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SHOULDER 3D RANGE OF MOTION AND HUMERUS ROTATION IN TWO VOLLEYBALL SPIKE TECHNIQUES: INJURY PREVENTION AND PERFORMANCE

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ABSTRACT:

Repetitive stresses and movements on the shoulder in the volleyball spike expose this joint to overuse injuries, bringing athletes to a career threatening injury.

Assuming specific spike techniques play an important role in injury risk, we compared the kinematic of the traditional (TT) and the alternative (AT) techniques in 21 elite athletes, evaluating their safety with respect to performance. Glenohumeral joint was set as the centre of an imaginary sphere, intersected by the distal end of the humerus at different angles. Shoulder range of motion and angular velocities were calculated and compared to the joint limits. Ball speed and jump height were also assessed. Results showed the trajectory of the humerus to be different for the TT, with maximal flexion of the shoulder reduced by 10 degrees, and horizontal abduction 15 degrees higher. No difference was found for external rotation angles, while axial rotation velocities were significantly higher in AT, with a 5% higher ball speed. Results suggest AT as potential preventive solution to shoulder chronic pathologies, reducing shoulder flexion during spiking. The proposed method allows visualisation of risks associated with different overhead manoeuvres, by depicting humerus angles and velocities with respect to joint limits in the same 3D space.

Word count: 200

Keywords: shoulder overuse injuries, spike styles, biomechanics, 3D kinematics.

INTRODUCTION

Volleyball is a very popular and complex sport discipline with high technical and athletic demands for players. Frequent sprints and dives, together with repeated maximal vertical jumps and overhead movements of the upper extremities make this activity a common cause of sport-related injuries (Chan, Yuan, Li, Chien, & Tsang, 1993; Kujala et al., 1995). Shoulder injuries (combination of acute and chronic) account for 8-20% of all volleyball injuries (Briner & Kacmar, 1997; Augustsson, Augustsson, Tomeeé, & Svantesson, 2006), representing the second most common overuse condition (Kugler, Krüger-Franke, Reininger, Trouillier, & Rosemeyer, 1996; Reeser, Verhagen, Briner, Askeland, & Bahr, 2006). Chronic injuries have low incidence rates compared to acute/traumatic events (about 0.6/1000 hours played) and symptoms appear gradually (Aagaard & Jorgensen, 1996; Verhagen, Van der Beek, Bouter, Bahr, & Van Mechelen, 2004). However, the majority of the shoulder injuries are usually overuse injuries. They account for approximately for 19% of all volleyball injuries (Seminati & Minetti, 2013), and result in the greatest time lost from training and competition (Verhagen et al. 2004). Repeated external rotation and elevation shoulder movements, are common manoeuvres in volleyball and in other disciplines classified as ‘overhead sports’. They are known to cause supra-scapular neuropathy, instability and rotator cuff pathologies such as impingement (Page, 2011). When spiking and serving, volleyball players place their arm in an extremely stressful position, abducting their glenohumeral joint to 150°, with the simultaneous eccentric contraction of the infraspinatus to decelerate the upper limb after ball contact (Ferretti, Cerullo, & Russo, 1987; Rokito, Jobe, Pink, Perry, & Brault, 1998; Reeser, Fleisig, Cools, Yount, & Magnes, 2013). This eccentric overload together with the repetitive stresses on the tendons of the shoulder rotator cuff muscles and capsule are believed to be the main causes of shoulder overuse injuries (Wang & Cochrane, 2001) and result in pain, weakness, and~~,~~ a reduced range of motion. This can jeopardize an athlete’s career, causing long periods of absence from the game. In 2004, Verhagen and collaborators reported a mean value of 6.2 ± 9.4 (SD) weeks' absence for shoulder overuse injuries.

Treating sports injuries is often difficult, expensive and time consuming. A successful injury surveillance and prevention program requires effective pre and post-intervention strategies, including rest periods combined with rehabilitation programs, diagnostic screening and pre-participation physical examination to identify injuries (Wu, Wang, Wang, Chen, & Wang, 2010) and stretching and warm up exercises prior to activity (Wang, Macfarlane, & Cochrane. 2000; Wang & Cochrane, 2001). In addition to these recommendations many authors promote collaboration between athletes and coaches in order to develop spike or serve techniques that could minimize stress on the shoulder (Schafle, 1993; Seminati & Minetti, 2013).

Different spike techniques are associated with different kinematics and different risk damage of the shoulder joint. This leads to different probabilities of certain injuries depending on an athlete's selected technique. Here we analysed two of the most common spike techniques in volleyball: the Traditional Technique (TT), also known as *Elevation Style* and the Alternative Technique (AT), also called *Backswing Style*. Oka introduced these two different styles in 1976 (Oka & Okamoto, 1976), and although other authors (Coleman, Benham, & Northcott, 1993) have described them since, no quantitative analysis of these movements has ever been conducted.

The main aim of this study was to assess whether the TT or AT spiking technique presented advantages from an injury prevention perspective, while maintaining athlete performance. We hypothesised that the two spiking techniques are associated with different shoulder ranges of motion, placing athletes at risk of different injuries of the shoulder joint. We decided to analyse female and male athletes separately, due to the different physical characteristics in terms of laxity, mobility and stiffness of the glenohumeral joint (Borsa, Sauers & Herling, 2000). In the present study the kinematics of the upper limb during the two techniques will be compared with an experimental protocol based on three different levels of investigation, both inside the laboratory and on a real volleyball court in order to record an ecologically correct movement and account for-performance in terms of ball speed and maximal hand height at the spike impact.

Spike techniques

Two different types of spike techniques were compared. The Traditional Technique (TT) is characterised by a loading phase of the spike in which the arms swing forward in the sagittal plane (shoulder flexion, phase 1-2 in Figure 1a) and during the flight phase, the forward-upward movement of the shoulders, initiated at take off, is continued over 90° until full flexion is reached (phase 3-4 in Figure 1a, video 1 in supporting information). In contrast, when performing an Alternative Technique (AT), the loading phase starts with a semi-circumduction of both upper limbs (phase 1-2 in Figure 1b) and during the flight phase the right shoulder do not reach the full flexion, but stops at approximately 90°, while completing the full horizontal abduction (phase 3-4 in Figure 1b). In this kind of spike the two segments of the upper limb move with a more pronounced whip-like pattern before hitting the ball (Figure 1b, video 2 in supporting information).

Participants

Twenty-one healthy volleyball players, eleven male and ten female, from high-level National categories (1st and 2nd Italian Indoor Volleyball League - *Vero Volley Consortium - Monza*), took part in the experimental protocol. They were free from any musculoskeletal shoulder injury and their anthropometric characteristics are shown in Table I. All athletes were right-hand dominant attackers, with an experience of 10.4 ± 6.5 years (14.0 ± 1.9 hours of training/match per week). They were highly skilled in performing volleyball attack movements. Six men and five women preferentially used the traditional technique and the other five men and five women the alternative one. However, all athletes were skilled in executing both techniques. The institutional ethics committee of the University of Milan had approved all methods and procedures, and the athletes gave their written informed consent prior to the start of testing.

