ABSTRACT

Background: High throwing velocity is essential for scoring goals in handball. Factors influencing throwing velocity are anthropometric characteristics of the player, throwing technique and strength. The core seems to be important for production and transfer of energy during a throw. Studies on general throwing and throwing in other sports have found a positive relationship between core strength and throwing performance. However, there is a lack of studies on core strength and throwing velocity in handball. **Aim:** The aim of this study was to investigate the relationship between core strength and overarm throwing velocity in elite female handball players**. Methods:** Seventeen elite female handball players (mean ± standard deviation 19.7 ± 3.1years, 68.3 ± 7.9kg, 171.7 ± 7.2cm) participated. Both standing and jump throws were performed, with a 3-step run-up and maximal execution. Core and arm strength exercises were performed in isokinetic and isometric modalities in a dynamometer. The relationship between standing and jump throw velocity and core strength, while controlled for arm strength, was examined with partial correlations. Correlations between throwing velocity and peak torque (τ_{peak}), mean torque (τ_{mean}) and peak rate of torque development ($R\tau D_{peak}$) for both the isokinetic and isometric tests were investigated. **Results:** No significant correlations could be seen. However, the standing throwing velocity showed tendencies for τ_{mean} and τ_{peak} during isometric core flexion. Standing throwing velocity and τ_{mean} had a large correlation with a shared variance of 26.6%, while τ_{peak} and standing throwing velocity had a moderate correlation with a shared variance of 23.7%. The jump throw velocity showed tendencies for τ_{mean} during isometric core flexion, with a moderate correlation and a shared variance 23.5%. All variables within the isometric core flexion test showed large or moderate correlations with maximal throwing velocity, while the variables within the isokinetic core flexion test showed small or trivial correlations with maximal throwing velocity. **Conclusion:** There seems to be a relation between core strength and throwing velocity. The results are not statistically significant, but the tendencies and sizes of some of the correlations indicate that core strength plays a role in throwing velocity.

Key words: Handball, throwing velocity, core flexion strength, isokinetic, isometric

SAMMENDRAG

Bakgrunn: Høy kasthastighet er essensielt for å score mål i håndball. Faktorer som påvirker kasthastighet er spillernes antropometriske karakteristikker, kastteknikk og styrke. Kjernen virker å være viktig for produksjon og overføring av energi i et kast. Studier som har sett på generell kasting og kasting i andre idretter har funnet en positiv relasjon mellom kjernestyrke og kastprestasjon. I håndball, derimot, er det mangel på studier om kjernestyrke og kasthastighet. **Mål:** Målet med denne studien er å undersøke sammenhengen mellom styrke i kjernemuskulaturen og overarms kasthastighet blant kvinnelige elitespillere i håndball. **Metode:** Sytten kvinnelige elitespillere i håndball deltok i studien (gjennomsnitt ± standardavvik 19.7 ± 3.1år, 68.3 ± 7.9kg, 171.7 ± 7.2cm) deltok. Det ble utført grunn- og hoppskudd, med 3-stegs tilløp og maksimal utførelse. Isokinetiske og isometriske kjerne- og armstyrkeøvelser ble utført i et dynamometer. Forholdet mellom grunn- og hoppskudd og kjernestyrke, kontrollert for armstyrke, ble undersøkt med *partial correlations*. Korrelasjoner mellom kasthastighet og maksimalt dreiemoment (τ_{peak}), gjennomsnittlig dreiemoment (τ_{mean}) og maksimal utviklingsgrad av dreiemoment ($R\tau D_{peak}$) for både de isokinetiske og isometriske testene ble undersøkt. **Resultater:** Ingen signifikante korrelasjoner ble funnet. Men hastigheten på grunnskudd viste tendenser for τ_{mean} og τ_{peak} ved isometrisk kjernefleksjon. Hastigheten på grunnskudd og τ_{mean} hadde en stor korrelasjon med en delt varians på 26.6%, mens hastigheten på grunnskudd og τ_{peak} hadde en moderat korrelasjon med en delt varians på 23.7%. Hastigheten på hoppskudd viste en tendens for τ_{mean} ved isometrisk kjernefleksjon, med en moderat korrelasjon og delt varians på 23.5%. Alle variablene blant de isometriske kjernetestene viste en stor eller moderat korrelasjon med maksimal kasthastighet, mens variablene blant de isokinetisk kjernetestene viste små eller ubetydelige korrelasjoner med maksimal kasthastighet. **Konklusjon:** Det ser ut til å være en relasjon mellom kjernestyrke og kasthastighet. Resultatene er ikke statistisk signifikante, men tendensene og størrelsene på noen av korrelasjonene tyder på at kjernestyrke spiller en rolle i kasthastighet.

