Human Movement Science 64 (2019) 203–212

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Shoulder kinematics and kinetics of team handball throwing: A scoping review

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ARTICLE INFO

Keywords:
Biomechanics
Glenohumeral joint
Handball
Kinematics
Shoulder

ABSTRACT

In recent years a number of studies have investigated shoulder biomechanics in handball throwing. The purpose of this scoping review is to summarize the current handball research in terms of shoulder joint kinematics and kinetics and identify gaps in the current research. Nineteen articles relevant to this topic were identified and included. The handball throw is characterized by large external shoulder rotation followed by a rapid internal rotation with minor changes in shoulder flexion and abduction. Generally timing sequence, joint angles and joint velocities were not affected by different conditions such as throwing type, arm position, ball weight and gender. However, large differences in shoulder angles and angular velocities were found between studies, which most likely are explained by methodological differences. Unfortunately, the information provided in the articles did not make it possible to transform measurements from one study to another and thereby eliminate the methodological differences. Only one study reported shoulder kinetics and found that kinetics were not affected by fatigue. This scoping review highlights the need for better descriptions of the methods used to obtain shoulder kinematics and for studies investigating shoulder kinetics in handball throwing.

1. Introduction

Handball is a widely popular sport with high technical, tactical and physical demands. One unique feature of handball compared to other throwing sports is the large variation in how the ball is thrown. These variations include the length of the run-up, whether or not the ball is thrown while jumping and many others. However, it is not clear how these variations may affect the throwing biomechanics.

The shoulder joint, acting as a part of the kinetic chain involved in transferring energy from the lower extremities to the ball, plays a central role in the throwing mechanism. Therefore it is especially interesting to examine how the aforementioned variations may affect both kinematics and kinetics of the shoulder. Several studies have investigated the biomechanics of handball throwing in recent years, but to date no comprehensive review of the shoulder biomechanics in handball exists. A scoping review can help identify gaps in knowledge and/or flaws in the current literature and thus guide future research towards currently unexplored areas. In addition, synthesizing the current research, can help researchers and practitioners better understand how to optimize throwing performance as

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https://doi.org/10.1016/j.humov.2019.02.006
Received 15 August 2018; Received in revised form 6 February 2019; Accepted 13 February 2019
Available online 18 February 2019

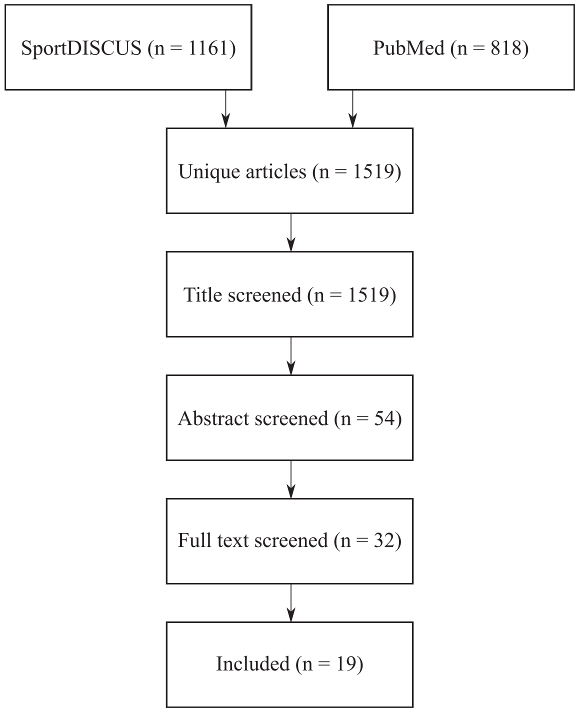

Fig. 1. Flowchart for the selection process for inclusion of articles in the review. Both databases were accessed March 18.

well as injury prevention and rehabilitation, which is very important considering the high prevalence and incidence of shoulder pain problems in handball (Asker, Holm, Källberg, Waldén, & Skillgate, 2018; Møller et al., 2017; Møller, Attermann, Myklebust, & Wedderkopp, 2012; Myklebust, Hasslan, Bahr, & Steffen, 2013).

Measuring shoulder biomechanics can however be challenging. The soft tissue surrounding the shoulder joint introduces errors when employing traditionally used methods such as motion capture (Blache & Begon, 2017), the shoulder joint center is not easily found (Crabolu et al., 2017) and the anatomical definition of a neutral glenohumeral rotation is unclear (Wu et al., 2005). Thus, as a part of this scoping review, the methods used to measure shoulder kinematics in the included studies will be thoroughly discussed. This is especially important considering the fact that the first studies of handball shoulder kinematics were published before the International Society of Biomechanics (ISB) published their guidelines in 2005 (Wu et al., 2005).

Therefore, the purpose of this review is 1) to summarize recent years' findings with regard to shoulder kinematics and kinetics in team handball throwing, 2) to compare biomechanics of different types of handball throws and 3) discuss the methods used to obtain the reported shoulder measures.

