1.85 (0.08)	84.47 (12.83)	10.31 (3.40)
Female	25 (5)	1.77 (0.08)	70.88 (10.02)	11.36 (5.24)

4.3.2 Collection Procedures.

All procedures were conducted at the Tidewater Volleyball Association gymnasium, which is a temperature controlled indoor sand volleyball facility in the Hampton Roads area. Four IMUs (Delsys Trigno® Avanti Sensors, 370Hz), each with a triaxial accelerometer (Range: ±16g, bandwidth: 24 Hz – 473Hz bandwidth) and gyroscope (Range: ±2000 °/s, bandwidth: 24Hz – 360 Hz), were used.

IMUs were placed on the forearm (halfway between the lateral humeral epicondyle and the radial styloid process), upper arm (halfway between the acromion and the lateral humeral epicondyle), trunk (on the sternum), and pelvis (midway between the posterior superior iliac spines) of each participant according to Agresta et al. (2022). Following device placement, a self-guided warmup and subsequent familiarization procedure was performed. Once sufficiently familiarized, participants performed 14 attacks, 7 down the line and 7 cross court on a sand volleyball court off a toss from an experienced player. They were allowed to follow-through naturally. The height of the net was regulation based on the sex of the participant (2.24m for women, 2.43m for men). Before performing each attack, participants stood in a T-pose for 2 seconds to set a baseline/reference pose for the IMUs. Multiple high-speed cameras (1080p, 240fps) were set up to record the ball velocity. Cones were placed in the sand and measured for the conversion of pixels to meters in Kinovea© (version 0.9.5) video software.

4.3.3 Data Processing.

Custom MATLAB (Version: 23.2.0 (R2023b)) software was built to process all data. The IMUs were calibrated according to Stančin & Tomažič (2014) to account for axis offset and bias in the accelerometer. Bias was removed using the stationary T-pose period at the beginning of each trial for the gyroscope. Angular velocity data above 1980°/s was removed and interpolated using a spline filter; accelerometer readings did not exceed ±16g. Following the removal of axis offset and bias, all data was run through the open-source MahonyAHRS filter for orientation calculation (Mahony et al., 2008). Initial orientation of the inertial reference frame for each sensor was calculated based on the assumption that the participant was standing in a T-pose during the selected time points. Take-off was selected as the peak vertical velocity calculated via the zero-velocity update approach using data from the IMU placed on the pelvis. Angles of the pelvis and trunk were calculated using quaternions and converted into Euler angles using an XYZ (mediolateral-anteroposterior-vertical) rotation sequence. Rotation about the third axis, the vertical, was recorded and used in data analysis to calculate HTS.

4.3.4 Data Analysis.

Peak trunk rotation velocity (TRV), pelvis rotation velocity (PRV), HTS, and the resultant upper arm angular velocity at contact (UAVC) were evaluated for their contribution to ball velocity and attack success. TRV and PRV were recorded as the maximum values from the gyroscope data in the vertical axis of the IMU placed on those segments to illustrate the rotation of the segment in the segment reference frame. UAVC was calculated as the vector norm of the gyroscope data at ball contact. Peak resultant forearm acceleration denoted ball contact; accuracy of forearm acceleration as a measure of ball contact was corroborated with motion capture in previous laboratory work. HTS angle was calculated as the difference in angle about the vertical axis between the IMUs on the trunk and pelvis.

A hierarchical linear regression with an alpha level of .05 was performed to determine the relationship between the variables of interest; upper arm velocity was inputted into the first block, with the rest of the variables in the second. According to previous research, upper arm resultant velocity is significantly correlated to ball velocity ($p<.01$) (Coleman et al., 1993), and therefore this variable was inputted into the first block. Normality was assessed via visual inspection and the Shapiro-Wilks test while collinearity was assessed via VIF. The influence of sex was evaluated via dummy coding with females coded as 1 and males as 0.