Nøkkelord: Håndball, kasthastighet, kjernestyrke, isokinetisk, isometrisk

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ABBREVATIONS AND FREQUENTLY USED SYMBOLS

CI	Confidence interval
Hz	Hertz (frequency)
Nm	Newton metre
ms	Millisecond
ROM	Range of motion
$R\tau D_{peak}$	Peak rate of torque development
SD	Standard deviation
$m \cdot s^{-1}$	Meters per second
$° \cdot s^{-1}$	Degrees per second
τ	Torque
τ_{mean}	Mean torque
τ_{peak}	Peak torque
α	Alpha (significance level)
Δ	Delta (finite difference)
$\varnothing$	Diameter

INTRODUCTION

With 50 members in The European Handball Federation (EHF, 2016) and 204 members in The International Handball Federation (IHF, 2016), handball is a popular and globally widespread team sport. The game consists of two teams playing against each other on a 20x40m court. Each team has six outfield players and one goalkeeper. Players pass the ball with their hands, and the aim of the game is to score more goals than the opposing team by the end of the match, which lasts 2x30min.

Handball is a dynamic game requiring good skills in key factors such as sprinting, jumping, throwing, technique, tactics and decision making. Wagner et al. (2014) point out five major individual factors and three major team factors determining performance in handball. These factors are coordination, strength, endurance, constitution-disposition, nutrition, cognition, social factors and tactics. In addition, external influences affect performance as well.

Even though many different factors are important for performance, the winning team is the one scoring the most goals. High throwing velocity is a crucial factor for scoring goals. A high throwing velocity may compensate for lack of accuracy or the inability to trick the goalkeeper with regard to where the player will shoot. This is especially true for situations where long distance shots are required. Bilge (2012) performed a game-analysis of teams ranked top eight in the world (all European) who attended the Olympics, World and European Championships from 2004 to 2010. The statistics show that 30.1% of all goals scored came from the back court positions. The wing positions contributed 13.7%, pivot position 19.3%, break-through goals 9.6%, fast breaks 17% and 7-meter goals 10.3% of all goals. With such a high amount of goals from long distance shots, the importance of high throwing velocity is strengthened.

Goals scored from fast breaks, break troughs and the pivot positions are considered “easy goals”. Therefore it is preferable to end up in these situations. Top European teams have more emphasis on close range shots and pass-ins to the pivot compared to non-European teams (Bilge, 2012). In addition, fast break efficiency is the main factor determining success among teams at the same level (Bilge, 2012). However, the nature of the game will always require successful distance shots from the back court positions. Without good long distance shots, the defence may lay flat and make it harder for the attacking team to break through or do pass-ins to the pivot. Good shooters will force the defence to open up, which will make it easier to break through or play the pivot and make close range goals. High throwing velocity may therefore be a direct reason for long distance goals and indirectly the cause of easy goals scored from break throughs and the pivot positions. Due to this, back and centre positions are often expected to take long distance shots during a match. Vila et al. (2012) found results in elite female handball players indicating that players at the back positions have a higher jump throw velocity compared to wings and pivots when throwing from the 9-m line with a 3-step run up.

Logically, the velocity of a throw is dependent on anthropometric characteristics of the player, technique and strength. With regard to anthropometry, general parameters (body mass, lean body mass, body height and BMI) and specific parameters (arm span, finger span, hand perimeter, ring-finger length and middle-finger length) have been shown to correlate with throwing velocity, with correlations ranging from .55 – .70 for general parameters and .35 – .51 for the specific parameters (Debanne & Laffaye, 2011). Other research also supports that players who are taller and heavier achieve higher throwing velocities in handball (Fieseler et al., 2017; Wagner et al., 2010).