2. Materials and methods

2.1. Literature search method and study selection

The search process is documented in Fig. 1 and was performed by the main author. In short, PubMed and Sport DISCUS were searched for the term "handball", with no restrictions set on the PubMed search, while the Sport DISCUS search was limited to articles written in English. Only articles accepted for publication in academic journals prior to May 19, 2017 were included. In order to be included in this review, articles had to report kinematic or kinetic parameters of the shoulder joint during handball throwing. Excluded topics included strength and/or flexibility measurements of the shoulder muscles, tactical and/or social aspects and injury prevalence and/or incidence. No restrictions were set for study design, gender, level or age of participants or type of throw investigated. Article titles were then screened and titles that clearly did not satisfy the aforementioned criteria were excluded. Next, abstracts of the remaining articles were read and the same exclusion criteria as previously were used to exclude articles at this step. Finally, the remaining articles were fully read and articles that did not contain information relevant to the review were excluded. In addition to the database search, references of the articles that were fully read were manually searched. Upon the first read-through of the articles the most commonly reported measures was determined and subsequently the following outcome measures were extracted for summary: Ball velocity, time of occurrence of maximal linear and angular velocity of the upper-extremity joints, maximal angular velocities and angular velocities at the time of ball release of the glenohumeral joint, maximal shoulder flexion, abduction and rotation angles and joint torques and the same angles at the instant of ball release. The methods of this study's search strategy, inclusion criteria and data analysis weren't pre-specified in a registered protocol before any study-related activities were started.

Table 1
Summary of joint angles measured throughout the entire throw and at ball release. Results from van den Tillaar (2016) are reported for both males and females, where female results are indicated by underlined text.

Author, year	Sex	Level	Type of throw	Maximal shoulder angle (°)			Shoulder angle at ball release (°)		
				External rotation	Flexion	Abduction	External rotation	Flexion	Abduction
Fradet et al, 2004	M	2nd League + top level U-18.	Standing with run-up	−41	–	–	–	–	–
Van den Tillaar and Ettema, 2007	M	Top and 1st division.	Standing without run-up	130	−12	87	−65	2	87
Van den Tillaar and Ettema, 2009a	M	Top and 1st division.	Standing without run-up, dominant arm	129	−8	86	−59	3	86
			Standing without run-up, non-dominant arm	115	−3	100	−69	14	99
Wagner et al., 2010a	M	–	Standing with run-up, above head	60	−29	114	14	9	100
			Standing with run-up, side-arm	62	−34	107	18	18	94
Van den Tillaar and Ettema, 2011	F	2nd and 3rd division.	Standing without run-up, −20% weight	139	−11	84	100	5	77
			Standing without run-up, normal weight	142	−11	83	95	6	76
			Standing without run-up, +20% weight	143	−11	84	100	6	75
Van den Tillaar and Marques, 2011	F	1st to 4th division.	Standing without run-up, pre-training	136	−14	85	−93	2	79
			Standing without run-up, post-training	136	−13	85	−99	3	79
Van den Tillaar and Cabri, 2012	M	Both Norwegian national level.	Standing without run-up	122	–	–	−102	10	103
	F		Standing without run-up	122	–	–	−103	7	97
Van den Tillaar et al, 2013	M + F	–	Standing without run-up, circular wind-up	−126	–	–	−67	3	97
			Standing without run-up, whip-like wind-up	−131	–	–	−65	9	97
Wagner et al, 2014	M	–	Jump throw	58	−35	–	–	–	–
Van den Tillaar, 2016	M/F	Highest Norwegian national competition.	Standing without run-up, circular wind-up	126/128	–	–	–	–	–
			Standing without run-up, whip-like wind-up	134/131	–	–	–	–	–
			Standing with run-up, circular wind-up	123/124	–	–	–	–	–
			Standing with run-up, whip-like wind-up	131/131	–	–	–	–	–
			Jump throw, circular wind-up	122/128	–	–	–	–	–
			Jump throw, whip-like wind-up	129/129	–	–	–	–	–
Plummer and Oliver, 2017	M	US national team training programme.	Jump throw, pre-fatigue	74.8	–	–	56	26	96
			Jump throw, post-fatigue.	79.0	–	–	59	25	99
Plummer et al., 2017	M	US national team training programme.	Standing without run-up at 50% effort	63.0	–	–	43.4	38.8	106.1
			Standing without run-up at 75% effort	60.9	–	–	44.3	31.7	105.6
			Standing without run-up at 100% effort	64.0	–	–	39.3	29.0	106

Table 2
Summary of ball velocities and internal rotation angular velocities. * = the maximal angular velocities were measured up until ball release. Results from van den Tillaar (2016) are reported for both males and females, where female results are indicated by underlined text.