4.4 Results

A reporting of the hierarchical linear regression results is provided in Tables 2-4. Averages and standard deviations for each variable are reported in Table 5. An example of the kinematic profiles of a male and female participant is displayed in Figure 1A and 1B.

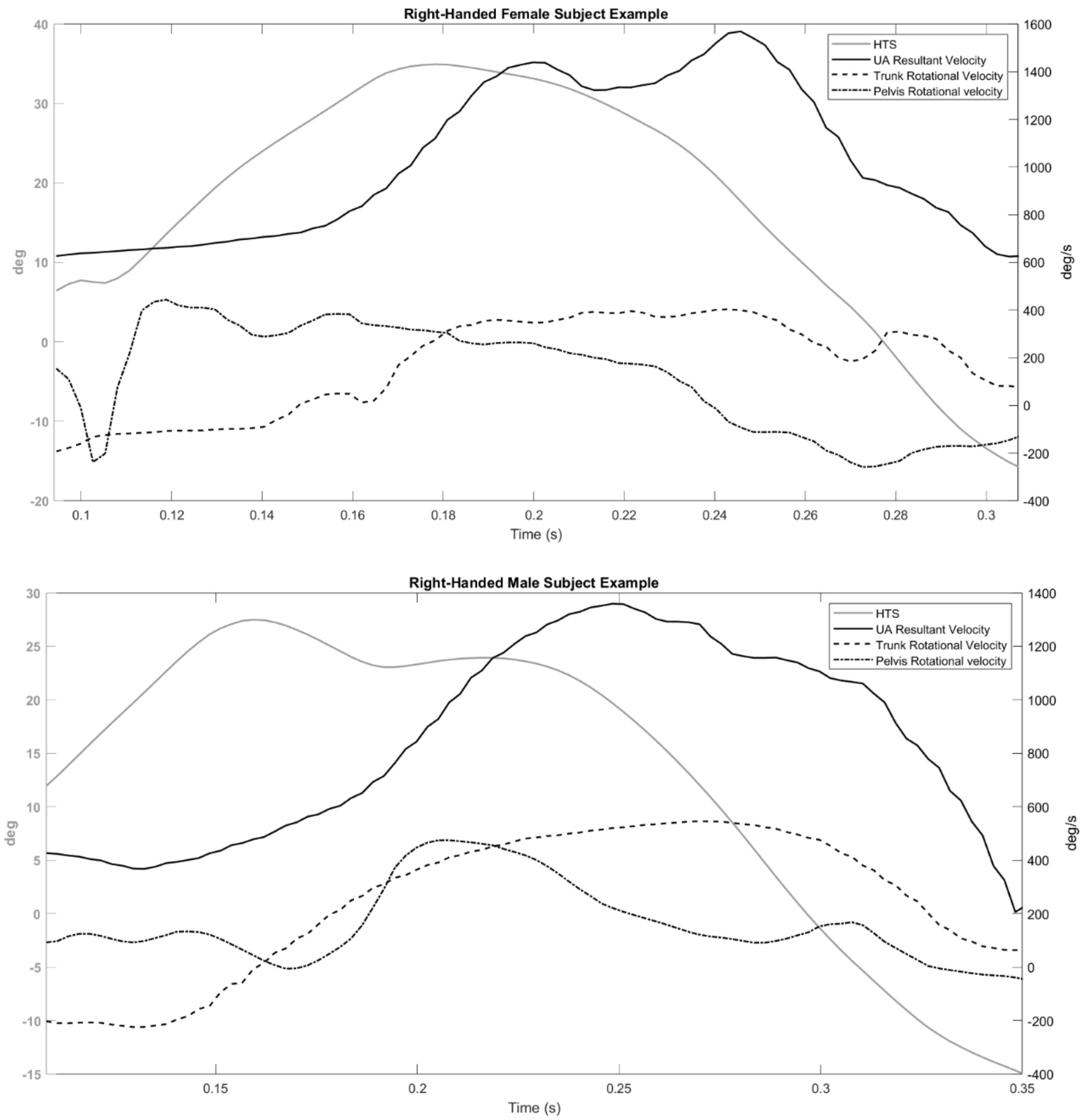
4.4.1 Line Attacks.