In the case of technique, the overarm throw is the most common throwing technique. Underarm throws are typically used only sparingly. In game situations, the jump throws constitute 73-75% of all throws, followed by standing throws, which constitute 14-18% (Wagner et al., 2011). Even though jump throws are most common, standing throws provide higher throwing velocity (Wagner et al., 2011). When studying the movements and mechanics of the overarm throw, it is apparent that production of velocity and a good throw is dependent on the interaction of different body parts, from the legs, through the core and up to the arms. According to Putnam (1993), forward acceleration of proximal segments will make the distal segments lag behind, while the proximal segments' angular velocity contributes to forward acceleration of distal segments. Joris et al. (1985) point out that high maximal segmental velocities are important pre-requisites for an optimal flow of energy to the ball during the last phase of the overarm throw in female handball players. During a handball throw, the most proximal segments are the legs and trunk, while the most distal segments include the fingers. Studies do not necessarily show a direct proximal-to-distal sequence in a handball overarm throw. The sequence may vary, depending on whether one looks at the imitation of movements, maximal velocity of the segments or maximal angular velocity of the joints. For example, van den Tillaar and Ettema (2009) studied the 7-m throw in handball and found a proximal-to-distal sequence to be the case only for the initiation of the movements.

The core is an important part of the sequence during a throw, especially for the transfer of energy. Manipulation of pelvis- and trunk movements may influence ball velocity. Wagner et al. (2011) found that the run-up and pelvis- and trunk movements significantly influenced ball velocity. The ball release speed and maximal trunk rotation velocity showed a significant correlation (.78). Serrien et al. (2015) compared male and female handball players during a standing throw with run-up. The males showed more activity in the transverse plane (pelvis and trunk rotation and shoulder horizontal abduction). The females showed more activity in the sagittal plane (trunk flexion). They reached a higher trunk flexion velocity (~260°·s^{-1} vs. ~210°·s^{-1} for men) and maximal velocity of trunk flexion occurred earlier. The male players reached their peak trunk flexion velocity nearly at ball release. At this stage, the female players already accelerated towards trunk extension. The males' and females' cocking manoeuver differed as well (Serrien et al., 2015). Whether these differences alone contribute to higher throwing velocity is unclear, since men generally are stronger and have different anthropometric characteristics. Angles and velocities of the trunk vary from phase to phase during the overarm throw. A study by Wagner et al. (2011) on male elite handball players found the angle of the trunk to go from ~10° in the cocking phase, to -5° in the acceleration phase and finally to ~30° at ball release (during both standing- and jump throws with run-up). At ball release, the velocity of trunk flexion has been shown to reach 258°·s^{-1} for elite male handball players and 128°·s^{-1} for low level male players (Wagner et al., 2010).

A variety of different strength aspects influence throwing velocity. Numerous studies have looked at the relationship between throwing velocity and one repetition maximum (1RM) in bench-press and found significant correlations (Gorostiaga et al., 2004; Granados et al., 2007; Hoff & Almåsbakk, 1995; Marques et al., 2007). There has been less emphasis on specific core strength and stability, which may play an important role in the complex motion of an overarm throw. Good core strength can contribute to a better throwing technique by improving core stability and energy flow during the throw. Shinkle et al. (2012) describe the muscles of the core as an imagined box consisting of the abdominals in the front, paraspinals and gluteals in the back, the diaphragm at the top, obliques on the sides and the pelvic and hip girdle at the bottom. They further describe that the core receives, adds and transfers energy from proximal to distal segments. The hip/trunk area contributes with around 50% of the kinetic energy and force to the throwing motion (Kibler et al., 2006). By interpreting the definition of core stability, being "the ability to control the position and movement of the trunk for optimal production, transfer, and control of forces to and from the upper and lower extremities during functional activities" (Silfies et al., 2015), it is reasonable to believe core stability is important for the transfer of energy during a throw. Two critical components for core stability are muscle capacity and neuromuscular control (Silfies et al., 2015). During whole-body movements, the central nervous system stabilizes the spine by contraction of the core muscles. Transversus abdominis, multifidus, rectus abdominis, and oblique abdominals have been shown to be constantly activated before limb movements (Hodges & Richardson, 1997). This shows the importance of the core during any movements including the legs or arms and is in line with the idea that the core produces, controls and transfers energy. If the core fails, it can weaken the forces being created and transferred, which most likely will affect the throw negatively.

