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Research article

Ball-To-Hand Contact Forces Increase Modeled Shoulder Torques during a Volleyball Spike

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Abstract
The volleyball spike is repeated many times in practices and games, presenting a high risk of overuse injury. Previous biomechanical analyses estimating forces on the shoulder during spiking have not included the force exerted on the arm by the ball, because no practical method exists to estimate the contact force between the ball and the hand. The objective of the study was to model the internal shoulder joint reactions while including the measured ball contact force. Ten adolescent female volleyball players performed spikes while we recorded 3D motion capture data for both ball and player. Using an impulse-momentum analysis, we estimated the ball contact force, then included the force in a computational simulation model to estimate the torques produced by the shoulder. The study found that post-contact ball velocities range from 8.6 m/s - 18.2 m/s with net forces between 238 N - 672 N. Most notably, when the ball contact force was included, the average modeled internal shoulder torque to internally rotate the arm increased from -26 N-m to +44 N-m ($p < 0.001$). These data suggest that neglecting the contact force may risk misinterpreting connections between biomechanics and injury due to spiking. More accurate joint mechanics models will lead to better injury prevention recommendations for volleyball players of all ages.

Key words: Kinematics, Micro Trauma, Shoulder Athletic Injuries, Patient-Specific Computational Modeling, Biomedical Engineering.

Introduction

The number of adolescent female athletes playing volleyball in the USA has increased by 2500% from 1971 to 2019, and more recently, early specialization and year-round participation have become common, leading to increased chances of players developing musculoskeletal injuries (DiCesare et al., 2019; NFHS, 2013). Epidemiological studies (considering injuries due to a traumatic event or that led to lost playing time) report between 10% and 23% of the total volleyball-related injuries are shoulder injuries (Aagaard and Jørgensen, 1996; Agel et al., 2007; Bahr et al., 2003; Forthomme et al., 2013; Wang and Cochrane, 2001). These reports tend to overlook overuse injuries, since they do not typically result in lost playing time. One attempt to account for this found that approximately 40% of adolescent volleyball players retrospectively reported experiencing shoulder pain not associated with a traumatic injury, though only 33% of those then reported taking time off related to the pain (Frisch et al., 2017). While pain is not necessarily predictive of injury, it is one of the primary symptoms of overuse injuries such as tendinopathy, and the associated accumulation of non-traumatic microdamage is believed to remodel poorly potentially leading to future acute tendon rupture (Millar et al., 2021; Sharma and Maffulli, 2005; 2006).

The volleyball spike has many mechanical similarities to the baseball pitch, the mechanics of which have been studied extensively for male players at all levels, and with the tennis serve. Youth baseball players have experienced similar play-volume increases in recent years and have experienced corresponding increases in prevalence of arm injuries (Fleisig et al., 2011). Fleisig et al. (1995), identified large shoulder and elbow loads at two key points – prior to maximum external rotation and directly after ball release – which potentially lead to strain and injury. Other studies have confirmed these findings, reporting frequency of elbow and shoulder pain that could be explained by the values reported by Fleisig (Fleisig et al., 1999; Lyman et al., 2001; 2002). This understanding of the correlation between mechanics, pain, and injury have led to evidence-based recommendations concerning what players (especially adolescents) are taught and how much they are allowed to throw, in order to reduce pain and injury (Fleisig et al., 2011; Lyman et al., 2002). Despite the mechanical similarities, to date, no similar guidelines are common in adolescent volleyball, and the mechanics of spiking and serving a volleyball remain relatively unstudied, especially in adolescent female populations (Christopher and Ricard, 2001; Fuchs et al., 2019; Mitchinson et al., 2013; Reeser et al., 2010; Shahbazi-Moghaddam, 2002; Shih and Wang, 2019; Wagner et al., 2014).