In model 1, a regression of ball velocity on UAVC did not explain a significant variance in ball velocity ($F(1,28)=.010$, $p=.921$). Adding HTS, PRV, and TRV in the second step of the hierarchical regression analysis led to a significant explanation of variance in ball velocity ($F(4,25)=4.249$, $p=.009$) and a significant improvement in R^2 ($\Delta R^2=.404$, $p=.004$). Adding sex in the final step of the hierarchical regression led to an additional significant change in R^2 (ΔR^2=.343, *p*<.001). A regression of ball velocity in line attacks on UAVC, HTS, PRV, TRV, and sex accounted for a significant 74.8% of the variance in ball velocity (F(1,24) = 32.683, *p*<.001). Every 1 standard deviation increase in TRV led to a .265 standard deviation increase in ball velocity, after controlling for UAVC, HTS, PRV, and sex. After controlling for UAVC, HTS, PRV, and TRV, females were found to produce significantly lower ball velocities (β=-.683, *p*<.001).

4.4.2 Cross-Court Attacks.

In model 1, a regression of ball velocity on UAVC explained a significant variance in ball velocity (F(1,28)=7.139, *p*=.012). Adding HTS, PRV, and TRV in the second step of the hierarchical regression analysis led to a significant change in R^2 (ΔR^2=.346, *p*=.002). Adding sex in the final step of the hierarchical regression led to an additional significant change in R^2 (ΔR^2=.236, *p*<.001), meaning sex accounted for 23.6% of variance in ball velocity. A regression of ball velocity in line attacks on UAVC, HTS, PRV, TRV, and sex accounted for a significant 78.5% of the variance in ball velocity (F(1,24) = 17.503, *p*<.001). After controlling for UAVC, HTS, PRV, and TRV, females were found to produce significantly lower ball velocities (β=-.644, *p*<.001).

Figure 6. Example waveforms for a female (top) and male (bottom) participant.



Note: Data begins at take-off and ends at hand contact.

Table 9. Multiple Linear Regression Results: Line

	Line						
Model	R	R^2	SEE	R^2 change	*p*-value	F change	Sig. F change
1. UAVC	0.019	.000	5.19		.921	0.01	.921
2. UAVC, HTS, PRV, TRV*	0.636	0.405	4.240	0.404	.009	5.660	.004
3. UAVC, HTS, PRV, TRV, Sex*	0.865	0.748	2.82	0.343	<.001	32.68	<.001

Notes: UAVC: Upper arm resultant velocity at ball contact; HTS: Peak hip-to-shoulder separation; PRV: Peak pelvis rotation velocity in the vertical axis; TRV: Peak trunk rotation velocity in the vertical axis; *: Significant model

Table 10. Multiple Linear Regression Results: Cross-court

	Cross						
Model	R	R^2	SEE	R^2 change	*p*-value	F change	Sig. F change
1. UAVC*	0.451	0.203	3.84		.012	7.139	.012
2. UAVC, HTS, PRV, TRV*	0.741	0.549	3.050	0.346	<.001	6.398	.002
3. UAVC, HTS, PRV, TRV, Sex*	0.886	0.785	2.15	0.236	<.001	26.26	<.001

Notes: UAVC: Upper arm resultant velocity at ball contact; HTS: Peak hip-to-shoulder separation; PRV: Peak pelvis rotation velocity in the vertical axis; TRV: Peak trunk rotation velocity in the vertical axis; *: Significant model