Author, year	Sex	Type of throw	Ball velocity (m/s)	Maximal angular velocity (rad/s)			Angular velocity at ball release (rad/s)		
				Internal rotation	Flexion	Abduction	Internal rotation	Flexion	Abduction
Jöris et al, 1985	F	Standing with run-up	17.2	–	–	–	–	–	–
Fradet et al, 2004	M	Standing with run-up	23.4	–	–	–	–	–	–
Van den Tillaar and Ettema, 2004	M	Standing without run-up	–	42.5	–	–	–	–	–
Van den Tillaar and Ettema, 2007	M	Standing without run-up	21.55	59.8	3.0	8.9	53.5	–	–
Van den Tillaar and Ettema, 2009a	M	Standing without run-up, dominant arm	21.5	44.6*	2.9*	9.0*	44.6	–	–
		Standing without run-up, non-dominant arm	16.1	21.3*	2.7*	7.1*	21.3	–	–
Wagner et al, 2010b	M	Jump throw, elite level	22.3	87.9	19.4	–	77.3	–	–
		Jump throw, low level	18.0	85.5	18.3	–	60.2	–	–
Wagner et al., 2010a	M	Standing with run-up, above head	24.0	95.6	19.5	10.1	81.2	−5.7	−1.2
		Standing with run-up, side-arm	22.6	88.7	16.8	9.8	67.3	−3.9	−1.5
Van den Tillaar and Ettema, 2011	F	Standing without run-up, −20% weight	19.3	44.4*	4.4*	6.0*	44.4	–	–
		Standing without run-up, normal weight	18.5	44.4*	4.6*	6.0*	44.4	–	–
		Standing without run-up, +20% weight	17.7	40.9*	4.2*	5.9*	40.9	–	–
Van den Tillaar and Marques, 2011	F	Standing without run-up, pre-training	18.0	25.1*	4.2*	7.5*	25.1	–	–
		Standing without run-up, post-training	18.5	31.5*	4.6*	8.8*	31.5	–	–
Wagner et al., 2011	M	Standing with run-up	23.9	–	–	–	–	–	–
		Standing without run-up	22.3	–	–	–	–	–	–
		Jump throw	21.9	–	–	–	–	–	–
		Pivot throw	20.4	–	–	–	–	–	–
Van den Tillaar and Cabri, 2012	M	Standing without run-up	21.1	45.2*	5.6*	8.7*	45.2	–	–
	F		19.2	49.1*	5.6*	7.5*	49.1	–	–
Wagner et al, 2012	M	Standing with run-up, elite	24.2	–	–	–	–	–	–
		Standing with run-up, experienced	22.7	–	–	–	–	–	–
		Standing with run-up, less experienced	17.8	–	–	–	–	–	–
Van den Tillaar et al, 2013	M + F	Standing without run-up, circular wind-up	21.9	44.4*	5.8*	8.1*	44.4*	–	–
		Standing without run-up, whip-like wind-up	20.6	40.2*	4.5*	7.9*	40.2*	–	–
Wagner et al, 2014	M	Jump throw	–	82.0	19.2	–	–	–	–
Serrien et al, 2015	M	Standing with run-up	21.05	–	–	–	–	–	–
	F		16.41	–	–	–	–	–	–
Van den Tillaar, 2016	M/F	Standing without run-up, circular wind-up	22.5/21.3	–	–	–	–	–	–
		Standing without run-up, whip-like wind-up	21.1/20.1	–	–	–	–	–	–
		Standing with run-up, circular wind-up	24.2/22.4	–	–	–	–	–	–
		Standing with run-up, whip-like wind-up	22.5/22.1	–	–	–	–	–	–
		Jump throw, circular wind-up	21.7/19.9	–	–	–	–	–	–
		Jump throw, whip-like wind-up	21.1/20.0	–	–	–	–	–	–
Plummer and Oliver, 2017	M	Jump throw, pre-fatigue	19.8	–	–	–	–	–	–
		Jump throw, post-fatigue.	18.8	–	–	–	–	–	–
Plummer et al., 2017	M	Standing without run-up at 50% effort	16.8	–	–	–	16.8	–	–
		Standing without run-up at 75% effort	19.7	–	–	–	19.0	–	–
		Standing without run-up at 100% effort	21.8	–	–	–	22.1	–	–

3. Results

3.1. Literature search and study selection

The PubMed and Sport DISCUS searches returned a total of 1519 unique articles. 1465 articles were excluded based on the title and an additional 22 articles were excluded after reading the abstract. The remaining 32 articles were fully read. 13 additional articles were excluded after this process, as it did not contain relevant information regarding shoulder kinematics or kinetics. No additional articles were found of relevance to the review topic by manually screening reference lists of the fully read articles, which leave a total of 19 articles included in this review.

3.2. Result outcomes

All studies were conducted in a non-competitive setting and without a defender. Type of throw and shoulder angles are summarized in Table 1 and ball velocity and shoulder angular velocities are summarized in Table 2. In the remainder of this section we compare these outcomes under different conditions such as the type of throw and arm position. Additionally, the timing sequence of the kinematic variables as well as shoulder kinetics is summarized in text form.

3.3. Ball velocity

The highest throwing velocities are found in the standing throw with run-up, followed by the standing throw without run-up then the jump throw and lastly the pivot throw (Wagner, Pfusterschmied, von Duvillard, & Müller, 2011). Other variables affecting the throwing velocity are gender (men achieves higher velocities than women) (Serrien, Clijsen, Blondeel, Goossens, & Baeyens, 2015; van den Tillaar & Cabri, 2012), arm position (overhead throw higher than side-arm) (Wagner, Buchecker, von Duvillard, & Müller, 2010a), skill level (elite players throws with a higher velocity than experienced players, who throws with a higher velocity than less experienced players) (Wagner, Pfusterschmied, Von Duvillard, & Müller, 2012) and weight of the ball (the lighter the ball, the higher the velocity) (van den Tillaar & Ettema, 2011).

Several studies (Jöris, Edwards van Muyen, van Ingen Schenau, & Kemper, 1985; Plummer & Oliver, 2017; van den Tillaar & Ettema, 2007; van den Tillaar & Marques, 2011; Wagner et al., 2011) have found significant correlations between ball velocity and other kinematic parameters. Upper arm internal rotation angular velocity appears to be an important factor. Van den Tillaar and Ettema (2007) found a significant correlation between internal rotation velocity at ball release and ball velocity of $r = 0.67$, and Wagner et al. (2011) found a correlation between the maximal angular velocity of internal rotation and ball velocity of $r = 0.47$. Van den Tillaar and Marques (2011) investigated how a training program affected ball release velocity and throwing kinematics, and while no significant differences in ball velocity before and after the intervention was found, there was a significant correlation between the change in ball velocity and the change in maximal angular velocity of internal rotation of $r = 0.75$. A number of other parameters have been reported to be correlated to ball velocity, including maximal pelvis and trunk internal rotation velocity (Wagner et al., 2011), total elbow angular displacement (van den Tillaar & Ettema, 2007), timing of maximum pelvis and trunk angles (van den Tillaar & Ettema, 2007; Wagner et al., 2011) and velocity of body center of mass in the direction of the goal (van den Tillaar & Ettema, 2007).