The limited number of studies on volleyball mechanics to date have considered a variety of populations and levels, including beginner, amateur, collegiate, elite, and professional athletes but have focused mainly on male athletes and disproportionately on elite-level players. Reeser et al. (2010) delineated phases for the spike and demonstrated that spiking generated large forces on the shoulder. Fuchs et al. (2019) studied a team of elite female players and found indications of a potential relationship between maximal joint angular velocities in the upper body and ball velocity. Mitchinson et al. (2013) found that rotational arm velocity, but not kinematic range, was different for injured vs uninjured players, while Shih and Wang

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(2019) found that scapular kinematics should be considered in training volleyball. Wagner et al. (2014) found similarities in timing sequencing and large joint velocities for volleyball spikes and tennis serves performed by elite athletes. Coupling the large shoulder joint velocities and accelerations found in volleyball with the knowledge that in baseball repeated high loads at the shoulder during pitching lead to greater injury risk, suggests that the volleyball spike may have a high risk for developing overuse injuries, making the loads in the shoulder an important focus of study. Unfortunately, almost all studies of volleyball mechanics have been limited by omitting the force on the hand due to ball contact, although Shahbazi did devise a method to measure ball speed and forces using a ballistic pendulum model but without including a kinetic analysis (Shahbazi-Moghaddam, 2002).

The quantitative results of these studies, generally support similar risk levels for shoulder injury while spiking a volleyball and throwing a baseball, however none of the kinematic studies considering force at the shoulder joint include the force due to ball contact in their models, as it is an external force applied to the hand at that point (Christopher and Ricard, 2001; Reeser et al., 2010). This oversight is troublesome, since the point of ball contact is where the kinematics and kinetics of spiking a volleyball diverge most significantly from throwing a baseball. EMG of the two motions reveals notable differences in shoulder muscle activity after this point, possibly resulting from the difference between releasing a ball moving with the hand and slowing the arm down compared to spiking a ball not traveling with the hand, which might act as a brake (Escamilla and Andrews, 2009). Additionally, the transient nature of the ball contact may result in high forces on the arm, which would increase the risk of overuse injury at that point.

To date, no studies that the authors are aware of combine the kinematics analysis of the body while spiking with a kinetics model that applies the force of the ball to the hand. In order to understand the forces at the shoulder and eventually create informed guidelines for praxis, it is important to have models that include this key point. The current study fills this gap by measuring the kinematics of the ball as well as the player and then incorporating the force applied to the hand by the ball in the kinematic and kinetic models. We hypothesize that including the ball contact force in the kinematic model will increase the internal shoulder torques for horizontal adduction and internal rotation and decrease the abduction torque.

Methods

Participants

Ten healthy right-handed female high school athletes (average age 15.5 ± 1.5 yrs, height 1.75 ± 0.07 m, mass 68.22 ± 12.08 kg) who played a hitter position were recruited for participation. Participants had an average of 4.7±1.7 years of experience playing for non-elite teams (e.g. club, AAU, or school). Each player reported no history of arm or shoulder injuries on their medical and volleyball history. All procedures were approved by the University Institutional Review Board and subjects provided both individual and guardian consent.

Data collection

Each athlete was required to wear a tight-fitting motion capture suit, to which the reflective markers were attached using the OptiTrack Biomechanics marker set (OptiTrack, 2017). All reflective markers were attached to subjects by one investigator (KF). A separate tetrahedral marker set was affixed to the ball to track its motion simultaneously.

Data was collected indoors in a retrofitted racquetball court using 12 OptiTrack Prime 17W cameras (360 fps) recorded using Motive (OptiTrack, Corvallis, OR). A women's regulation height volleyball net was placed across the narrow direction of the lab, with sufficient space front and back for the subject's spike approach and for the ball to travel after contact. All data was collected on a single day and the motion capture system was calibrated using a standard procedure at the start of data collection. For each attempt, the ball was placed on a custom-built spike trainer which supported the stationary ball until contact then allowed the ball to move freely after contact (Figure 1), and the height was adjusted to the preferred jump height for each subject. The ball was oriented so the markers were not on the contact surface. A 10 ft (304.8 cm) line was marked on the floor and players were instructed to attack the ball with their usual approach, spiking the ball in a line shot. Players warmed up by taking 5 - 10 practice attempts until they were comfortable with the set-up.