Based on data taken from the literature (Wagner et al., 2012; Mitchinson et al., 2013), regarding shoulder kinematics (range of motion) and performance (ball speed), we fixed the sample size, with the goal to detect changes corresponding, to 5% and 10% of the mean respectively. The minimum number of participants for our study was evaluated starting from the mean and the Standard Deviation of shoulder flexion and ball velocity measured by Mitchinson and collaborator in 2013 on a group of 12 participants. Statistical power analysis (GPower 3.1, http://www.gpower.hhu.de/), reported a probability of finding true significance (1 - type II error (β)) between 0.7 and 0.8 for α (type I error) equal to 0.05 and 0.1 respectively.

Study design and Experimental Protocol

This was a cross sectional study in which two groups of participants (male and female) performed repetitions of spike trials adopting two different techniques. The study consisted of three different tests performed on two separate days (see details in Table II). On the first day, experimental sessions took place inside the laboratory without using the ball. Subjects were asked to perform a minimum of three successful alternative and three traditional spike actions without jumping (first test, without the approaching phase) and with jumping (second test, with the approaching phase before the spike movement). On the second day, two weeks later, athletes completed at least three successful spike actions for each of the investigated techniques, by jumping and hitting a ball set by an experienced player as in a game scenario (third test) in an indoor volleyball competition court.

Participants performed a self-directed warm up before each of the three measurements conditions. In addition, in order to kinematically record the articular limits (range of motion) of the dominant shoulder of each athlete, starting from an anatomical standing position all the athletes performed a complete circumduction of the shoulder to determinate maximal shoulder flexion and horizontal abduction and successively a maximal internal and external rotation movement with the shoulder 90° abducted in the frontal plane and elbow 90° flexed.

The same biomechanical model was used to assess this as during the spike movements.

Data were collected during the National volleyball season period, to ensure all athletes were match fit. Athletes were asked to perform spike movements to competition standard.

Data collection and processing

3D positions of 16 reflective markers were recorded with a 6-camera optoelectronic system (Vicon MX13, Oxford, UK). Sampling frequency was 250 Hz and markers were positioned according to the Vicon Upper limb model on the right upper limb of the athletes (Table III and Figure 2 – left panel). In addition to the kinematic recording in the third condition, ball speed was measured with a high-frequency camera (CASIO Exilim, 210Hz) for each spike executed on the competition court. The camera was oriented perpendicular to the plane of motion (sagittal) at a distance of 10 m and participant were asked to hit the ball straight on, in a corridor of 1 meter wide. Horizontal and vertical scaling was performed prior the test by videoing a 3 m side length calibration square, with reflective markers placed on the corners.

Raw data collected with the optoelectronic system were filtered with a quintic spline filter (Mean Square Error = 10) (Woltring, 1986; Woltring, 1992) and joints positions were calculated according to the upper limb model proposed by Murray (Murray, 1999; Murray & Johnson, 2004).

To facilitate the description of glenohumeral joint motion, two sets of coordinate systems were defined (see Table IV) (An, Browne, Korinek, Tanaka, & Morrey, 1991) and as shown in the right panel of Figure 2, the glenohumeral joint was set as the centre of an imaginary sphere intersected by the distal end of the humerus, with a radius of 200 mm. In order to obtain intersection angles (*shoulder flexion* (θ): latitude and *horizontal abduction* (ϕ): longitude) independently from the overall movements of the body, the sphere has been considered as firmly attached to the trunk. The intersection point I (x_I, y_I, z_I) between the sphere and the humerus was computed, starting from the joint centre~~s~~ positions expressed in local coordinates of the moving system in order to obtain the intersection angles:

$$\theta = \arcsin\frac{y_I}{\sqrt{x_I^2 + y_I^2 + z_I^2}} + \frac{\pi}{2} \qquad (1)$$

$$\text{if } x_I \geq 0\text{, } \phi = \arccos\frac{z_I}{\sqrt{x_I^2 + z_I^2}} - \frac{\pi}{2} \qquad (2)$$

$$\text{if } x_I < 0\text{, } \phi = \arccos\frac{-z_I}{\sqrt{x_I^2 + z_I^2}} + \frac{\pi}{2} \qquad (3)$$

The time course of humerus rotation about its longitudinal axis (internal-external rotation) was calculated with appropriate coordinate transformations built on the Eulerian angles system based on a YZ'Y'' rotation sequence: the first rotation (*shoulder flexion:* ϕ) about the Y axis fixed on the scapula defined the horizontal abduction angle, the second rotation (*horizontal abduction:* θ) about the Z'-axis corresponded to the flexion of the shoulder and the third rotation (ψ) about the Y'' axis corresponded to humeral axial *Rotation*. The initial resting or reference position and angular rotation was defined with the humeral shaft held at right angle to the trunk segment (θ = 90°). When the shoulder was 90° abducted in the frontal plane, with the elbow 90° horizontally flexed, *horizontal abduction* (ϕ) and axial *Rotation* (ψ) angles assumed a value of 0°. Starting from this position *horizontal abduction* had positive and negative values respectively when the shoulder moved horizontally forward (*horizontal adduction*) and backward, while positive values were assigned for internal axial *Rotation* and negative values for external axial *Rotation*.

The location of the glenohumeral joint centre, as measured, is not truly representative of the joint behaviour since it does not account for the scapular motion. The 3D reference framework, despite the many markers adopted, should be regarded as a first attempt to describe the complex motion of the shoulder joint in this context. Protraction/retraction, elevation/depression and upward/downward rotation of the scapula have been evaluated in volleyball players (Ribeiro & Pascoal, 2013). In addition, in vivo measurements have shown that glenoid contact between scapula and humerus shifts superiorly during shoulder abduction and the contact area between the glenoid fossa and the humerus does not change significantly during abduction movements of the shoulder over 90° (Omori et al., 2014). However abnormal conditions (either because of extreme positions and force) could cause the displacement of the glenohumeral joint centre, and further studies will be necessary to assess whether the movements of the scapula during the volleyball spike are small enough not to affect the present conclusions.

Time derivative function was exploited in order to evaluate linear and angular velocities, starting from the trajectories of the markers and the 3D angular values respectively. The right finger marker (see Table III) was chosen to evaluate maximal linear velocity and height of the spiking hand.

Parameters analysed and statistics

Kinematic data were normalised according to time to a spike cycle from 0 to 100%, from one frame before the humerus intersected the upper half of the sphere (shoulder flexion > 90°) to the exit from it at the end of the spike event (shoulder flexion < 90°). Data could then be averaged across each subject's trials and presented graphically for each condition both for angles values and angular velocities. Range of motion of the shoulder was evaluated in terms of maximal shoulder flexion, maximal horizontal abduction, and maximal axial rotation (internal and external) with the respective angular velocities. The trajectory of the humerus intersection point on the sphere was represented on the imaginary sphere in the 3D space as a function of both angular velocity (internal and external), and angular axial rotation (internal and external). To assess performance, maximal height of the hand, hand linear velocity and ball speed have been evaluated, as well.

The following variables were analysed: maximal shoulder flexion, maximal horizontal abduction, and maximal axial rotations with the respective angular velocities. Paired T tests were performed in order to detect differences between techniques for each of the three conditions, while T tests for independent variables were used to detect possible differences between male and females for each condition and technique.