3.4. Joint angles

All maximal shoulder angles as well as shoulder angles at the instant of ball released are summarized in Table 1. Only a few studies directly compared kinematics for different types of throws, while the majority of the included studies only reported kinematics for one type of throw. The results of the comparison studies are summarized in text in the following section.

Both van den Tillaar (2016) and Wagner et al. (2011) found that the maximal shoulder angles did not differ between different types of throw. At ball release, significant differences in shoulder rotation has been reported only when comparing throwing with balls of different weights (van den Tillaar & Ettema, 2011) and throwing with the dominant vs non-dominant arm (van den Tillaar & Ettema, 2009a). Significant differences in maximal external rotation between different types of wind-up (van den Tillaar, 2016; van den Tillaar, Zondag, & Cabri, 2013) have also been found.

Wagner et al. (2010a) compared throwing with overhead arm position and throwing with a sidearm throw, and found that significantly higher values of shoulder flexion as well as lower values of shoulder abduction was found at ball release when using the side-arm throw. Differences in shoulder flexion at ball release has also been shown when comparing different levels of perceived effort, with flexion being greatest at lowest levels of perceived effort (Plummer, Gascon, & Oliver, 2017).

3.5. Joint velocities

In studies directly comparing elite players vs. low level players, Wagner et al. (2010b) found no significant difference in the maximal internal rotation angular velocity, and similarly, van den Tillaar and Cabri (2012) did not measure any significant difference between males and females. However, significant differences were found in the maximal internal rotation angular velocity when Wagner et al. (2011) compared various throwing techniques, with the velocity being higher in the two types of standing throws compared to the jump throw and the pivot throw. Significant differences were also found by Wagner et al. (2010b) when comparing the internal rotation angular velocity at ball release of elite players and low-level players, with the velocity being highest for the elite players. Similarly Plummer et al. (2017) found that the rotational velocity of the humerus at ball release was higher at 100% perceived effort compared to balls thrown at 75 and 50% perceived effort.

Statistically significantly higher maximal shoulder abduction angular velocity was found when comparing dominant arm throwing to non-dominant arm throwing (van den Tillaar & Ettema, 2009a) and higher maximal shoulder flexion angular velocities was found by Wagner et al. (2010a) in above the head throwing compared to sidearm throwing.

3.6. Timing sequence

Both when measured on human participants and computer simulated, the most effective throwing technique has been found to be utilizing a proximal-to-distal sequence, i.e., the distal segments achieve their maximal linear velocity later in the throwing motion than the proximal segments (Chowdhary & Challis, 2001; Liu, Leigh, & Yu, 2014; Marshall & Elliott, 2000). However, several studies have found that handball players do not utilize such a proximal-to-distal sequencing (Fradet et al., 2004; van den Tillaar & Cabri, 2012; van den Tillaar & Ettema, 2009b, 2009a, 2011; van den Tillaar et al., 2013; Wagner et al., 2010a, 2010b, 2012). Specifically, maximal linear velocity of the elbow is achieved between 0.066 and 0.055 s before ball release while maximal linear velocity of the shoulder is achieved between 0.051 and 0.03 s before ball release (Fradet et al., 2004; Jöris et al., 1985; van den Tillaar & Cabri, 2012; van den Tillaar et al., 2013). Maximal angular velocity of the elbow extension occurs between 0.004 and 0.018 s before ball release, while maximal angular velocity of the shoulder internal rotation happens very shortly after ball release (van den Tillaar & Cabri, 2012; van den Tillaar & Ettema, 2007, 2009a, 2011; van den Tillaar et al., 2013; Wagner et al., 2014, 2010a, 2010b, 2012). This sequence is independent of arm position (Wagner et al., 2010a), type of throw (Wagner et al., 2011), which arm the throw is performed with (van den Tillaar & Ettema, 2009a), weight of the ball (van den Tillaar & Ettema, 2011), type of wind-up (van den Tillaar et al., 2013) and gender (van den Tillaar & Cabri, 2012).

3.7. Joint kinetics

The review process revealed only one article that was concerned with kinetics of handball throwing (Plummer & Oliver, 2017). These authors report a mean peak shoulder internal rotation torque of 38.3% BW occurring between ball release and maximal internal rotation for the jump shot. They also found that shoulder kinetics were not affected by a fatigue protocol. The highest reported mean peak shoulder internal rotation torque for the remaining part of the throw was 13.8% BW, which occurred between lead foot contact and external rotation of the shoulder.

3.8. Definition of shoulder rotation

A number of different methods were used for measuring shoulder rotation. The most notable differences in these methods were whether trunk tilt was accounted for or not and whether neutral rotation was clearly defined. These findings are summarized in Table 3.

4. Discussion

The main findings of this scoping review are: 1) throwing kinematics are relatively stable across various conditions, when compared directly, 2) only one study reported kinetic measures, 3) a large variation in absolute values across studies and research groups are reported and 4) the methods used to obtain shoulder kinematics differs greatly and are not sufficiently described in most studies.

In general, the kinematic parameters were quite stable in studies directly investigating the effect of different conditions. Differences in maximal external shoulder rotation were only found when comparing different types of wind-up. In contrast, skill level, type of throw, level of fatigue, gender and effort did not impact the maximal external shoulder rotation. For maximal angular velocity of the shoulder rotation, statistically significant differences were only found when comparing different types of throw. Throwing velocity was also different between different types of throw and in addition throwing velocity was found to be affected by gender, arm position and ball weight.