Table 11. Coefficients

		Line			Cross		
	Variable	Standardized β	Sig.	Part	Standardized β	Sig.	Part
Model 1	UAVC	-0.019	0.921	-0.019	**0.451**	**0.012**	**0.451**
Model 2	UAVC	0.040	0.801	0.039	**0.339**	**0.047**	**0.28**
	HTS	0.312	0.057	0.308	0.051	0.756	0.042
	PRV	-0.193	0.256	-0.18	0.060	0.691	0.054
	TRV	**0.550**	**0.003**	**0.502**	**0.558**	**0.001**	**0.499**
Model 3	UAVC	0.006	0.955	0.006	0.174	0.157	0.138
	HTS	0.157	0.156	0.15	-0.019	0.873	-0.015
	PRV	0.053	0.657	0.046	0.175	0.12	0.152
	TRV	**0.265**	**0.041**	**0.221**	0.184	0.165	0.136
	Sex	**-0.683**	**<.001**	**-0.586**	**-0.644**	**<.001**	**-0.485**

Notes: UAC: Upper arm resultant velocity at ball contact; HTS: Peak hip-to-shoulder separation; PRV: Peak pelvis rotation velocity in the vertical axis; TRV: Peak trunk rotation velocity in the vertical axis; Bolded values: significant coefficients; Sig.: *p*-value; Part: Part correlation

Table 12. Variables of Interest Averages

	Line		Cross	
Variable	M	F	M	F
BV	20.91±3.50	12.86±2.61	18.27±2.89	11.40±1.76
UAC	788.92±218.35	788.72±276.87	958.60±326.22	743.44±270.19
HTS	33.04±17.45	24.20±13.96	34.10±13.79	23.71±14.83
PK PEL	294.94±103.82	339.48±126.99	355.19±123.14	323.84±118.70
PK TRUNK	414.81±138.66	335.29±102.64	498.16±13.79	361.51±107.28

Notes: Data reported as Average ± Standard deviation

4.5 Discussion

Our model including UAVC, TRV, and sex significantly explained over 70% of the variance in ball velocity in attacks in both directions, with greater amounts explained in the cross-court direction (74.8% vs. 78.5%). Our results partially supported our hypothesis: peak trunk rotational velocity significantly predicted ball velocity when attacking down the line after accounting for UAVC, PRV, HTS, and sex. However, this was not case in the cross-court attacks ($p>.05$), contrasting with previous literature stating trunk velocity did not predict ball velocity (Brown et al., 2014). One possible explanation for the disparity between results is the floor surface. Our study was conducted on the sand, while Brown et al. (2014) was conducted on an indoor hard court. With smaller jump heights and push-off forces, it is possible players in the sand rely more on the movement of their trunk to generate velocity (Giatsis et al., 2018). Our results did not support our second hypothesis that HTS would significantly predict ball velocity. It is possible that HTS predicts pitch velocity in baseball players because the legs are still on the ground and therefore the efficiency of the kinetic chain in transferring force is more impactful (Agresta et al., 2022). In volleyball, the body is rotating in the air, removing the influence of the ground, and making the muscles the predominant force-producing avenue. HTS was significant in predicting ball velocity in indoor players; however (Brown et al., 2014), which may be a product of the differences found in jumping mechanics between surfaces. It is possible there is not enough time in the air in the sand specifically to develop similar levels of HTS and rotation as seen in indoor. Another potential reason for contrasting results is the methodology in which HTS was calculated; we used IMUs, while previous research used video analysis or three-dimensional motion capture.

While HTS was not a significant predictor in our regression model, another aspect of the kinetic chain, TRV, proved fruitful. One explanation for this phenomenon is increased reliance on trunk motion when performing the attack in sand volleyball. Sand players approach with shorter strides and reduced velocity, potentially due to the dissipative effect of sand (Pavlov & Buzhinskiy, 2019; Tilp et al., 2008). Additionally, jump height is more variable in the sand (Pavlov & Buzhinskiy, 2019). Increased variability in jump height and reduced lower extremity power may require greater reliance on trunk motions in sand players when compared to indoor players. Given the importance of trunk velocity, it is possible the trunk angle alone is more indicative of high performance rather than the combination of trunk and pelvis angle we see in HTS. This variable should be investigated further for its contribution to performance.