In order to check differences between the three experimental conditions, our analysis was completed by performing a one-way ANOVA for repeated measures, both for the traditional and the alternative technique (for maximal shoulder flexion, maximal horizontal abduction, maximal axial rotation and the relative angular velocities, maximal hand height and hand velocity). Pearson's correlation coefficient was computed to compare the angle traces (represented in Figure 3) in the three different experimental conditions. For each condition, the average curve of the participants was calculated (both for male and female) and utilised for the correlation analysis. Statistical significance was accepted when $p < 0.05$.

RESULTS

Humerus trajectory of the two techniques (TT and AT) travelled along two different paths on the imaginary sphere (Figure 5a-d). In Figure 3, angular time course data are presented for the three different conditions, averaged and normalised according to the spike cycle described above. Averaged durations of the normalised cycles were 0.62 ± 0.01, 0.53 ± 0.02 and 0.56 ± 0.04 seconds, for the three experimental conditions respectively.

In each of these conditions maximal shoulder flexion was significantly reduced in AT both for female and male athletes (on average by 10 degrees), while horizontal abduction angular amplitude was significantly higher (on average 15 degrees). No significant difference between TT and AT was found for external rotation angular values in the three different conditions (online supporting information, Table A).

Angular velocity time courses are presented in Figure 4, averaged and normalised as previously described. In Table B (on line supporting information) the maximal angular positive and negative velocity values are reported for each condition, both for male and female athletes.

We found no significant differences between angular velocities in the spike techniques, neither for horizontal ab/adduction, nor for shoulder flexion/extension. In contrast, internal and external angular velocity was found to be higher in most cases for the AT (Table B, on line supporting information). This technique was also characterized by higher spike-hand velocities compared to the traditional one in all the experimental sessions and higher ball speeds in the third experimental condition, while no differences were found for maximal hand height between the two techniques (Table V).

Females displayed a greater range of motion than males (Table A, on line supporting information) especially during field-based experiments (Figure 3c), while male subjects achieved higher values for internal rotation angular velocity. Parameters reflecting athletes' performances also showed significant differences between genders; as expected, males could perform higher jumps, reach higher hand velocities and obtain higher ball speeds (Table V). In addition, maximal hand height and hand velocity presented significantly different values in the three experimental conditions with the highest values obtained during the third condition (indoor volleyball competition court). The pattern of the three measured angles, normalised in time was maintained in the three different experimental conditions, both for TT and AT. Pearson correlation coefficients, together with the related *p*-value are reported in Table C (on line supporting information), showing high significant correlation values for all pairs of variables. While the trajectory of the three shoulder angles is verified in the three experimental conditions, female athletes exhibited significantly higher maximal external rotation values when spiking on the competition court. Also, angular velocities showed significant differences when performing the spike in the different experimental situations. Significantly higher values were recorded when jump-spiking in the laboratory both for male and female athletes for shoulder flexion, internal and external rotational angular velocities (online supporting information Table B).

DISCUSSION AND IMPLICATIONS

The aim of this study was to compare two of the most used spike techniques in volleyball, not only in terms of kinematics, but also taking into account performance parameters, in order to promote preventive solutions for shoulder overuse injuries. For these reasons we analysed the range of motion of the spiking shoulder not only simulating the movement in the laboratory, but also performing the spike on a volleyball court, replicating real playing conditions. Our studies intent is to help clinicians, coaches, biomechanists and athletes to better understand risks associated with different spike manoeuvres. As hypothesized, the spiking arm of the athletes moves within a different range of motion when adopting TT or AT (Figure 3a-c and Figure 5a-d). Shoulder flexion was significantly reduced in AT both for female and male athletes, maintaining the same pattern in the three experimental conditions, and suggesting AT as a safer spiking style. Although horizontal abduction increased during the AT, it exceeded the coronal/scapular plane for less than half of the spike cycle, reaching values considered dangerous for impingement just for a few frames of the movement. It has been shown that contact pressure at the glenohumeral joint increases proportionally when horizontal abduction exceeds the coronal plane, with external rotation and 90° of shoulder abduction (Mihata, McGarry, & Kinoshita, & Lee, 2010). However the most dangerous manoeuvres during the volleyball attack are shoulder flexion during the elevation of the spiking arm, together with maximal external ~~(axial negative)~~ rotation (Leonard & Hutchinson, 2010; Page, 2011). Subacromial and internal impingement occurs predominantly against the anterior edge of the acromion and the coracoacromial ligament affecting the vasculature of these structures (Neer, & Welsh, 1977; Rathbun, & Macnab, 1970, Page, 2011). When the humerus is flexed over 90° degrees, the supraspinatus tendon and other structures involved in the spiking movement (Rokito et al., 1998) are at highest risk for irritation and subsequent injury. During elevation, structures such as the rotator cuff, biceps tendon long head, and subacromial bursa become compressed and are at risk of inflammation under the coracoacromial ligament, leading athletes' shoulders to suffer structural subacromial impingement, due to the soft tissue inflammation and consequent decreased stability, due to the tightness of the pectoralis major (Page, 2011). In addition during the spike the shoulder is affected by a significant amount of stress: prior to ball contact, at the end of cocking (phase 5 in Figure 1a and 1b) and acceleration phases (phase 6-7 in Figure 1a and 1b), (as described by Rokito and collaborators in 1998) a maximum internal rotation torque is placed on the shoulder, while after the impact (phase 8-9 in Figure 1a and 1b) a shoulder adduction torque is generated, and the glenohumeral compressive force reaches its maximum value. Based upon kinematic analyses, Reeser and collaborators tried to estimate the forces acting on the glenohumeral joint during the volleyball spike (Reeser, Fleisig, Bolt, and Ruan, 2010) and further studies, based on finite element methods, electromyography or musculoskeletal simulation, could estimate these forces and the effect of the single actuators in the compression of the glenohumeral joint.

With our novel analysis framework we have observed different techniques performed by the same player to give origin to two distinctive 3D curves on the imaginary sphere (Figure 5a-d). Because of the high effort and physical demand during the spike motion, both TT and AT bring the shoulder near and beyond its articular limits (previously evaluated in term of range of motion), but AT trajectory travels along a safer path. Figures 5a-d demonstrate both static and dynamic~~s~~ features of the two different techniques. Shoulder flexion was always greater in the TT. Additionally at the position of the spiking action, when the stresses are thought to peak, we observed the sudden transition from negative to positive angular velocity of the spiking shoulder occurring on a more dangerous level (closer to the articular limits) for the TT compared to the AT (Figure 5b and 5d). In the same way, ball impact (where hand velocity is supposed to decrease suddenly after its maximal value), occurs at a lower shoulder flexion degree for the AT compared to the TT (Figure 5c and 5d). We can state that, spikes performed with the AT maintained the spiking arm of the players far from their articular limits in term of shoulder flexion. This is because the shoulder in the AT starts its motion with internal rotation and the sudden transition from negative to positive angular velocity occurs only in the last phase of the trajectory, very far from its articular limits.