The only study that investigated the kinetics of handball throwing found that the shoulder internal rotation torque was peaking

Table 3
Methods used for calculating shoulder rotation angle.

Paper	Accounts for trunk tilt?	Neutral rotation clearly defined?
Fradet et al., 2004	Yes	Yes
van den Tillaar, 2016; van den Tillaar & Cabri, 2012; van den Tillaar & Ettema, 2007, 2009a, 2011; van den Tillaar & Marques, 2011; van den Tillaar et al., 2013	No	Yes
Wagner et al., 2010a, 2010b, 2011, 2012, 2014	Yes	No
Plummer and Oliver, 2017, Plummer et al., 2017	No	Yes

after ball release (Plummer & Oliver, 2017). This is in contrast to previous studies on baseball pitching (Aguinaldo, Buttermore, & Chambers, 2007; Fleisig, Andrews, Dillman, & Escamilla, 1995) and water polo (Feltner & Taylor, 1997). This finding might indicate an important difference between handball throwing and other types of throwing, but considering that the internal rotation angular velocity is decreasing very shortly after ball release, it seems counter-intuitive that the internal rotation torque would peak during this phase. One potential explanation for this surprising finding, could be sub-optimal throwing mechanics of the participants. Wagner et al. (2010b) showed that low-level players may not reach their maximal internal rotation angular velocity until after the ball is released and similarly flawed throwing mechanics, could potentially result in the internal rotation torque peaking after ball release.

While measurements of ball velocity and timing sequence were in fairly good agreement across studies, the presented joint angles and velocities differed greatly between studies.

In the studies conducted by van den Tillaar et al. (van den Tillaar & Cabri, 2012; van den Tillaar & Ettema, 2007, 2009a, 2011; van den Tillaar & Marques, 2011; van den Tillaar et al., 2013) the maximal absolute angles reported seem coherent, but sometimes the angle is reported as external rotation and sometimes it is reported as internal rotation. Considering the fact that the timing of the maximal angle was similar in the studies, that reported timing sequence, it seems reasonable to assume that this reflects differences in the definition of internal/external rotation, rather than actual differences and therefore the maximal absolute angles were the foundation of the analysis performed on these data.

The discrepancies between the absolute values measured in the different studies could be due to a number of factors, but most likely this is caused by methodological differences (see Table 2). Firstly, it is not always clear from reading the articles how shoulder rotation is calculated and how a neutral shoulder rotation is defined, which is likely caused by the fact that the anatomical definition of neutral internal/external rotation is unclear (Wu et al., 2005). However, intuitively the two most likely ways to define neutral shoulder rotation are with the shoulder-elbow-wrist plane either parallel or orthogonal to the horizontal plane, such a difference in definition of shoulder rotation would result in a 90° offset between studies. Adding 90° to the values reported by Wagner et al., Plummer et al. and Fradet et al., limits the range of reported maximal absolute shoulder rotation to 122–169°, which seems more plausible.

Secondly, the method used for calculating the shoulder rotation angle has varied. For example, van den Tillaar et al. has calculated the shoulder rotation angle as "the angle between the shoulder-elbow-wrist plane and the horizontal plane." (van den Tillaar, 2016; van den Tillaar & Cabri, 2012; van den Tillaar & Ettema, 2004, 2007, 2009a, 2011; van den Tillaar & Marques, 2011) It is not clear whether the horizontal plane that the authors refer to is the horizontal plane of the laboratory or of the participant. However, since the authors give no explanation to how the horizontal plane of the participant would be constructed, we assume that it is the horizontal plane of the laboratory. This implies that trunk tilt is not accounted for (see Fig. 2) and therefore rotation angles measured this way most likely differ from the actual glenohumeral rotation as a significant trunk tilt is present in a large part of the motion (Wagner et al., 2011).

In contrast, Wagner et al. (2010a, 2010b, 2014) firstly use a computer model of the human body to calculate the position of the shoulder joint centre and kinematics. Subsequently joint angles are calculated using cardan angles and shoulder rotation is defined as "the rotation of the humerus along the longitudinal axis of the humerus" (Wagner et al., 2010b). The use of cardan angles means that trunk tilt is accounted for, however information relating to which sequence of rotation axes is used, whether the first, second or third rotation is used to calculate the shoulder rotation and the construction of the humeral coordinate system is not readily available and thus neutral rotation cannot be established with certainty. A third method was used by Plummer et al. who used Euler angle

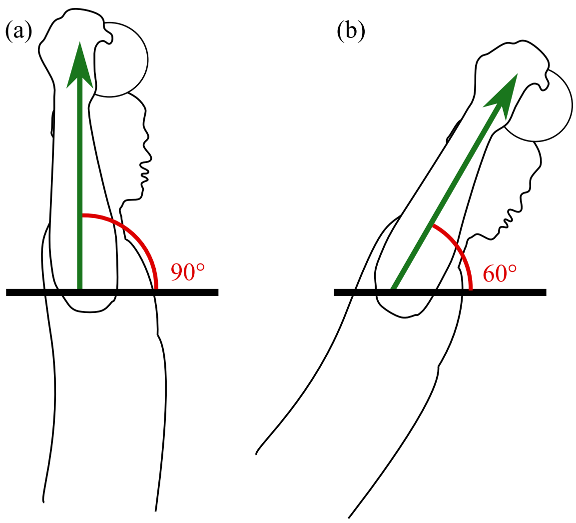

Fig. 2. Illustration of computing shoulder rotation angle relative to the lab horizontal plane. The glenohumeral rotation is the same in both (a) and (b), but the reported shoulder rotation angle is different, when computed relative to the lab horizontal plane.

decomposition to find shoulder plane of elevation, rotation and elevation and yet another method was used by Fradet et al. (2004) who used the method conceived by Feltner and Dapena (1986). Both of these methods accounts have a clear definition of neutral rotation but only the method used by Fradet et al. accounts for trunk tilt. A fifth method is the ISB guidelines (Wu et al., 2005) which is based on Euler angle decomposition. Due to the widespread use in other fields and it being an internationally agreed upon guideline, we suggest that future studies follow the ISB guidelines when measuring and reporting shoulder angles, which will ensure comparability across studies.