Numerous studies have shown that the core partakes in the transfer and control of energy flow during general overarm throwing (Hirashima et al., 2002; Kibler et al., 2006; Young et al., 1996). However, there is a lack of studies looking at the relationship between core strength and throwing velocity in handball. The effect of core stability training on throwing velocity among 16-year old female handball players has been investigated in an intervention study by Saeterbakken et al. (2011). Training twice a week with various closed kinetic chain exercises in unstable slings for six weeks improved maximal throwing velocity significantly with 4.9% for the intervention group, while the control group experienced no change.

In general, correlations between core strength and throwing performance have been shown in several studies. Krishnan et al. (2013) found significant correlations (.39) between lumbar core muscle strength and seated throwing distance of a tennis ball in untrained subjects. Another study done on various collegiate athletes found the double straight leg lowering test (lying with a flat back and lowering the legs to the point where the lower back loses floor-contact) to have a significant correlation (-.39) with the throwing of a medicine ball in a tall-kneeling position (Sharrock et al., 2011). Prokopy et al. (2008) found that softball players training three times a week for 12 weeks with closed kinetic chain exercises in unstable slings improved throwing velocity with 3.4%. Another group performing open kinetic chain exercises with free weights and dumbbells improved throwing velocity with .5% only. Even though the mentioned studies show significant correlations, studies on the subject of core strength and throwing velocity are limited and it is challenging to draw conclusions since existing studies test on various sports and use different throwing objects and methods. In addition, there exist no standard testing methods for core strength, as it is difficult to isolate the core muscles. This makes it methodologically challenging to do research on core strength.

Previous studies have shown that there is a transfer of energy in overarm throwing, with the core muscles having a role in this energy flow. Speed, positioning, timing and controlling when and how much one should activate the core are determinant factors. To what degree core strength performance correlates with throwing velocity in handball is unclear. The aim of this study was to investigate the relationship between core strength and overarm throwing velocity in elite female handball players. Based on the theoretical functions of the core muscles and previous research on throwing, it was hypothesized that positive correlations exist between core strength and throwing velocity in handball.

METHODS

Design and experimental approach

A cross-sectional study design was used to investigate the association between overhand throwing velocity in handball and core strength, while controlling for arm strength. All strength exercises were performed in isokinetic and isometric modalities in a dynamometer. The overarm throws were executed as standing and jumping throws, with a 3-step run-up, as this is the maximal amount of steps allowed to take in a game.

Testing took place during the players' mid-season break from handball matches. To avoid any effects of fatigue, the tests were performed on two different days, starting with the strength tests on day one and the throwing tests approximately ten days later.

Participants

A total of 19 players from a top level Norwegian handball team participated in the study. Out of these 19 players, one did not complete all the strength tests and one did not participate in the strength tests, which resulted in complete data for 17 participants (mean ± standard deviation (SD) age 19.7 ± 3.1years, body mass 68.3 ± 7.9kg, height 171.7 ± 7.2cm). Of these 17 participants, nine played at the back court positions, three were pivots and five played at the wing positions. Ten were regular first-team players, while the remaining seven participated in training sessions with the team.

All participants were free of injury during data collection and signed informed consent where they got information about the general procedures and aim of the study. They were also made aware they could withdraw from the study whenever they wanted, without providing any explanation. The study was considered and approved by the Norwegian Centre for Research Data (NSD) and conducted in accordance with the Declaration of Helsinki.

Data collection

Data regarding age, playing position, throwing arm and elite team handball experience was collected prior to participation. Height and body mass was measured on the first test day.

Strength tests

Participants performed a dynamic warm up for 15 minutes using an ergometer cycle and elastic bands. The order of the strength tests was the same for all participants, starting with isokinetic and isometric core strength tests, followed by three isokinetic and isometric strength tests for the throwing arm. All strength tests were done on the Biodex System 3 PRO (model 830-210, Biodex Medical Systems, Inc., Shirley, NY, USA) and recorded at 100Hz. Before each test, participants were given instructions on how to perform the movement, followed by a test-trial. For every isokinetic movement, the participants were instructed to perform the movement as fast and explosively as possible. Three repetitions with self-regulated rest between each repetition were done for the isokinetic tests. For the isometric tests, the participants were instructed to press as hard as possible in the given direction for three seconds. This was done three times, with 30s rest between each repetition.