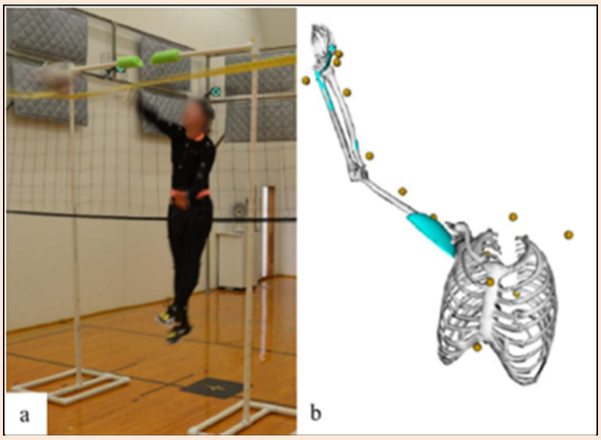

Figure 1. a) A subject spikes the ball over the net; prior to ball contact, the ball was resting on the green part of the spike trainer. b) The corresponding MoBL-ARMS model for analyzing the subject's Inverse Kinematics results using OpenSim.

Contact force estimation - kinematic & kinetic theory

The force exerted by the ball on the hand can be estimated by considering the change in motion the ball experienced during contact using the impulse-momentum theorem and Newton's 3rd law. In short, any rigid motion can be described as a combination of the object's center of mass (COM) translation and rotation about the COM (Hibbeler, 2004a). Tracking 4 retroreflective markers affixed to the ball in a tetrahedral pattern as a spherical rigid body produces position data for each marker and for a virtual marker located at the shape's centroid, which is coincident with the COM (Figure 2a). In the global <XYZ> reference frame, the COM follows a parabolic trajectory after contact, consistent with a rigid body with some initial horizontal velocity in free-fall (Figure 2b), while the surface markers trace circles around the COM in the ball's local <xyz> frame (Figure 2c).