Thirdly, some studies have looked at the standing throw without run-up (van den Tillaar, 2016; van den Tillaar & Ettema, 2004, 2007, 2009a, 2011; van den Tillaar & Marques, 2011; van den Tillaar et al., 2013), while others have looked at the standing throw with run-up (Wagner et al., 2010a) or the jump throw (Plummer & Oliver, 2017; van den Tillaar, 2016; Wagner et al., 2014). However, both van den Tillaar (2016) and Wagner et al. (2011) found that the maximal shoulder rotation and flexion angles did not differ depending on type of throw.

Lastly, local differences in the way proper throwing technique is taught might explain some of the variation, although one would expect these differences to be relatively minor as the throwing velocities achieved in the various studies as well as the level of the participants are fairly similar. Therefore, it seems that the most likely explanation for the large differences between studies is caused by different methods for calculating the shoulder rotation.

While the large differences in reported shoulder rotation angle could be explained by different computations of shoulder rotation angle, the differences in internal rotation angular velocities are more puzzling as the angular velocity does not depend on how the neutral rotation is defined. However, not accounting for trunk tilt will have an impact on the calculated angular velocity and may therefore explain some of the variance. It should also be noted that some studies only calculated angular velocities up until ball release (see Table 2). As the angular velocities are known to increase after ball release (Wagner et al., 2012), this difference in methods might also explain the differences in maximal angular velocities. Nonetheless, large differences in angular velocities at ball release are also reported, indicating that other factors must be considered.

The use of skin-mounted trackers or markers is practical, but can also introduce some amount of uncertainty in the measurements. For instance, all studies that used reflective markers placed a marker on the lateral tip of the acromion, which can be a problematic position as markers placed here are easily affected by soft tissue artefacts such as muscle bulging (Roren et al., 2015). Similarly, a skin-mounted marker moves relatively to the humerus when extending or flexing the elbow, and markers placed between the elbow and shoulder can be affected by wobbling of the muscle mass during fast movements. While all these problems may introduce errors in the measurements, these are problems that are not easily solvable as only the use of bone pins can effectively eliminate the effect of soft tissue artefacts. However, future studies should seek to quantify the size of these errors and investigate whether alternative placements of markers and trackers can alleviate the effect of soft tissue artefacts.

Only studies that reported kinematic or kinetic parameters were included in this review. However, it should be noted that ball velocity has been registered in a number of other studies, that do not report kinematic parameters, but instead investigates parameters like strength (Marques, van den Tillaar, Vescovi, & González-Badillo, 2007; Marques, Saavedra, Abrantes, & Aidar, 2011) and/or flexibility (Schwesig et al., 2016). While these results certainly are relevant with regards to performance and injury prevention, they fall outside of the scope of this review, which was to summarize shoulder kinematics and kinetics.

It is critical that future research provide detailed descriptions of how angles are calculated, which will enable readers to transform results from one coordinate system to another and thereby be able to compare results across studies. Considering the high prevalence of shoulder pain in handball (Clarsen, Bahr, Andersson, Munk, & Myklebust, 2014; Møller et al., 2017; Myklebust et al., 2013) studying handball throwing kinematics with an emphasis on injury implications is also important in future studies. Finally, future research should focus on obtaining not only kinematic, but also kinetic data. Kinematic analysis essentially only describes motion – in order to understand what causes these motions and how a given motion loads the structures of the body, kinetic analysis must be employed (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2004). Performing such kinetic analyses can give important information regarding how to improve performance and increase understanding of why some players get injured, while others do not.

5. Conclusion

In recent years several studies have reported shoulder kinematics of handball throwing. The throwing velocity is highest in the standing throw with run-up, followed by the standing throw without run-up, the jump throw and finally pivot throw.

Studies of timing sequencing have shown that handball throwing does not follow a proximal-to-distal sequencing as the elbow achieves its maximal linear velocity before the shoulder. This handball-specific sequencing is stable across a number of conditions including the type of throw.

With regards to shoulder angles and angular velocities, the handball throw is characterized by large external rotation and abduction, while shoulder flexion and extension only happens to a minor degree. Similarly, very large angular velocities of shoulder rotation have been found, while the angular velocities of shoulder flexion and abduction are relatively low. In studies that have compared different level of players and/or types of throws no significant differences in the maximal angles have been found, except when comparing the whip-like wind-up to the circular wind-up, and differences in angles at ball release have only been found when comparing the dominant arm to the non-dominant arm or when comparing throwing with ball of different weights. However, differences in maximal internal rotation angular velocities have been found when comparing different types of throws, with the velocity being higher in the two types of standing throws compared to the jump throw and the pivot throw, which likely can explain some of the variation seen in the throwing velocity of different types of throws.

This review shows that a number of studies of shoulder kinematics have been performed in recent years highlighting that the throwing kinematics are fairly stable across a number of conditions. However, the lack of a common standard for measuring and reporting shoulder angles makes it difficult to compare results across studies and therefore future studies should seek to use a well-defined method that accounts for trunk tilt and clearly describes what constitutes neutral alignment, e.g. the ISB guidelines.