Our third hypothesis was supported by our findings; sex was a significant predictor of ball velocity. Previous research highlighted ball velocities in men and women but have not performed a direct comparison in adults (Brown et al., 2014). Our findings suggest men hit the ball harder than women in both the cross court (β=-.644, p<.001) and line attacks (β=-.683, p<.001). Further research is required to tease out the specifics of this relationship and whether higher performance by men is due to sex specifically or as a result of superior kinematic profiles. The influence of sex is especially interesting when looking at how the inclusion of this variable affected TRV's relationship to ball velocity in the regression. TRV is a significant predictor of ball velocity in both directions without sex; however, when sex is included in the regression, the prediction strength is diminished. In the cross-court direction, TRV even drops to insignificance. This may indicate males rotate their trunks faster to hit harder. Men average about 456 °/s TRV while women average 348 °/s TRV. We can postulate that men rotate their trunk faster, which could then induce greater performance. A robust statistical analysis must be performed, however, to confirm this hypothesis.

When comparing the results of this study to other literature, our ball velocities tended to be on the lower end of reported findings; notably, all previous reports were performed on a hard surface. In males, our average ball velocities were slightly lower than reported in some literature (~19m/s vs. ~27 m/s) (Coleman et al., 1993; Forthomme et al., 2005), but similar to levels in others (~19m/s (Mitchinson et al., 2013). Previous literature reports ball velocities anywhere between 13 m/s-19 m/s for females (Brown et al., 2014; Ferris et al., 1995; Reeser, Fleisig, et al., 2010). Ball velocities by females in the current study fall on the lower end of this spectrum as well (~12 m/s). A direct comparison cannot be made; however, we hypothesize the seemingly lower ball velocities are due to performing the attack on the sand. More research is required to establish normative values for each sex on different surfaces.

UAVC significantly predicted ball velocity without accounting for PRV, TRV, HTS, and sex in the cross-court attack; however, this relationship was attenuated following the inclusion of the other independent variables. In line attacks, the influence of UAVC on ball velocity is nonexistent. This contrasts with previous research supporting a positive relationship between UAVC and ball velocity ($r=.75$, $p<.001$) on a hard surface (Coleman et al., 1993). It is possible players are required to reduce their UAVC right before contact to a greater degree in the sand compared to indoor, allowing sand players to account for a smaller court; a smaller target area increases the importance of accuracy when attacking.

Our findings revealed differences between directions as well. Trunk velocity significantly predicted ball velocity in line attacks ($p=.041$), but not cross-court attacks ($p=.165$) regardless of sex; this conflicts with previous research suggesting the opposite (Brown et al., 2014). One major methodological note is the location of the participant in relationship to the net when attacking. In this study, participants attacked from the “weak” side of the court (same side as dominant hand), whereas previous research investigated attackers from the “strong” side of the court (same side as nondominant hand) (Brown et al., 2014). Additionally, many studies did not report the side of court from which participants attacked (Chang et al., 2022; Coleman et al., 1993; Reeser, Fleisig, et al., 2010). While seemingly inconsequential, this has vast implications. Performing the attack “cross-court” from the strong side would mean right-handed players are attacking in the direction of their dominant hand; the opposite is true for left-handed players. Conversely, a cross-court attack from the weak side directs the ball towards the non-dominant hand. If we compare our results with that of Brown et al. (2014) in terms of direction towards hand dominance, rather than line and cross-court, our findings align: TRV is significantly related to attacks towards the dominant hand side. However, when put in terms of “cross-court” and “line”, we report contrasting results. We make two statements based on these factors: (1) close attention should be paid to the methodological reporting of direction in the volleyball attack and the location of the participant, and (2) players performing attacks in the direction of their dominant limb rely more on their trunk to produce ball velocity when compared to the non-dominant direction. In this study the line attacks were in the direction of the dominant limb and vice versa for cross-court attacks. This greater reliance on trunk motion could be due to this directionality: in order to attack towards the dominant hand side, players may increase the trunk angle and generate greater velocities. Future research should investigate the influence of participant positioning coupled with attack direction to parse out these idiosyncrasies.