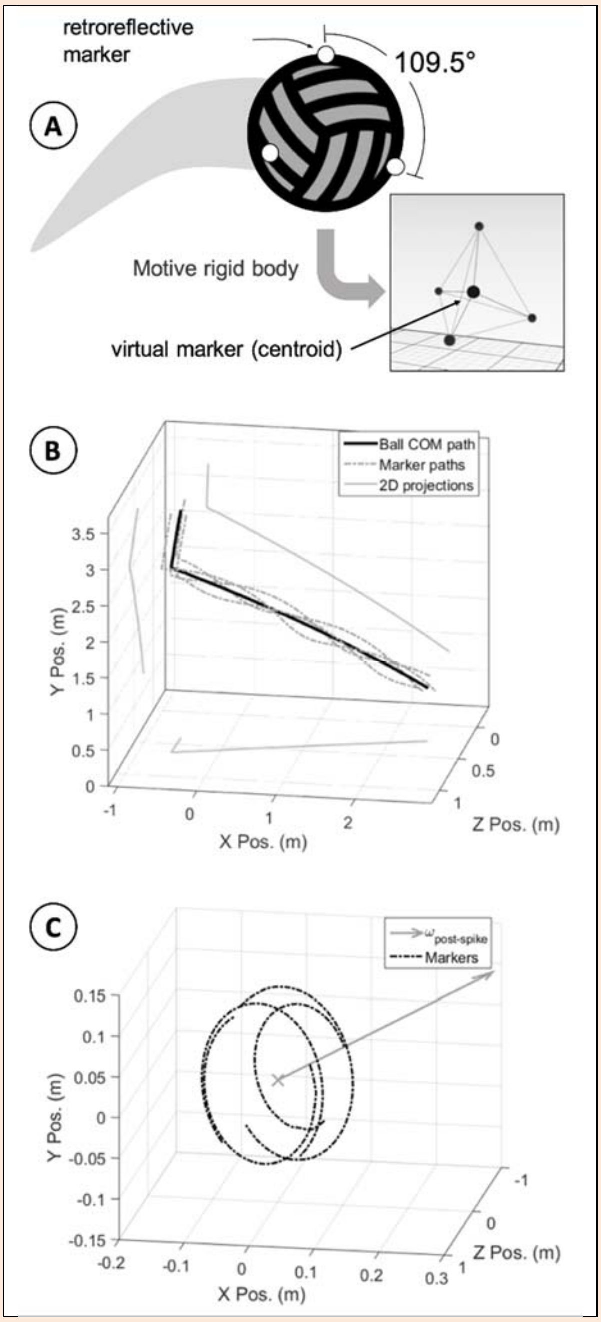

Figure 2. a) A ball with tetrahedral markers can be tracked as a rigid body, with a virtual centroid marker. b) In the <XYZ> frame the COM follows a rigid body projectile path in 3D space while the surface markers rotate about the centroid. c) When the path of the markers is considered in the <xyz> frame they trace circular paths with an angular velocity described by the vector.

Ball velocities can then be computed by numerically differentiating the marker positions in the respective reference frames to produce linear and rotational velocities for the ball. Using Singular Value Decomposition (SVD) to fit a plane to the point cloud of each marker's position over time in the <xyz> frame and averaging them generates an axis of rotation for determining angular velocity. Immediately before and after contact the ball is in free fall and gravity and air resistance are the only forces acting. Over a sufficiently short time span, the acceleration resulting from these gravitational and resistance forces will be negligible and instantaneous velocity can be approximated by averaging the appropriate number of data points. Gravitational force has minimal effect on rotation, allowing for a longer averaging window for angular velocity. By measuring velocities immediately before and after contact with contact duration, the total impulse applied to the ball can be computed and an average force calculated (Hibbeler, 2004b). For the translation velocity calculation, a window of 8 frames after the end of contact was used, while for the rotational velocity a longer window of 50 frames was used, since rotational velocity is not affected by the gravitational force. The contact time is the duration of the rapid increase in the x-direction velocity, which averaged to be about 20 ms. The temporal force profile of the volleyball bouncing on a force plate approximated a Gaussian distribution, so the peak force was estimated by creating a Gaussian function with an area equal to the impulse and a width of the contact time. This calculated force is equal and opposite to the force that the ball applies to the hand.

Modeling of shoulder kinematics and dynamics

Biomechanical parameters for the subjects were derived from their marker position data in OpenSim (Delp et al., 2007; Seth et al., 2018) using the MoBL-ARMS Dynamic Upper Limb model (Saul et al., 2015) modified to match the joint coordinate system recommended by the International Society of Biomechanics (Wu et al., 2005; Xu et al., 2012) and to fulfill the range of motion requirements of a volleyball spike. After iterative visual optimization of filter cutoff frequencies, the marker data was run through a 10 Hz lowpass, 2nd order Butterworth filter prior to analysis. At the beginning of each analysis the modified MoBL-ARMS model was iteratively scaled for each player to minimize marker error. The Inverse Kinematics (IK) tool was used to calculate the three shoulder angles (external rotation, abduction, and horizontal adduction) from the point where their feet left the ground to them landing back on the ground following ball contact. Joint angles were calculated independently from the hand force, so including the hand force in the model does not affect the kinematic values. After obtaining IK results, the OpenSim Inverse Dynamics (ID) tool was used to calculate the internal joint moments in the shoulder for two conditions: neglecting any forces due to the contact ("no force" condition), and applying the external force exerted by the ball on the hand during contact ("contact force" condition).

Statistical analysis

For each of the shoulder torques, the peak torques within the ball contact window were compared using paired t-tests with a significance level of alpha = 0.05. Multiple comparisons were corrected for using a Bonferroni correction, resulting in an alpha level of 0.017 for significance.

Table 1. Values at key kinematic and kinetic points during the volleyball spike. All values are average ± standard deviation.