While the kinematics of the handball throw is relatively thoroughly investigated, the field is lacking research into the shoulder kinetics of handball throwing, which is an essential part of moving the research forward and optimizing training, injury prevention and rehabilitation.

Disclosure of interest

The authors report no conflict of interest.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Aguinaldo, A. L., Buttermore, J., & Chambers, H. (2007). Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *Journal of Applied Biomechanics, 23*(1), 42–51 Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/17585177.

Asker, M., Holm, L. W., Källberg, H., Waldén, M., & Skillgate, E. (2018). Female adolescent elite handball players are more susceptible to shoulder problems than their male counterparts. *Knee Surgery, Sports Traumatology, Arthroscopy, 26*(7), 1–9. https://doi.org/10.1007/s00167-018-4857-y.

Blache, Y., & Begon, M. (2017). Influence of shoulder kinematic estimate on joint and muscle mechanics predicted by musculoskeletal model. *IEEE Transactions on Biomedical Engineering, 9294*(c), https://doi.org/10.1109/TBME.2017.2716186 1–1.

Chowdhary, A. G., & Challis, J. H. (2001). The biomechanics of an overarm throwing task: a simulation model examination of optimal timing of muscle activations. *Journal of Theoretical Biology, 211*, 39–53. https://doi.org/10.1006/jtbi.2001.2332.

Clarsen, B., Bahr, R., Andersson, S. H., Munk, R., & Myklebust, G. (2014). Reduced glenohumeral rotation, external rotation weakness and scapular dyskinesis are risk factors for shoulder injuries among elite male handball players: A prospective cohort study. *British Journal of Sports Medicine, 48*(17), 1327–1333. https://doi.org/10.1136/bjsports-2014-093702.

Crabolu, M., Pani, D., Raffo, L., Conti, M., Crivelli, P., & Cereatti, A. (2017). In vivo estimation of the shoulder joint center of rotation using magneto-inertial sensors: MRI-based accuracy and repeatability assessment. *BioMedical Engineering OnLine, 16*(1), 34. https://doi.org/10.1186/s12938-017-0324-0.

Feltner, M., & Dapena, J. (1986). Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. *International Journal of Sports Biomechanics, 2*(4), 235–259 Retrieved from http://ci.nii.ac.jp/naid/10010918477/.

Feltner, M. E., & Taylor, G. (1997). Three-dimensional kinetics of the shoulder, elbow, and wrist during a penalty throw in water polo. *Journal of Applied Biomechanics, 13*(3), 347–372.

Fleisig, G. S., Andrews, J. R., Dillman, C. J., & Escamilla, R. F. (1995). Kinetics of baseball pitching with implications about injury mechanisms. *The American Journal of Sports Medicine, 23*(2), 233–239. https://doi.org/10.1177/036354659502300218.

Fradet, L., Botcazou, M., Durocher, C., Cretual, A., Multon, F., Prioux, J., & Delamarche, P. (2004). Do handball throws always exhibit a proximal-to-distal segmental sequence? *Journal of Sports Sciences, 22*(5), 439–447. https://doi.org/10.1080/02640410310001641647.

Jöris, H. J., Edwards van Muyen, A., van Ingen Schenau, G., & Kemper, H. C. (1985). Force, velocity and energy flow during the overarm throw in female handball players. *Journal of Biomechanics, 18*(6), 409–414. https://doi.org/10.1016/0021-9290(85)90275-1.

Liu, H., Leigh, S., & Yu, B. (2014). Comparison of sequence of trunk and arm motions between short and long official distance groups in javelin throwing. *Sports Biomechanics/International Society of Biomechanics in Sports, 13*(1), 17–32. https://doi.org/10.1080/14763141.2013.865138.

Marques, M. C., van den Tillaar, R., Vescovi, J. D., & González-Badillo, J. J. (2007). Relationship Between Throwing Velocity, Muscle Power, and Bar Velocity During Bench Press in Elite Handball Players. *International Journal of Sports Physiology & Performance, 2*(4), 414–422 Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=28047088&site=ehost-live.

Marques, M., Saavedra, F., Abrantes, C., & Aidar, F. (2011). Associations between rate of force development metrics and throwing velocity in elite team handball players: a short research report. *Journal of Human Kinetics, 29A*, 53–57. https://doi.org/10.2478/v10078-011-0059-0.

Marshall, R. N., & Elliott, B. C. (2000). Long-axis rotation: the missing link in proximal-to-distal segmental sequencing. *Journal of Sports Sciences, 18*(4), 247–254. https://doi.org/10.1080/026404100364983.

Møller, M., Attermann, J., Myklebust, G., & Wedderkopp, N. (2012). Injury risk in Danish youth and senior elite handball using a new SMS text messages approach. *British Journal of Sports Medicine, 46*(7), 531–537. https://doi.org/10.1136/bjsports-2012-091022.

Møller, M., Nielsen, R. O., Attermann, J., Wedderkopp, N., Lind, M., Sørensen, H., & Myklebust, G. (2017). Handball load and shoulder injury rate: A 31-week cohort study of 679 elite youth handball players. *British Journal of Sports Medicine, 51*, 231–237. https://doi.org/10.1136/bjsports-2016-096927.

Myklebust, G., Hasslan, L., Bahr, R., & Steffen, K. (2013). High prevalence of shoulder pain among elite Norwegian female handball players. *Scandinavian Journal of Medicine & Science in Sports, 23*(3), 288–294. https://doi.org/10.1111/j.1600-0838.2011.01398.x.