Values of internal and external rotation angles and angular velocities were similar to those reported by Wagner in 2012 (Wagner et al., 2012) for other typical overhead sports activities. We found higher internal rotation velocities values for AT, particularly in male athletes. Differently, females, especially when jumping, exploited a greater range of motion probably due to ligament laxity and lower stiffness of the shoulder joint. Range of motion and angular velocity time courses maintained the same pattern in the three experimental conditions, although during field experiments the differences between techniques decreased. This is probably because athletes, when required to hit the ball, prefer a successful spike to a completely correct technique. Angular velocities increased when spiking while jumping, though we noticed significantly decreased values, particularly of the internal rotational component, during on–court experiments, likely due to ball impact.

In terms of performance, values of ball speed, hand height and velocities matched values reported by other studies on high-level professional player spiking analyses (Coleman, 1993; Wagner et al., 2012; Mitchinson, Campbell, Oldmeadow, Gibson, & Hoppe, 2013). While maximal hand height in jumping remained constant, hand velocity before impact had greater values for the AT in each of the three considered conditions. Higher values were also recorded for ball speed in the field experimental sessions when athletes performed the AT.

The current study did not analyse the cause-effect relationship between techniques and injury rates. We can therefore speculate that the decreased shoulder flexion during AT may be associated decreased risk for certain injuries. However, future studies are needed to confirm this theory. In addition some limitations have to be mentioned: i) in this study different comparisons have been assessed (different T test have been performed within the different conditions of spike). Type I error rate inflation could occur when a set of hypotheses is tested simultaneously if each hypothesis test is compared to α. This increases the probability of making at least one Type I error (accidentally judging as significant a difference that is not), when multiple and independent null hypotheses are true; ii) marker based motion capture system might introduce significant amount of errors because of skin motion, with consequent possible errors in the estimation of the humerus intersection; iii) The location of the glenohumeral joint centre, as measured, is not truly representative of the joint behaviour since it does not account for the scapular motion and the other structures of the shoulder such as muscles and ligaments.

Despite these limitations our method suggested to be effective in visualising the risks associated with different spike manoeuvres ~~not only~~ for biomechanists, ~~but also~~ clinicians, athletes, coaches and athletic trainers, showing information regarding both humerus range of motion, its speed and axial angular velocities in the same 3D space. This allows simultaneous evaluation of the single or combined changes in trajectory and speed, with respect to articular angular and torsional limits. Other shoulder movements could benefit from the proposed framework in future research: skills in sports as tennis and handball, which also strongly rely on overhead shoulder movements, could similarly be compared to the physiological constraints of the relevant joint, giving musculoskeletal specialists the chance to inspect results and associate them with the potential cause of articular diseases.

CONCLUSION

Sport movements usually bring athletes close to the limits of their musculoskeletal system and the volleyball spike is a good example of this. Although the shoulder is a complex structure and the risk factors for shoulder injury during spiking can be different (e.g. forces acting on the joint, velocity of the arm, range of motion, previous history of injury, number of spikes in a season), the use of the alternative technique can potentially reduce shoulder overuse injuries. The structures of the shoulder are exposed to high stresses regardless of technique, but we suggested that the alternative technique could potentially be a safer solution to the chronic pathologies of the shoulder. By allowing the rotator cuff to function within a range of motion which is considered less dangerous, the AT technique may reduce shoulder impingement risk, while retaining, or even enhancing performance, not only in elite athletes, but also in recreational and school/collegiate players (both male and female). In addition to pre- or post-injury interventions, the encouragement of a newly validated spike technique, such as the one here called AT, could be a prevention strategy in the field of shoulder overuse injuries, especially if taught to the young athletes, where a specific spike technique has not already been fully established as the individual’s chosen technique.

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Table I: Anthropometric characteristics of the athletes participating the study

	Age (years)	Stature (m)	Body Mass (kg)
Male	22.1 ± 5.8	1.94 ± 0.04	84.8~~3~~ ± 8.6~~3~~
Female	22.8 ± 7.5	1.81 ± 0.04	72.8~~75~~ ± 5.4~~2~~
Total	22.4 ± 6.5	1.88 ± 0.07	79.1~~08~~ ± 9.4~~1~~

Table II: Description of the different conditions analysed, included in the experimental protocol: Test 1 was performed to verify the differences in term of range of motion between the two spike techniques. Successively players performed test 2 and 3, in order to confirm the kinematical differences also during a movement increasingly 'ecologically correct', and to assess the *performance* in term of jump height, arm velocity and ball speed.

	Test	**Actions**	**Details**
Laboratory (1st day)	1	3 successful alternative style spikes 3 successful traditional style spikes	Without jumping and without ball.
	2	3 successful alternative style spikes 3 successful traditional style spikes	Jumping, without ball.
Indoor volleyball competition court (2nd day)	3	3 successful alternative style spikes 3 successful traditional style spikes	Jumping and hitting the ball positioned over the net by an experienced setter player.

Table III: Description of the Marker Position represented in Figure 2: * indicates that the marker was utilised only for static acquisition; the medial and lateral elbow epicondyle positions were calculated during the static trial, such that their position could be replicated virtually during dynamic trials.

	Definition	**Marker Anatomical Position**
1	7th cervical vertebra	On the spinous process of the 7th cervical vertebra.
2	Right back	Over the right scapula.
3	10th thoracic vertebra	On the spinous process of the 10th thoracic vertebra.
4	Clavicle	On the jugular notch where the clavicles meet the sternum
5	Sternum	On the xiphoid process of the sternum.
6	Right shoulder	On the right acromio-clavicular joint.
7	Left shoulder	On the left acromio-clavicular joint.
8	Right upper arm A	On the lateral upper right arm (technical reference frame).
9	Right upper arm B	On the lateral upper right arm (technical reference frame).
10	Right upper arm C	On the lateral upper right arm (technical reference frame).
11	Right elbow	On the lateral epicondyle approximating the elbow joint axis.
12	Right medial epicondyle	On the humerus medial epicondyle*
13	Right forearm	Right Forearm.
14	Right wrist marker A	Right wrist marker A. At the thumb side of the right radial styloid attached symmetrically with a wristband on the posterior of the right wrist, as close to the wrist joint centre as possible.
15	Right wrist marker B	Right wrist marker B. At the little finger side of the right ulnar styloid attached symmetrically with a wristband on the posterior of the right wrist, as close to the wrist joint centre as possible.
16	Right finger	Right finger just below the right third metacarpus.

Table IV: Definition of the coordinate systems for Trunk and Upper arm segment: technical and anatomical frames are described starting from the marker (*Mk*) positions indicated in Figure 2 and Table III.