A constant range of motion (ROM) was set for the core tests. For the remaining tests, an individual ROM was set for each participant. This was done to make sure the participants' limbs remained in a comfortable ROM with minimal risk of injury. The setup of the tests was in accordance with the manufacturer's specifications. For the tests involving the arm and shoulder, the participants' limb-segment and the relevant attachment were statically weighed to provide gravity compensation data and corrections. During testing, the participants were verbally supported with no visual feedback from the computer screen.

The ROM, velocities and isometric angles used in the dynamometer for the strength tests mirror those appearing for the various body segments during a throw (van den Tillaar & Ettema, 2007; Wagner et al., 2010; Wagner et al., 2011). The study of Wagner et al. (2011) tested for both standing and jump throw, and similar outcomes for velocities and limb angles could be seen between the techniques.

Core flexion

Participants were secured to the chair with straps across the femur, pelvis and the torso. In order to isolate the core as much as possible, their feet only rested on the footrest and were not secured, as that would enable them to activate the legs. The participants' hands were crossed over the chest during the tests. Figure 1 illustrates the setup of the core flexion tests.

The chair could maximally be moved from 40° to 95°, which was used as the ROM during isokinetic flexion. Rotation of the segment was in the sagittal plane, about the transverse axis through the hip/pelvis. The movement was performed at 120°·s^{-1}. The isometric test was performed at 80°.

Figure 1 Setup of the isokinetic and isometric core flexion strength test.

Shoulder flexion

Participants were secured with straps by the pelvis and torso, diagonally from the contralateral shoulder. The arm that was not involved in the movement rested on their thigh. The movement was performed with a nearly extended elbow and a pronated grip.

During isokinetic testing, the ROM was set from ~0° to ~180°, with 0° representing the arm being straight up relative to their own body composition. Likewise, 180° represents the hand positioned straight down. ROM varied slightly from participant to participant, as their flexibility differed. Therefore, consideration was needed to provide comfort and reduce the risk of injury. Rotation of the segment was in the sagittal plane, about the transverse axis through the glenohumeral joint. The movement was performed at 180°·s^{-1}. The isometric test was performed at 15°.

Internal shoulder rotation

Participants were secured with straps by the pelvis and torso, diagonally from the contralateral shoulder. The arm that was not involved in the movement rested on their thigh. The movement was performed using a pronated grip with the shoulder abducted 90° and a 90° flexion in the elbow. Figure 2 illustrates the setup of the internal shoulder rotation tests.

During isokinetic testing, the ROM was set from ~-10° to ~100°, with 0° representing the hand pointing straight upwards. Rotation of the segment was in the sagittal plane, about the transverse axis through humerus. The movement was performed at 270°·s^{-1}. The isometric test was performed at 5°.

Figure 2 Setup of the isokinetic and isometric internal shoulder rotation strength test.

Pronation of the forearm

Participants were secured with straps by the pelvis and torso, diagonally from the contralateral shoulder. The arm involved in the movement was secured to a limb support pad. The other arm rested on their thigh. The movement was performed with a neutral shoulder position and ~100° in the elbow.

During isokinetic testing, ROM was set from 0° (full supination) to 180° (full pronation). The movement started from a supinated grip. Rotation of the segment was in the transverse plane, about the sagittal axis through the centre of the head of the radius proximally, and through the centre of the head of the ulna distally. The velocity was set to $240°\cdot s^{-1}$. The isometric test was performed at 115°.

<u>*Throwing tests*</u>

Preparation

For the throwing tests, eight 3-D motion capture cameras (Oqus 400, Qualisys AB, Gothenburg, Sweden) were used. See figure 3 for illustration of the set up. The cameras primarily focused on the throwing spot. Four cameras were located on one side, three on the other side and one camera was placed directly behind the participant. The cameras on the sides were placed 4m sideways from the midline of the throwing spot. The gap between cameras was 2–5m. Calibration of the camera system was done according to the manufacturer's specifications. The kinematic signals were recorded at 250 Hz, using Qualisys Track Manager 2.10 (Qualisys AB). A mattress with a 1x1m taped target was set up 8m from the throwing spot. The target was equivalent to the center of a regulation handball goal (meaning the center of the target was 1.1m above the ground). A standard women's handball (weight: ~360g and circumference: 54cm) was used for throwing, and resin was allowed.