	Kinematic Values		Contact Window Peak Kinetic Values	
	ROM [°]	Shoulder Rotations at Ball Contact Phase [°]	Max Torque During Ball Contact [N·m]	Max Torque Excluding Ball Contact [N·m]
Internal Rotation	174 ± 36	-83 ± 28	44.0 ± 30.5	-25.5 ± 12.0 *
Abduction	70 ± 28	122 ± 10	-110.5 ± 70.2	-19.9 ± 54.6 *
Horizontal Adduction	109 ± 26	12 ± 23	63.0 ± 50.3	-45.5 ± 28.1 *

The difference between peak torque estimates at ball contact was statistically significant (* $p < 0.001$) for each torque pair.

Results

Force estimation

The post-contact linear ball velocity was found to be 13.4 ± 2.4 m/s with contact times between 16 and 27 ms. The estimated hand force was 416 ± 99 N with a range of 242 N to 681 N due to translation and 8 N to 82 N due to rotation. The variability inherent from estimating force from the discrete time steps of the frame rate caused uncertainty on the force ranging from 10.1% to 17.1%, though only 8 of the 30 trials exceeded 12.7%.

Kinematics and kinetics

Throughout the spike, players demonstrated an average range of motion (ROM) of 70° for Abduction, 109° for Horizontal Adduction, and 174° for Internal Rotation (Table 1). At the time of ball contact the players exhibited high values of external rotation and abduction, while being at minimal horizontal adduction (Figure 3).

The internal torque time-series data (Figure 4) are identical at all time points except during the contact window, when the peak internal torques for the contact force model differ significantly and, in some cases, reverse direction when compared with the no-force model. In the model excluding the ball force, the greatest average torque on the shoulder was 48 N-m due to internal rotation (Figure 4a). During the contact window, the average internal rotation torque and other angles increased (Table 1).

Discussion

The joint kinematics and kinetics together describe the motion of the volleyball spike, along with the forces that generate the motions. In preparation for ball contact, players externally rotate their arms to a maximum point (Figure 3a), concurrently exhibiting a large internal rotation torque (Figure 4a), which slows the external rotation, then transitions into an internal rotation that continues through the approach to ball contact. Similarly, while the arm is horizontally abducting (Figure 3c), a horizontal adduction torque redirects the arm from horizontal abduction to horizontal adduction shortly before ball contact (Figure 3c). The abduction of the shoulder (Figure 3b) remains constant and elevated through the approach and ball contact phases, then rapidly decreases in the post-contact follow through, requiring a small abduction torque (Figure 3b). These kinematics are generally similar to those found previously in other volleyball populations, and the shape of the present curve and associated peak values match those reported by Reeser et al. when the force due to the ball is not included in the kinetic model (Mitchinson et al., 2013; Reeser et al., 2010; 2013; Shih and Wang, 2019; Wagner et al., 2014).