4.6 Conclusion

Sex contributed the most to our predictive model, accounting for about 65% of variance in ball velocity when performing the volleyball attack in the sand; males hit the ball faster than females. Peak trunk rotational velocity in the vertical axis also significantly predicted ball velocity in attacks down the line, and a deeper dive into the influence of this variable is warranted. As greater trunk velocity led to greater ball velocity, coaches and players should place an emphasis on improving this metric to enhance sport performance. More research is necessary to elucidate differences due to sex, surface, and participant location on the court to provide coaches and players with the most robust and accurate recommendations.

CHAPTER 5

CONCLUSION

The overall purpose of this dissertation was threefold: (1) to review current literature surrounding training modalities aimed to improve the health of the volleyball player's shoulder, an important aspect of attack performance, (2) to establish ideal methodological protocols for the calculation of kinematics for volleyball players during the attack, as this gap in the literature needed to be filled before making training recommendations, and (3) to evaluate the role of the kinetic chain when performing the volleyball attack. Because the attack is intrinsic and pivotal in the sport of volleyball, it is essential research is performed analyzing the various aspects of this movement. As the attack is predominately an overhand movement, the shoulder plays an integral role in performance. It is therefore crucial to investigate tactics to improve the health of this joint.

The first manuscript in this study reported a few major training modalities that positively impact shoulder flexibility, strength, and pain in volleyball players. Stretching programs including the sleeper stretch were reported to reduce pain and instances of GIRD commonly seen in this population. Instrumented interventions were effective in improving muscular strength and proprioception at the shoulder; however, more research is needed to define the best instrument to induce muscular adaptation. Finally, specialized programming was found to improve shoulder aspects of shoulder, and shoulder girdle, health as well. Specifically, the implementation of a kinetic chain specific training protocol was found to improve scapular movement consistency to a greater degree than conventional training when performing the volleyball attack, suggesting an influence of the kinetic chain when performing this movement.

Throughout this literature review, a growing concern for the reporting of methodological steps for the calculation of shoulder kinematics surfaced. Many research studies provided unclear steps for the calculation of shoulder kinematics, or the methodology itself was unclear. As the rotation sequence implemented has a drastic effect on angle outcomes, it is crucial to clearly and accurately report the protocol used. No established protocol existed for the calculation of shoulder kinematics in the volleyball attack, although the ISB recommends an Euler YXY sequence for all shoulder motion. The second manuscript filled the need to establish a conventional protocol to perform these calculations in the volleyball attack. In agreement with current ISB recommendations, the YXY rotation sequence presented with the smallest amount of angle coherence and gimbal lock errors and should be the selected methodology in the future. One drawback of this sequence is the difficulty in understanding the angles in anatomical terms. The XYZ sequence is a feasible alternative to the YXY if simpler anatomical understanding is desired.

The potential influence of the kinetic chain, coupled with a deeper understanding of rotational sequences, led to the final aim of the dissertation evaluating the role of the torso in volleyball attack performance. Peak trunk rotational velocity significantly predicted ball velocity in the attack in the line direction regardless of sex, however sex was found to be the biggest determinant of ball velocity. Sex accounted for around 65% of the variance in ball velocity in both line and cross-court attacks, with males hitting significantly faster than females. This was the first study to evaluate these variables while performing the attack in the sand; based on our findings, players performing the attack in the sand seem to be reliant on trunk motion to generate significant ball velocity.

Taking all findings together, this dissertation provides evidence for a few different recommendations for volleyball players and researchers. First, as it pertains to research, the suggested rotation sequence for the calculation of shoulder kinematics is the YXY sequence. Second, coaches and players should include the sleeper stretch in their daily exercise programs to improve levels of GIRD and shoulder pain. Third, an emphasis should be placed on training the kinetic chain to improve scapular movement consistency when performing the attack. Finally, players should focus on increasing the speed at which they rotate their trunk to hit the ball faster in the sand.