Plummer, H. A., Gascon, S. S., & Oliver, G. D. (2017). Biomechanical comparison of three perceived effort set shots in team handball players. *Journal of Strength and Conditioning Research, 31*(1), 80–87. https://doi.org/10.1519/JSC.0000000000001475.

Plummer, H. A., & Oliver, G. D. (2017). The effects of localised fatigue on upper extremity jump shot kinematics and kinetics in team handball. *Journal of Sports Sciences, 35*(2), 182–188. https://doi.org/10.1080/02640414.2016.1160143.

Robertson, G., Caldwell, G., Hamill, J., Kamen, G., & Whittlesey, S. (2004). Research Methods in Biomechanics (1st ed.). Human Kinetics.

Roren, A., Lefevre-Colau, M. M., Poiraudeau, S., Fayad, F., Pasqui, V., & Roby-Brami, A. (2015). A new description of scapulothoracic motion during arm movements in healthy subjects. *Manual Therapy, 20*(1), 46–55. https://doi.org/10.1016/j.math.2014.06.006.

Schwesig, R., Hermassi, S., Wagner, H., Fischer, D., Fieseler, G., Molitor, T., & Delank, K.-S. (2016). Relationship between the range of motion and isometric strength of elbow and shoulder joints and ball velocity in women team handball players. *Journal of Strength and Conditioning Research, 30*(12), 3428–3435. https://doi.org/10.1519/JSC.0000000000001450.

Serrien, B., Clijsen, R., Blondeel, J., Goossens, M., & Baeyens, J.-P. (2015). Differences in ball speed and three-dimensional kinematics between male and female handball players during a standing throw with run-up. *BMC Sports Science, Medicine & Rehabilitation, 7*, 1–12 Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=111154839&site=ehost-live.

van den Tillaar, R. (2016). Comparison of range of motion tests with throwing kinematics in elite team handball players. *Journal of Sports Sciences, 0414*, 1–7. https://doi.org/10.1080/02640414.2016.1149601.

van den Tillaar, R., & Cabri, J. M. H. (2012). Gender differences in the kinematics and ball velocity of overarm throwing in elite team handball players. *Journal of Sports Sciences, 30*(8), 807–813. https://doi.org/10.1080/02640414.2012.671529.

van den Tillaar, R., & Ettema, G. (2004). A force-velocity relationship and coordination patterns in overarm throwing. *Journal of Sports Science & Medicine, 3*, 211–219 Retrieved from http://www.jsportscimed.org/vol3/n4/3/v3n4-3pdf.pdf.

van den Tillaar, R., & Ettema, G. (2007). A three-dimensional analysis of overarm throwing in experienced handball players. *Journal of Applied Biomechanics, 23*, 12–19.

van den Tillaar, R., & Ettema, G. (2009a). A comparison of overarm throwing with the dominant and nondominant arm in experienced team handball players. *Perceptual and Motor Skills, 109*(1), 315–326. https://doi.org/10.2466/pms.109.1.315-326.

van den Tillaar, R., & Ettema, G. (2009b). Is there a proximal-to-distal sequence in overarm throwing in team handball? *Journal of Sports Sciences, 27*(9), 949–955. https://doi.org/10.1080/02640410902960502.

van den Tillaar, R., & Ettema, G. (2011). A comparison of kinematics between overarm throwing with 20% underweight, regular, and 20% overweight balls. *Journal of Applied Biomechanics, 27*(3), 252–257 Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/21844614.

van den Tillaar, R., & Marques, M. C. (2011). Effect of training on ball release velocity and kinematics in overarm throwing among experienced female handball players. *Kinesiologia Slovenica, 46*(2), 38–46.

van den Tillaar, R., Zondag, A., & Cabri, J. M. H. (2013). Comparing performance and kinematics of throwing with a circular and whip-like wind up by experienced handball players. *Scandinavian Journal of Medicine & Science in Sports, 23*(6), e373–e380. https://doi.org/10.1111/sms.12091.

Wagner, H., Buchecker, M., von Duvillard, S. P., & Müller, E. (2010a). Kinematic comparison of team handball throwing with two different arm positions. *International Journal of Sports Physiology & Performance, 5*(4), 469–483 Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=58704705&site=ehost-live.

Wagner, H., Buchecker, M., von Duvillard, S. P., & Müller, E. (2010b). Kinematic description of elite vs. Low level players in team-handball jump throw. *Journal of Sports Science & Medicine, 9*(1), 15–23 Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3737958&tool=pmcentrez&rendertype=abstract.

Wagner, H., Pfusterschmied, J., Tilp, M., Landlinger, J., von Duvillard, S. P., & Müller, E. (2014). Upper-body kinematics in team-handball throw, tennis serve, and volleyball spike. *Scandinavian Journal of Medicine & Science in Sports, 24*(2), 345–354. https://doi.org/10.1111/j.1600-0838.2012.01503.x.

Wagner, H., Pfusterschmied, J., von Duvillard, S. P., & Müller, E. (2011). Performance and kinematics of various throwing techniques in team-handball. *Journal of Sports Science & Medicine, 10*(1), 73–80 Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3737895&tool=pmcentrez&rendertype=abstract.

Wagner, H., Pfusterschmied, J., Von Duvillard, S. P., & Müller, E. (2012). Skill-dependent proximal-to-distal sequence in team-handball throwing. *Journal of Sports Sciences, 30*(1), 21–29. https://doi.org/10.1080/02640414.2011.617773.

Wu, G., Van Der Helm, F. C. T., Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C., ... Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion – Part II: Shoulder, elbow, wrist and hand. *Journal of Biomechanics, 38*(5), 981–992. https://doi.org/10.1016/j.jbiomech.2004.05.042.