		Trunk		Upper Arm
Technical frame	Origin:	$Mk\,[5]$	Origin:	$Mk\,[11]$
(Origin and Axis):	z-axis:	$\overrightarrow{ZT} = Mk[4] - Mk[5]$	x-axis:	$\overrightarrow{xt} = Mk[8] - Mk[11]$
	Inter:	$\vec{i} = Mk[5] - Mk[1]$	Inter:	$\vec{i} = Mk[9] - Mk[11]$
	x-axis:	$\overrightarrow{XT} = \overrightarrow{ZT} \times \vec{i}$	y-axis:	$\overrightarrow{yt} = \overrightarrow{xt} \times \vec{i}$
	y-axis:	$\overrightarrow{YT} = \overrightarrow{ZT} \times \overrightarrow{XT}$	z-axis:	$\overrightarrow{zt} = \overrightarrow{xt} \times \overrightarrow{yt}$
Anatomical frame	Origin:	RGH	Origin:	RGH
(Origin and Axis):	y-axis:	$\vec{Y} = Mk[A] - Mk[B]$	y-axis:	$\vec{y} = RGH - REJC$
	Inter:	$\vec{i} = Mk[5] - Mk[3]$	Inter:	$\vec{i} = RWJC - REJC$
	x-axis:	$\vec{X} = \vec{Y} \times \vec{i}$	x-axis:	$\vec{x} = \vec{y} \times \vec{i}$
	z-axis:	$\vec{Z} = \vec{X} \times \vec{Y}$	z-axis:	$\vec{z} = \vec{x} \times \vec{y}$

Table V: Maximal Hand Height, Hand Velocity and Ball speed for the three different analysed conditions. Significantly higher values for the AT compared to the TT are indicated with ** ($p < 0.01$) and * ($p < 0.05$). $^{\#\#}$ indicates significant differences ($p < 0.01$) between male (M) and female (F) athletes. (††) indicates significant differences between the three experimental sessions ($p < 0.01$).

		Max Hand Height $^{(\dagger\dagger)}$ **(m)**	**Hand Velocity** $^{(\dagger\dagger)}$ **(m/s)**	**Ball Speed (m/s)**
1st condition	M (TT)	$2.29 \pm 0.07^{\#\#}$	$16.19 \pm 2.55^{\#\#}$	-
	M (AT)	$2.30 \pm 0.07^{\#\#}$	$17.07 \pm 2.34^{\#}$	-
	F (TT)	2.11 ± 0.08	13.99 ± 1.24	-
	F (AT)	2.10 ± 0.06	$14.88 \pm 1.59^{**}$	-
2nd condition	M (TT)	$2.89 \pm 0.14^{\#\#}$	$18.95 \pm 2.19^{\#\#}$	-
	M (AT)	$2.90 \pm 0.10^{\#\#}$	$20.44 \pm 2.12^{\#\#*}$	-
	F (TT)	2.54 ± 0.07	16.11 ± 1.81	-
	F (AT)	2.55 ± 0.06	$17.27 \pm 1.56^{**}$	-
3rd condition	M (TT)	$3.04 \pm 0.09^{\#\#}$	$20.66 \pm 1.32^{\#\#}$	$25.56 \pm 3.35^{\#\#}$
	M (AT)	$3.05 \pm 0.10^{\#\#}$	$21.90 \pm 2.03^{\#\#}$	$26.25 \pm 2.04^{\#\#}$
	F (TT)	2.72 ± 0.06	17.86 ± 1.98	20.41 ± 3.68
	F (AT)	2.73 ± 0.06	18.65 ± 1.40	22.19 ± 2.54

Figure Legends

Figure 1: A) Traditional Spike Technique (TT), also called *Elevations style,* B) Alternative Spike Technique (AT), also called *Backswing style*. Movies regarding real movements filmed with a high frequency camera are available in the online supporting information (Video 1 and Video 2). See details in the paragraph 'Techniques'.

Figure 2: Left panel: Marker set utilized on participants. The relative description of markers' numbers is reported in Table III. Points A and B represent the middle points respectively between markers 1 – 4 and markers 3 – 5. RGH, REJC and RWJC represent the rotation centre, respectively for Right Glenohumeral joint, Right Elbow Joint and Right Wrist Joint. Right panel: In order to describe the range of motion of the shoulder in term of *Flexion* (θ), *Horizontal Abduction* (ϕ) *and Axial Rotation* (ψ) angles, two sets of coordinate systems are represented: the reference system XYZ (Trunk anatomical frame), fixed to the trunk together with the imaginary sphere (radius = 200mm) centred on the humerus head (RGH), and the moving system xyz (Upper Arm anatomical frame). Both the reference system XYZ and the moving coordinate system xyz were fixed and centred on the glenoid RGH and their respective axes are described in Table IV.

Figure 3: Horizontal Abduction, Flexion and axial Rotation angles, normalised on a spike cycle: 0% = first frame in which Flexion angle goes over 90°, 100% = last frame in which goes under 90°. A) without jumping, B) jumping without hitting the ball, C) jumping and hitting the ball. Dashed curves represent females, while continuous lines represent males (AT in black and TT in grey).

Figure 4: Horizontal Abduction, Flexion and axial Rotation angular velocities, normalised on a spike cycle: 0% = first frame in which Flexion angle goes over 90°, 100% = last frame in which goes under 90°. A) without jumping, B) jumping without hitting the ball, C) jumping and hitting the ball. Dashed curves represent females, while continuous lines represent male (AT in black and TT in grey).

Figure 5: Examples of typical 3D trajectories of humerus intersection on the imaginary sphere for the Alternative Technique (AT, labelled 1) and for the Traditional Technique (TT, labelled 2). Panels A and B show trajectories recorded during the second experimental condition (with jumping in the laboratory), while panels C and D refer to the third experimental condition (with jumping and hitting the ball). The trajectory obtained during Maximal Circumduction (MC) indicates the articular limits of the subjects' shoulder and is represented on the sphere in black.

A and C: Trajectory color intensity reflects the corresponding internal (blue) and external (red) angular value of humerus axial rotation.

B and D: Trajectory color intensity reflects positive (blue) and negative (red) angular velocity of humerus axial rotation. * indicates the impact with the ball, occurring on average 0.5 seconds after the humerus intersects the upper half of the sphere.

Table A: Max Horizontal Abduction, Maximal Flexion and External axial rotation angle values for the three different analysed conditions. Significant differences between TT and AT are indicated with ** ($p < 0.01$) and * ($p < 0.05$). ## indicates significantly differences ($p < 0.01$) between male (M) and female (F) athletes. †† indicates significantly differences ($p < 0.01$) with the 1st condition. °° indicates significantly differences ($p < 0.01$) with the 2nd condition.

		Max Horizontal Abduction (°)	Max Flexion (°)	Max Ext. rot (°)
1st condition	M (TT)	-10.1 ± 21.5	142.0 ± 12.6	-121.8 ± 57.4
	M (AT)	-28.8 ± 16.1**	128.7 ± 11.5**	-139.4 ± 17.8
	F (TT)	-16.8 ± 15.2	146.9 ± 9.8	-141.5 ± 16.2
	F (AT)	-33.4 ±19.3**	134.5 ± 11.1**	-141.6 ± 14.1
2nd condition	M (TT)	-14.6 ± 18.43	146.6 ± 14.2	-131.3 ± 38.6
	M (AT)	-35.3 ± 12.5**	137.8 ± 13.8**	-141.0 ±18.2
	F (TT)	-26.0 ± 19.0	146.3 ± 7.5	-141.4 ± 24.9
	F (AT)	-45.7 ± 20.1**	139.6 ± 8.9*	-137.0 ±14.3
3rd condition	M (TT)	-18.7 ± 21.3	139.9 ± 9.5	-141.8 ± 23.7$^{\#\#}$
	M (AT)	-33.7 ± 16.2$^{\#\#*}$	133.1 ± 10.5*	-143.5 ± 20.92$^{\#}$
	F (TT)	-41.5 ± 20.8†	145.1 ± 11.4	-162.8 ± 13.2$^{\dagger\dagger\circ\circ}$
	F (AT)	-45.0 ± 20.6*	138.8 ± 12.0*	-160.83 ± 15.8$^{\dagger\dagger\circ\circ}$

Table B: **Maximal values for Horizontal Ab/Ad-duction, Flexion/Extension and Internal-External rotation angular velocities for the three different analysed conditions.** Significant differences between TT and AT are indicated with ** ($p < 0.01$) and * ($p < 0.05$). ## indicates significantly differences ($p < 0.01$) between male (M) and female (F) athletes. †† indicates significantly differences ($p < 0.01$) with the 1st condition.