There are still gaps in the literature that need to be filled in order to provide coaches, players, and clinicians with the evidence necessary to improve the performance and health of volleyball players. Future research should evaluate the influence of kinetic chain training on shoulder kinematics and kinetics in the attack. This form of training has the potential to change attack mechanics that may reduce loading of the shoulder and mitigate injury. Much of the current research surrounding the attack focuses on a hard-court setting; thus, there is a paucity of research on volleyball in the sand. This variation of indoor volleyball is rising in popularity, and since it presents with distinct biomechanical differences from its indoor counterpart, research aimed at improving sport performance should be performed in this setting specifically. Finally, our findings support a significant difference between sexes in ball velocity, yet the underlying mechanisms for this disparity remain unknown. To recommend sex-specific interventions, and to establish possible kinematic and kinetic profiles distinguishing men from women that may drive greater ball velocities, more research is necessary.

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EDUCATION

Old Dominion University
PhD, Kinesiology and Rehabilitation Science
2021-2024
Dissertation: The volleyball attack: training, kinematics, and the influence of the torso

Troy University
M.S., Kinesiology
2019-2021
Thesis: Effects of Footwear on Jump and Balance Performance in Division 1 Collegiate Volleyball Players

Troy University
B.S., Exercise Science
2015-2019

PROFICIENCIES

Vicon Motion Systems Ltd. UK
- 3 years experience
- Collected data with visually impaired individuals, those with ASD, and elite athletes

Visual 3d
- 3 years experience
- Employed software to analyze motion capture data in a variety of projects
- Implemented a variety of rotation sequences in Visual3d for calculation of shoulder angles for manuscript publication

Python, Matlab Programming
- 4 years combined experience
- Utilized to write custom software designed to reduce data collected from IMUs, EMG electrodes, and motion capture technology

Bertec Force Plate
- 5 years experience
- Integrated into Vicon and MotionMonitor to measure balance in volleyball players, loading during squats, and foot-strike in gait

EXPERIENCE BY THE NUMBERS

- 3 first-authored peer-reviewed publications
- 1 under review in Injury Prevention
- 12 international/national conference presentations since 2019
- 5 awards and grants worth over $2500
- 6 professional affiliations/memberships with national and international professional development groups
- 4 years teaching experience

PUBLICATIONS

Barrett KB, Parrish, K., & Bennett, H. J.. Rotation sequences for the calculation of shoulder kinematics of the volleyball attack. *Journal of Biomechanics*, 2024.162: 111906.

Barrett KB, Sievert ZA, Bennett HJ. A Comparison of Squat Depth and Sex on Knee Kinematics and Muscle Activation. *J Biomech Eng*. 2023 Jul 1;145(7):071010.

Barrett KB, Page LB, Szczyglowski MK, Martin TD, Mouser JG. Comparison of Vascular Dopplers in Measuring Limb Occlusion Pressure for Blood Flow Restriction Therapy. *Topics in Exercise Science and Kinesiology*. 2023 4(1) Article 7

UNDER REVIEW

Barrett KB, Parrish K, Laverdure, P. Interventions to Improve Shoulder Health in Volleyball Players: A Systematic Review. *Under review in Injury Prevention*

PROFESSIONAL EXPERIENCE

Research Assistant
Old Dominion University — 2021-Present
- Managed confidential participant information for various research projects
- Completed front-end software development in python and MATLAB for data reduction
- Recruited professional and semi-professional athletes for participation in research
- Performed data reduction and analysis in Visual3D software

Social Coordinator
American Society of Biomechanics Student Chapter — 2022-Present
- Spearheaded organization for Old Dominion University's National Biomechanics Day outreach event
- Created content for various social media outlets to promote member success
- Visited student organizations to improve group engagement and outreach