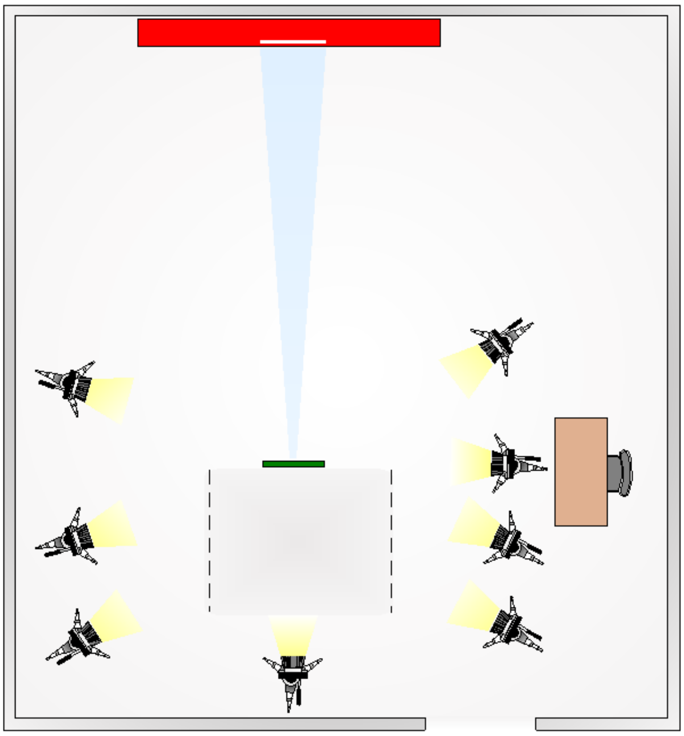

Figure 3 Laboratory setup. The space within the dashed line represents the run-up area and the vertical green line represents the throwing spot. Eight cameras were placed aorund the run-up area, with main focus on the throwing spot. The thick red and thin white line illustrate the mattress and target, respectively.

Each subject got reflective markers (⌀ 16mm) attached, as illustrated in figure 4:

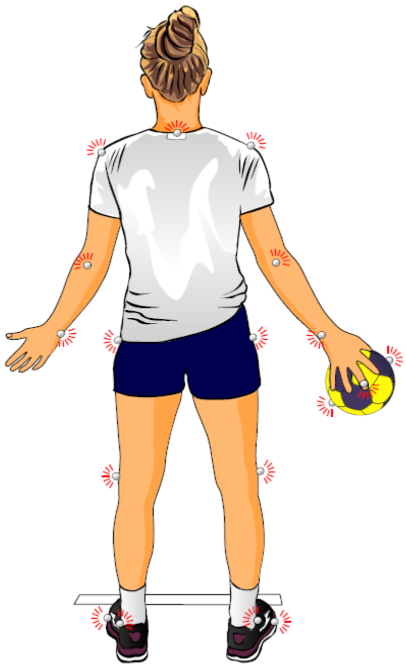

Figure 4 Complete setup of the reflective markers, with 16 of them attached to the participant and two on the ball.

Markers were placed on the shoe over the distal end of the 5th metatarsal (foot), lateral malleolus (ankle), lateral femoral epicondyle (knee), trochanter major (hip), lateral tip of the acromion (shoulder), lateral humeral epicondyle (elbow), ulnar styloid process (wrist), middle phalanx III on the throwing arm (hand) and C7 (neck). Two opposing markers were placed on the ball. Calculating the average of these ball-markers made it possible to find the centrum of the ball, and thus avoiding the effect of rotational velocity, which could interfere with calculations of the linear ball velocity.

Additional reflexes on the subjects' clothes or shoes, which could be perceived as markers by the cameras, were covered by tape. All participants wore tight-fitting clothes, to prevent movement of markers.