		Max Ang Vel Abduction (rad/s)	**Max Ang Vel Extension (rad/s)**	**Max Int Rot Ang Vel (rad/s)**
1st condition	M (TT)	-9.06 ± 3.52	-14.82 ± 3.97	56.93 ± 27.54$^{\#\#}$
	M (AT)	-10.06 ± 3.96	-13.48 ± 4.29	66.21 ± 31.42$^{\#}$
	F (TT)	-12.13 ± 8.08	-13.40 ± 2.46	26.44 ± 8.67
	F (AT)	-7.60 ± 3.68	-13.40 ± 2.07	37.33 ± 7.46*
2nd condition	M (TT)	-15.18 ± 5.32†	-18.49 ± 2.72$^{\#}$	66.39 ± 36.51
	M (AT)	-12.71 ± 2.76	-18.57 ± 2.96	77.47 ± 35.92*
	F (TT)	-15.60 ± 4.80	-16.85 ± 2.58	41.64 ± 18.71
	F (AT)	-11.53 ± 5.01	-17.99 ± 2.56††	55.83 ± 15.65*††
3rd condition	M (TT)	-11.41 ± 4.16	-14.81 ± 3.23	43.07 ± 11.6
	M (AT)	-13.63 ± 2.47	-16.11 ± 3.35	66.25 ± 22.53$^{\#\#}$*
	F (TT)	-11.69 ± 3.77	-13.00 ± 3.65	32.47 ± 5.11
	F (AT)	-11.97 ± 4.17	-14.06 ± 1.59††	32.59 ± 8.87††

		Max Ang Vel Adduction (rad/s)	**Max Ang Vel Flexion (rad/s)**	**Max Ext. Rot. Ang Vel (rad/s)**
1st condition	M (TT)	14.70 ± 4.81	7.27 ± 1.73	-6.24 ± 9.14
	M (AT)	15.58 ± 4.50	6.86 ± 1.76	-15.30 ±6.02*
	F (TT)	14.24 ± 5.27	7.51 ± 2.81	-10.83 ± 7.03
	F (AT)	15.09 ± 6.61	6.37 ± 1.98	-9.85 ± 9.33
2nd condition	M (TT)	21.95 ± 12.03	10.43 ±1.56	-16.87 ± 6.39††
	M (AT)	19.04 ± 4.38	11.82 ±3.75††	-24.43 ± 5.45*
	F (TT)	16.50 ± 3.17	10.18 ± 2.45	-13.71 ± 3.36
	F (AT)	16.75 ± 4.72	9.90 ± 1.90††	-19.39 ± 6.81*

3rd condition	M (TT)	17.67 ± 7.02	11.50 ± 3.13††	-20.61 ± 6.13††
	M (AT)	21.88 ± 7.81	13.88 ± 5.18††	-37.97 ± 34.33
	F (TT)	19.47 ± 3.06	9.74 ± 2.00	-18.51 ± 3.49†
	F (AT)	19.98 ± 3.38	9.60 ± 1.92††	-21.65 ± 5.05†