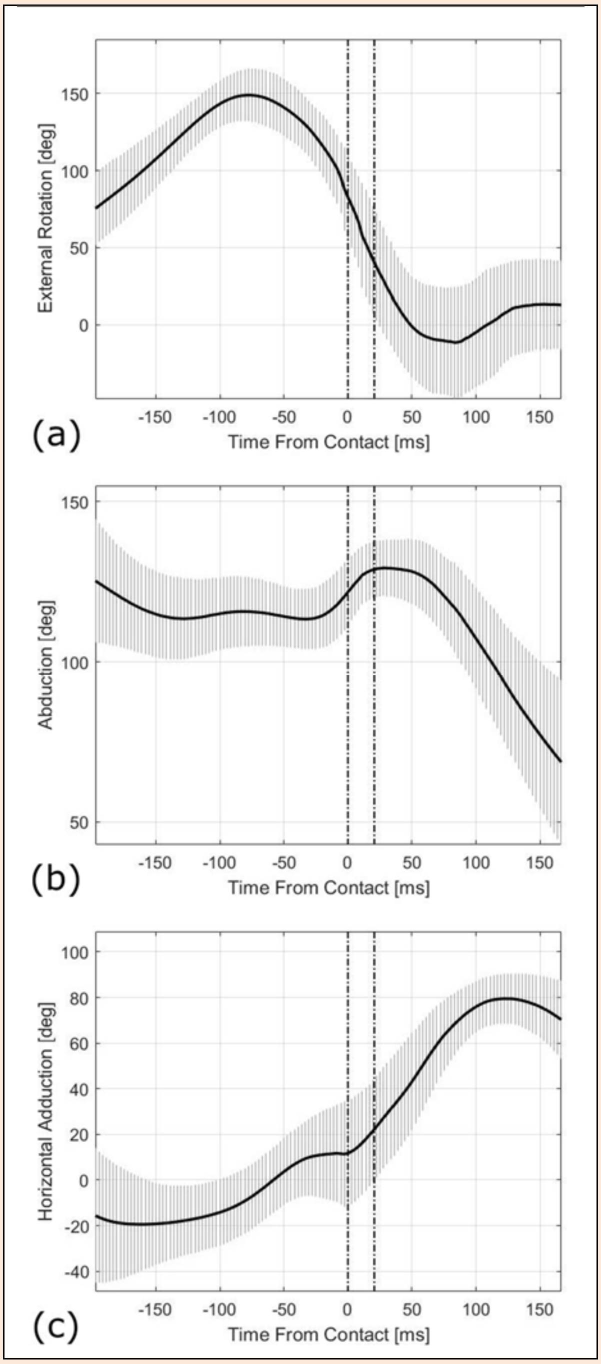

Figure 3. Shoulder angles during a spike for a) external rotation, b) abduction, and c) horizontal adduction. Positive values correspond to external rotation, abduction, and horizontal adduction respectively. The solid line is the mean for the 10 participants, and the vertical bars are plus or minus one standard deviation. Ball contact occurs at t = 0, and the vertical dotted lines indicate the ball contact window.