Procedures for throwing tests

A self-regulated warm up for 15 minutes, including treadmill jogging, arm- and shoulder exercises with elastic bands and throwing against the mattress, was performed before data collection. A 5s measurement with a normal grip on the ball was done to find the distance from middle phalanx III and centrum of the ball (grip distance). This distance was used to identify ball release.

The instructions were to perform five maximal overarm standing throws and five maximal overarm throws with a one-foot jump (jump throws). Order of the throwing technique was counterbalanced between the participants to avoid any systematic effects of order. After permission to throw the ball, a ten-second time frame was given to complete the throw. The participants had a 30-60s pause between each throw.

For the throws to be approved, they had to start with the ball in their hands from a stationary position and take three steps before throwing as fast as possible from the marked spot on the floor and hit the target (see figure 3 for throwing spot and target). If the target was missed, they had to repeat the throw.

Data analysis

All data were processed in Matlab R2016b (version 9.1.0.441655, Mathworks, Natick, MA, USA). The strength test data was low-pass filtered at 40Hz with an eighth-order Butterworth filter. In order to reflect movements during a throw, for analysis, ROM for the segments was taken from the acceleration phase to a point past ball release during the overarm throw, whereas the angles used for the isometric tests were taken from approximately the ball release point (van den Tillaar & Ettema, 2007; Wagner et al., 2010; Wagner et al., 2011). Table 1 summarizes the velocities and angles from which data was extracted. For both isokinetic and isometric strength tests, the peak torque (τ_{peak}), mean torque (τ_{mean}), and peak rate of torque development ($R\tau D_{peak}$) were determined. τ_{peak} was determined as the highest value from a 10-sample moving average throughout the movement. τ_{mean} was calculated by taking the average torque throughout the movement. $R\tau D_{peak}$ was determined as the highest value from the first 250ms from a 3-sample moving average of continuous rate of torque development (Δtorque / Δtime) throughout the movement. These values were extracted from the specific ROM for the isokinetic tests and from the whole duration of the repetition for the isometric tests. For all variables, the repetition where they created most torque was used for further analysis.

Data from the throwing test was low-pass filtered at 20Hz with a fourth-order Butterworth filter. A 5-point differentiating filter on the time signals of marker positions was used to calculate velocity. To find the throwing velocity, it was first necessary to find the centrum of the ball and ball release. The average of the two opposing markers on the ball indicated the center of the ball. Ball release was determined to occur when the distance from the finger marker to the centrum of the ball became and stayed ≥1.3 times the grip distance (the distance between middle phalanx III and centrum of ball when holding a neutral grip). This threshold (which was determined through visual inspection of the data) indicates a continuous increase between the finger marker and centrum of the ball, before the ball was actually released. The final throwing velocity was found by taking the vector sum of horizontal and vertical velocity, and then calculating the average of three samples: one right before ball release, one at ball release and one right after ball release. An average of the three fastest throwing velocities ($m \cdot s^{-1}$) from the standing and jump throws, respectively, was selected for further analysis.

Run-up velocity was calculated as the horizontal velocity from the mean of the hip-markers at last touchdown, which was set to occur when the ankle marker of the leg contralateral to the throwing arm stopped moving forward before jumping or throwing.

Table 1 Extracted range of motion (ROM) and velocities for the isokinetic strength tests and set angles for the isometric strength tests.

	ROM (°)	Velocity ($° \cdot s^{-1}$)	Angle (°)
Core flexion	50 – 90	120	80
Shoulder flexion	0 – 30	180	15
Internal shoulder rotation	-5 – 15	270	5
Forearm pronation	70 – 160	240	115

For core flexion, 0° represents the legs and trunk being in line with each other. For shoulder flexion and internal shoulder rotation, 0° represents the fist pointing straight upwards. For forearm pronation, 0° represents full supination.

Statistical analysis

All statistical analyses were performed in IBM SPSS Statistics version 24 (IBM Corp. Armonk, NY, USA). The variables are presented with mean and SD. No deviations from the normal distribution or significant outliers could be seen from the Shapiro Wilk test, histograms and normal Q-Q plots. Correlations between run-up velocity and throwing velocity, as well as the correlation between standing and jump throw velocity, were found by using bivariate correlations. Third order partial correlation analyses were used to examine the relationships between core flexion strength and throwing velocity while taking consideration of arm strength. 95% confidence intervals (CI) were constructed using bootstrapping.