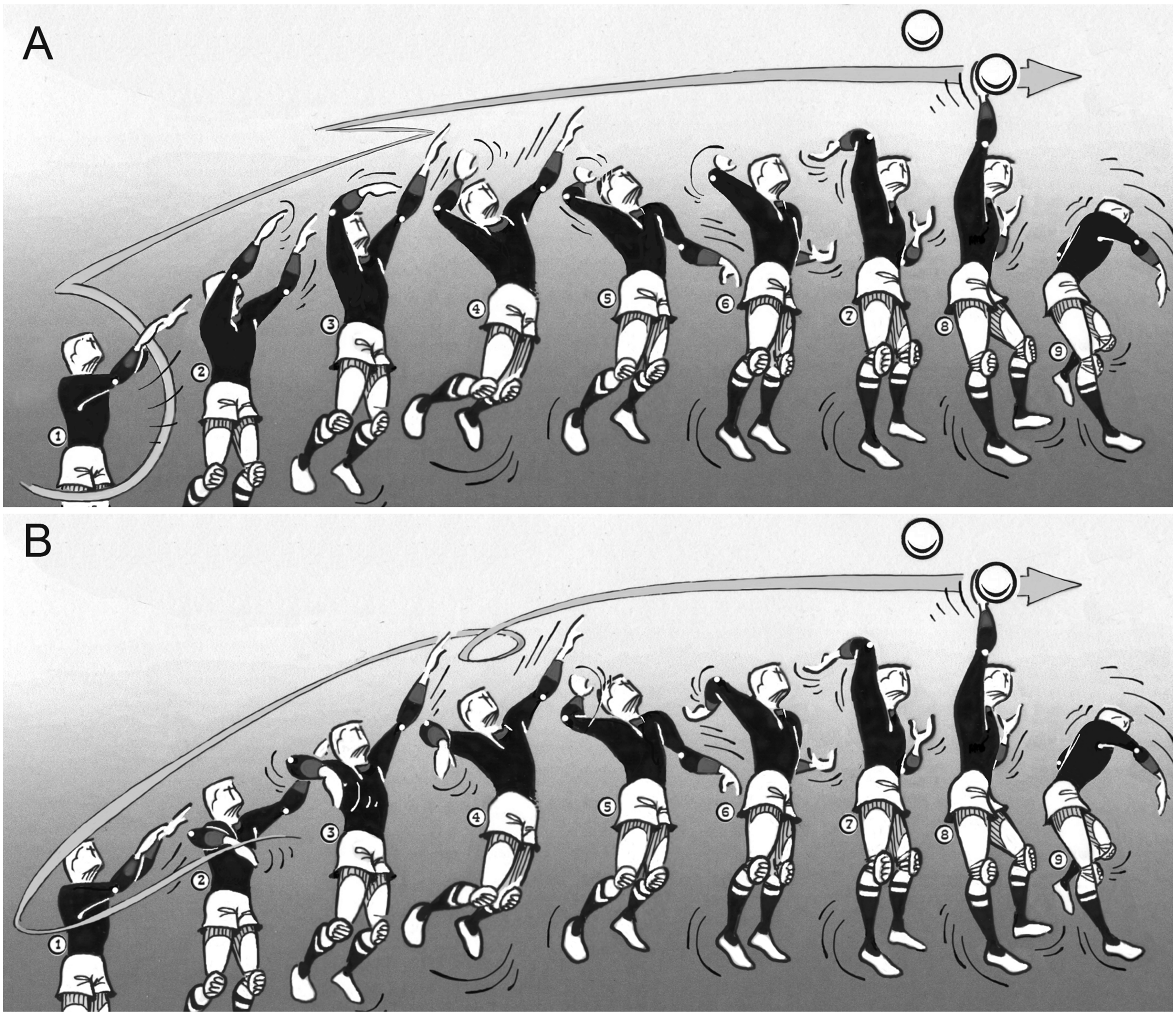

Figure 1

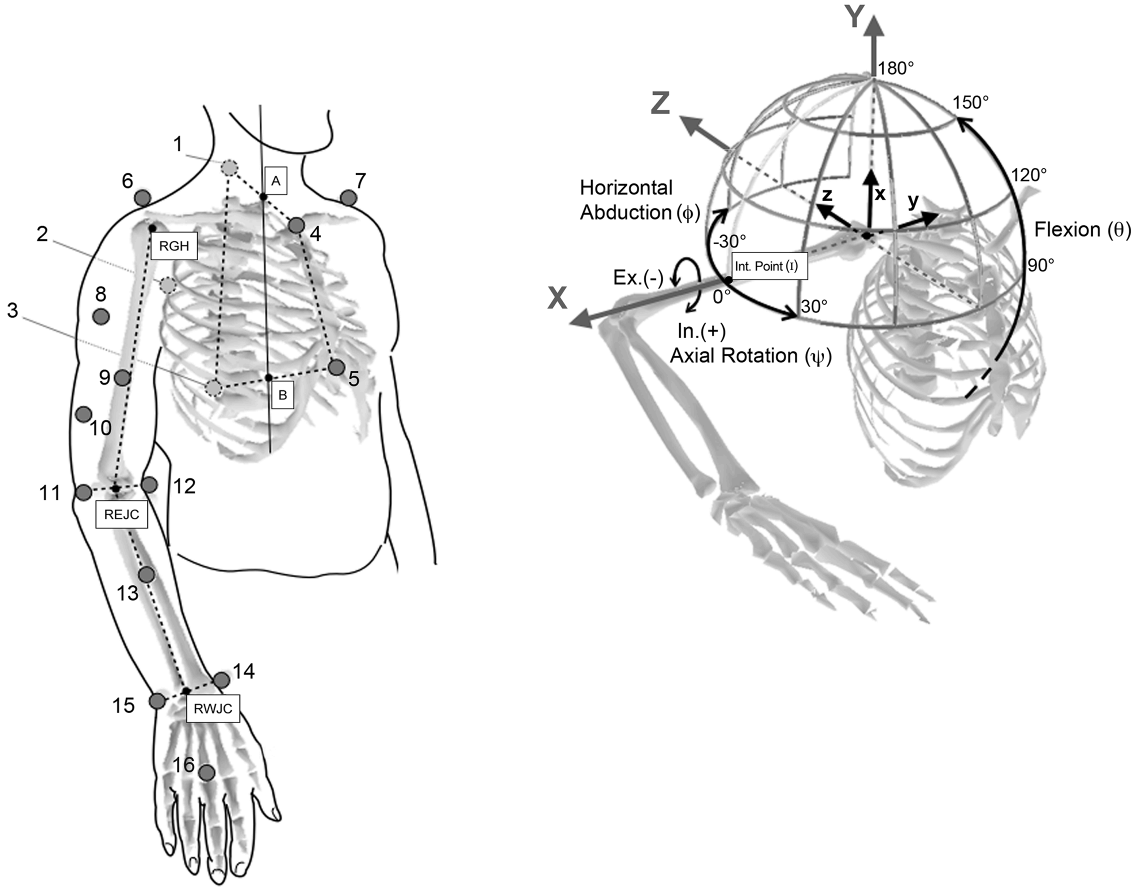
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
A
B
RGH
REJC
RWJC
Y
Z
X
180°
150°
120°
90°
Horizontal Abduction (ϕ)
-30°
0°
30°
z
x
y
Flexion (θ)
Int. Point (ι)
Ex.(-)
In.(+)
Axial Rotation (ψ)

Figure 2

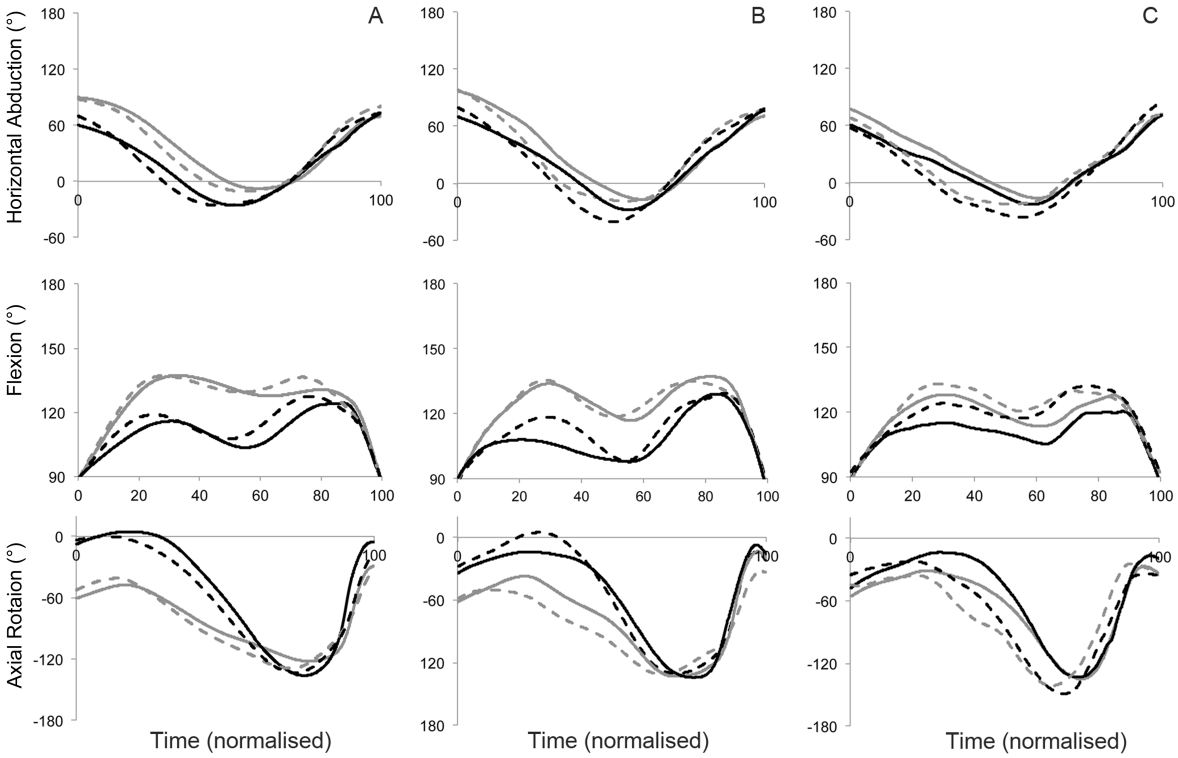
A
B
C
Horizontal Abduction (°)
Flexion (°)
Axial Rotaion (°)
180
120
60
0
-60
150
90
-120
-180
0
20
40
60
80
100
Time (normalised)