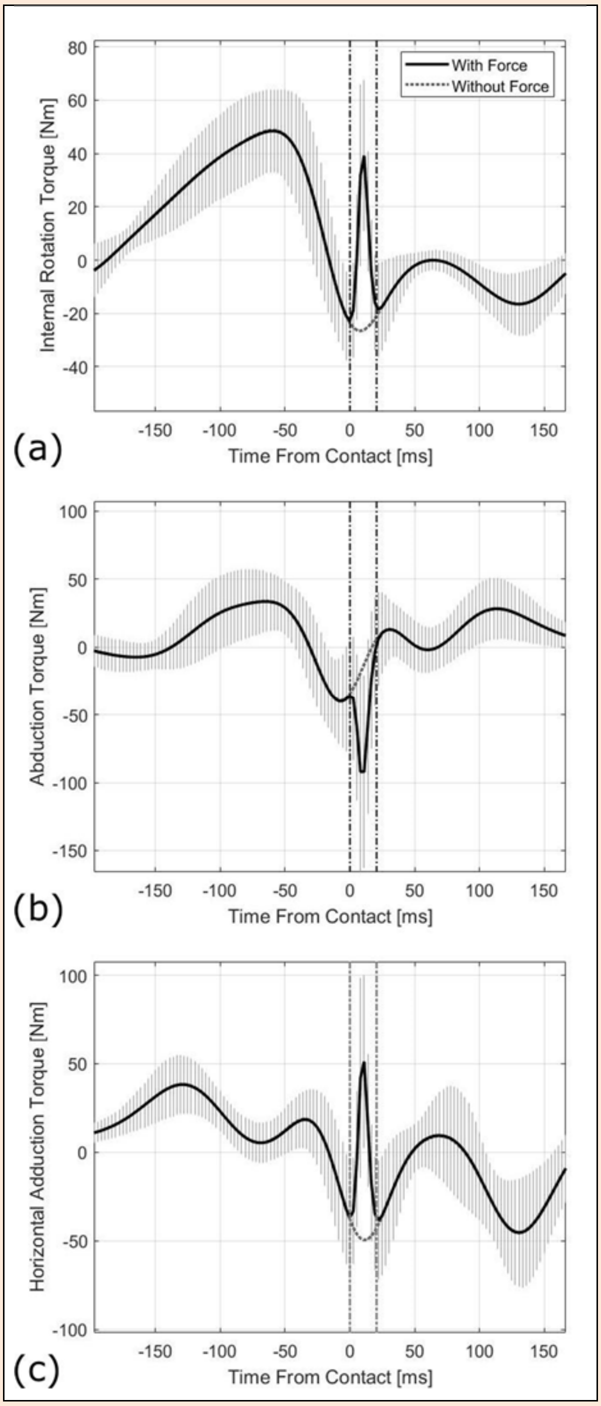

Figure 4. Shoulder torques during a spike for a) internal rotation, b) abduction, and c) horizontal adduction. Positive values are (a) internal rotation torque, (b) abduction torque, and (c) horizontal adduction torque respectively. The solid line is the mean for the 10 participants, and the vertical bars are plus or minus one standard deviation. Ball contact occurs at t = 0, and the vertical dotted lines indicate the ball contact window.

During the volleyball spike motion, a player's arm experiences a notable impact force due to striking the ball. Including the impact force in a kinematic model is challenging, since *in situ* force measurement is difficult due to the hollow bladder construction of the ball. The method used in this study attaches reflective markers directly to the ball and tracks the ball along with the player, providing kinematics of both the ball and the player, providing a simple experimental set-up to collect information to estimate the force experienced by the ball, which is equal and opposite to the force experienced by the hand. Ball velocities measured using this simple *in situ* technique are comparable to, if slightly lower than, those reported for female university athletes by Reseer et al. (2010) and also compare favorably with the values for beginner and university players found by Shahbazi-Moghaddam, (2002), which used an elaborate ballistic pendulum set-up. The ball tracking method used in this study produces comparable results while being easier to use in an experimental setting.

Including the force that the ball applies to the hand is essential to fully understand the risks associated with the motion, since the force required to propel the ball forward results in an equal and opposite force pushing backward on the hand. In order to overcome this force opposite to the hand's direction of motion, the body must exert large rotational torques to continue the desired motion of the arm. Unsurprisingly, then, including the force that the ball applies to the hand makes a significant difference in the estimated internal torques at the shoulder (Figure 4). Without any external force estimate on the hand, the modeled shoulder torques curves continue smoothly. However, when the estimated external force is included in the model, large peaks appear during the short duration of ball contact, often temporarily reversing the direction of the generated torque. For example, the internal rotation torque spikes upwards at ball contact because the act of striking the ball exerts a force on the hand opposite to the direction of motion; to continue the internal rotation of the spike motion without decelerating, the muscles must exert an increased internal rotation torque (Figure 4a). Similarly, the act of spiking the ball applies a horizontal abduction force on the shoulder, so continuing in the horizontal adduction motion without slowing down requires the shoulder muscles to generate a horizontal adduction torque (Figure 4c). A rapid change in the abduction torque (Figure 4b) is perhaps unexpected, since an ideal ball contact would not cause any torque in the frontal plane, however, due to the players' hands often being slightly externally rotated at contact, some of the force on the hand acts under the pinky towards the thumb causing abduction, requiring the body to create an opposing adduction torque. These internally generated torques support Escamilla and Andrews's (2009) hypothesis that contacting the ball acts as a brake to help slow down the moving arm based on reported muscle activations during a volleyball spike for the teres major (internal rotator), subscapularis (internal rotator), pectoralis major (internal rotator and horizontal/vertical adductor), and latissimus dorsi (internal rotator and adductor). When coupled with the ball-on-plate anatomy of the shoulder joint, these frequently repeated and relatively extreme abduction and external rotation joint torques make it challenging for an athlete to maintain a stable shoulder joint, raising their risk of tendinopathy, subluxation, and suprascapular neuropathy (Fleisig et al., 1995; Briner and Kacmar, 1997).

There are obvious kinematic similarities between the overhand throwing motion and the volleyball spike as noted by Wagner et al. (2014), though kinetically the throw lacks the abrupt impact force due to ball contact. EMG studies of muscle activities have shown different muscle activation patterns during the deceleration phase of the two motions, with large muscle activation of subscapularis and teres minor in the volleyball spike, likely due to the contact phase (Escamilla and Andrews, 2009). Kinetic studies on baseball pitching in youth and adolescents have found horizontal abduction torques ranging from 69 ± 25Nm (high schoolers) to 40 ± 14Nm (youth), with professional athletes measuring noticeably higher (Fleisig et al., 1995; 1999). The no-contact kinetic model used in this study produced similar values for these torques (Table 1), but when the ball contact force was included the patterns changed substantially, with the torque briefly changing directions as a result of the ball contact. This suggests that despite the kinematic similarities between throwing and spiking, there are potential differences in the associated injury mechanisms. Understanding these risks and how to mitigate them will require volleyball-specific studies similar to the extensive work done by Fleisig and colleagues (e.g. Fleisig et al., 1995; 1999; 2011; Lyman et al., 2001; 2002) to identify injury causes and preventative practices. In addition to considering maximum and minimum forces and angles, these risk factor analyses studies should also consider rate-of-change related variables. Until more research provides a better understanding of injury mechanisms, we recommend that coaches be aware of the number of swings players are taking and consider building in recovery days as well as adapting training regimens for high risk players.

This study provides a technique for acquiring force data and a comparative data set for an understudied volleyball population (non-elite adolescent females), however the study has several limitations. One potential source of error is the placement of the reflective markers on a Velcro suit rather than directly on the participants' skin, which makes the data more susceptible to noise, as well as drifting off bony landmarks. To mitigate potential effects of marker drift, the location of the markers was documented photographically for each subject and the images were used to refine the scaling and virtual marker placement of the MoBL-ARMS model in OpenSim. A second limitation is the assumptions embedded in the MoBL-ARMS OpenSim model, in particular modeling the shoulder as a ball joint. For the present study, this was an acceptable simplification but future studies attempting to model muscle forces should consider whether the translation of the humeral head relative to the thorax is necessary. A third limitation is the camera frame rate of the motion capture system, which affects the contact force estimate. In the present study, the frame rate was set as high as possible without losing spatial resolution (360 frames per second); however, the contact duration between the ball and the hand is only about three times the Nyquist frequency for the system, which makes the force estimates (calculated directly from contact time), sensitive to measurement uncertainty, though any bias is likely to result in forces higher than those calculated in this study. The force values estimated using this method and sampling rate are similar to forces directly measured by Shahbazi, et.al. (2002), however, we recommend that future studies use a higher frame rate to provide more refined estimates of the force the ball exerts on the hand. Finally, the players in this study spiked the ball off a spike trainer, which may have contributed to slightly different kinematics when compared to the real-time adjustments of spiking a live set.

Conclusion

In summary, considering forces due to ball contact resulted in different estimations of joint forces in the shoulder. These internal shoulder joint forces have similar magnitudes to joint forces that have been linked to overuse injuries in baseball. Because volleyball is increasingly popular among adolescent female athletes, these young women are potentially at increased risk of overuse injury. We recommend further research to elucidate biomechanical factors and spike counts that are predictive of shoulder injury risk, as well as to develop evidence-based injury prevention guidelines such as strength and conditioning protocols, and "hit count" guidelines for coaches, parents, and players.

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Key points

- A simple way to estimate the force applied to the volleyball during the spike is to place four markers on the ball, and use impulse-momentum methods.
- Including the externally applied load from the ball significantly changes the magnitude (and sometimes direction) of the joint force at the shoulder
- More accurate joint mechanics models will lead to better injury prevention recommendations for volleyball players of all ages.

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