Figure 3

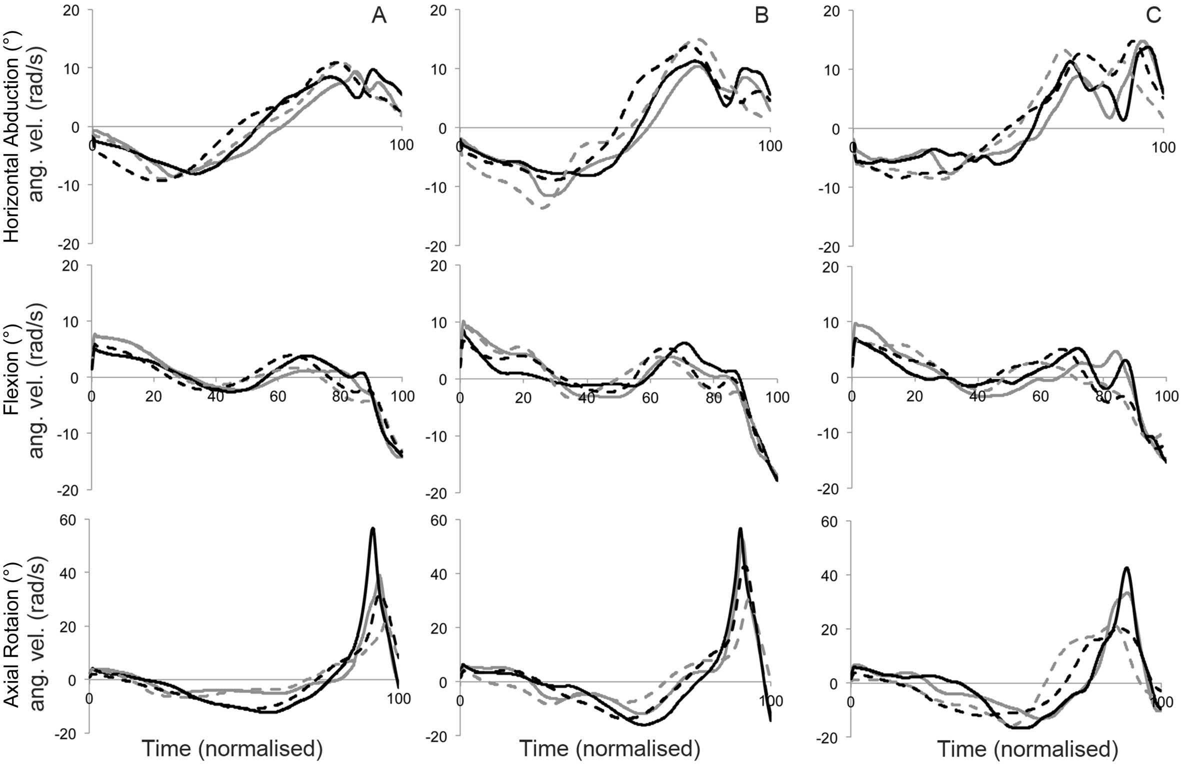
A
B
C
Horizontal Abduction (°) ang. vel. (rad/s)
Flexion (°) ang. vel. (rad/s)
Axial Rotaion (°) ang. vel. (rad/s)
20
10
0
-10
-20
60
40
0
20
40
60
80
100
Time (normalised)

Figure 4

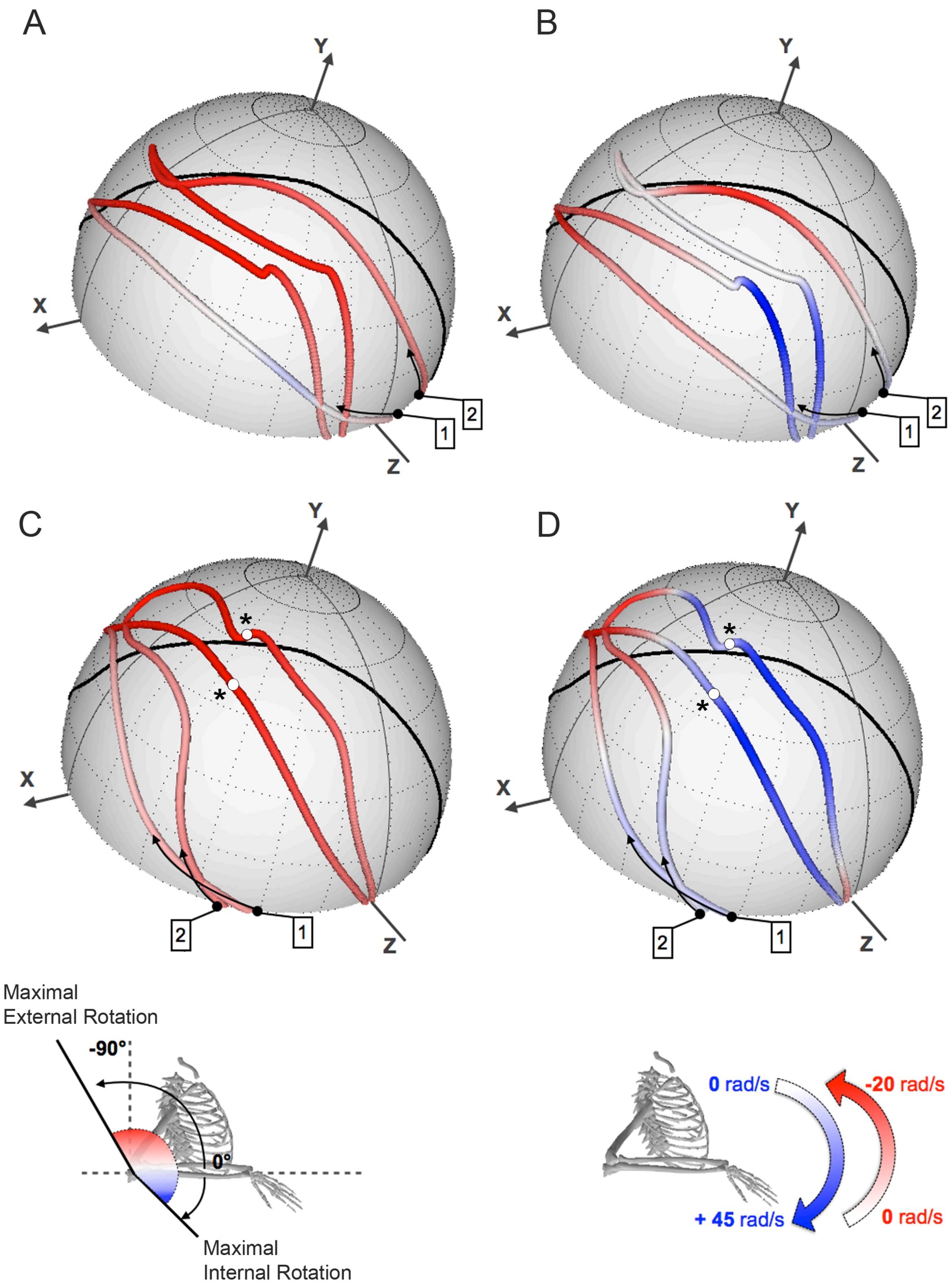
A
B
C
D
Y
X
Z
1
2
*
Maximal External Rotation
-90°
0°
Maximal Internal Rotation
0 rad/s
-20 rad/s
+ 45 rad/s
0 rad/s

Figure 5