The dependent variables were the standing and jump throw velocity. The independent variables were isokinetic and isometric core flexion strength. Control variables were shoulder flexion strength, internal shoulder rotation strength and forearm pronation strength. Isokinetic control variables were used for the isokinetic core flexion strength tests and isometric control variables were used for the isometric core flexion strength tests. Correlation values were categorized as presented by Hopkins et al. (2009). These correlation categories are trivial (< .1), small (.1 – 3), moderate (.3 – .5) and large (> .5). Significance levels were set to $\alpha = .05$.

RESULTS

Seventeen participants were included in the analysis and results. Table 2 shows mean values across participants for all strength tests. The average of the three maximal standing and jump throws were respectively 23.2 ± 1.2m·s^{-1} and 22.2 ± 1.1m·s^{-1}. The standing and jump throws correlated significantly (r = .905, p = .001). The run-up velocities prior the standing and jump throws were respectively 2.7 ± .4m·s^{-1} and 3.8 ± .4m·s^{-1}. There were no significant correlations between run-up velocity and throwing velocity. The correlations were -.075 (p = .775) for the standing throw and -.257 (p = .319) for the jump throw.

Table 2 Descriptive statistics with values for the strength tests. Values are presented as means ± SD. N = 17

		Core flexion	Shoulder flexion	Internal shoulder rotation	Forearm pronation
τ_{peak} (Nm)	Isokinetic	137.7 ± 34.5	55.9 ± 12.4	31.7 ± 5.3	7.0 ± 1.2
	Isometric	138.7 ± 25.1	64.0 ± 13.1	46.2 ± 10.6	7.4 ± 2.5
τ_{mean} (Nm)	Isokinetic	111.3 ± 26.2	41.4 ± 10.6	30.0 ± 5.3	5.2 ± 1.1
	Isometric	121.8 ± 18.8	55.9 ± 12.4	41.2 ± 10.8	6.5 ± 2.3
RτD$_{peak}$ (Nm·s^{-1})	Isokinetic	1513.1 ± 665.8	633.8 ± 221.7	107.4 ± 4.0	18.2 ± 7.1
	Isometric	1299.9 ± 696.9	614.9 ± 455.6	257.1 ± 108.6	78.7 ± 60.6

Correlations between core strength and the throwing velocities are shown in table 3. No significant correlations could be seen from the results. However, the standing throw showed tendencies for both τ_{peak} and τ_{mean} during isometric core flexion. τ_{peak} showed a moderate correlation with the standing throwing velocity, with a shared a variance of 23.7%, while τ_{mean} showed a strong correlation with the standing throwing velocity, with a shared a variance of 26.6%. τ_{mean} showed a moderate correlation with the jump throw velocity as well, with a shared variance of 23.5%. All variables within the isometric tests had large or moderate correlations with the throwing velocities. Variables within the isokinetic tests had small or trivial correlations with the throwing velocities.

Table 3 Correlations (r) between core strength tests and throwing velocity, including significance values (p) and 95% confidence intervals (CI). N = 17.

		Standing throw			Jump throw		
Parameters		r	p	95% CI	r	p	95% CI
Isokinetic	τ_{peak}	-.058	.843	-.607 – .775	-.156	.594	-.776 – .766
	τ_{mean}	.212	.467	-.407 – .740	.135	.645	-.562 – .784
	$R\tau D_{peak}$	.190	.515	-.533 – .602	-.122	.679	-.719 – .487
Isometric	τ_{peak}	.487	.078	-.283 – .890	.445	.111	-.191 – .871
	τ_{mean}	.516	.059	-.024 – .812	.485	.079	-.100 – .827
	$R\tau D_{peak}$	.356	.212	-.516 – .808	.448	.109	-.246 – .812

Figures 5 and 6 show the relationships between isokinetic and isometric τ_{peak} and τ_{mean} with the standing- and jump throw. Looking at table 3 and comparing the results with the figures, where no control variables are included, it seems that the relationship between isokinetic core flexion strength and throwing velocity was much more affected by arm strength than the relationship between isometric core flexion strength and throwing velocity.

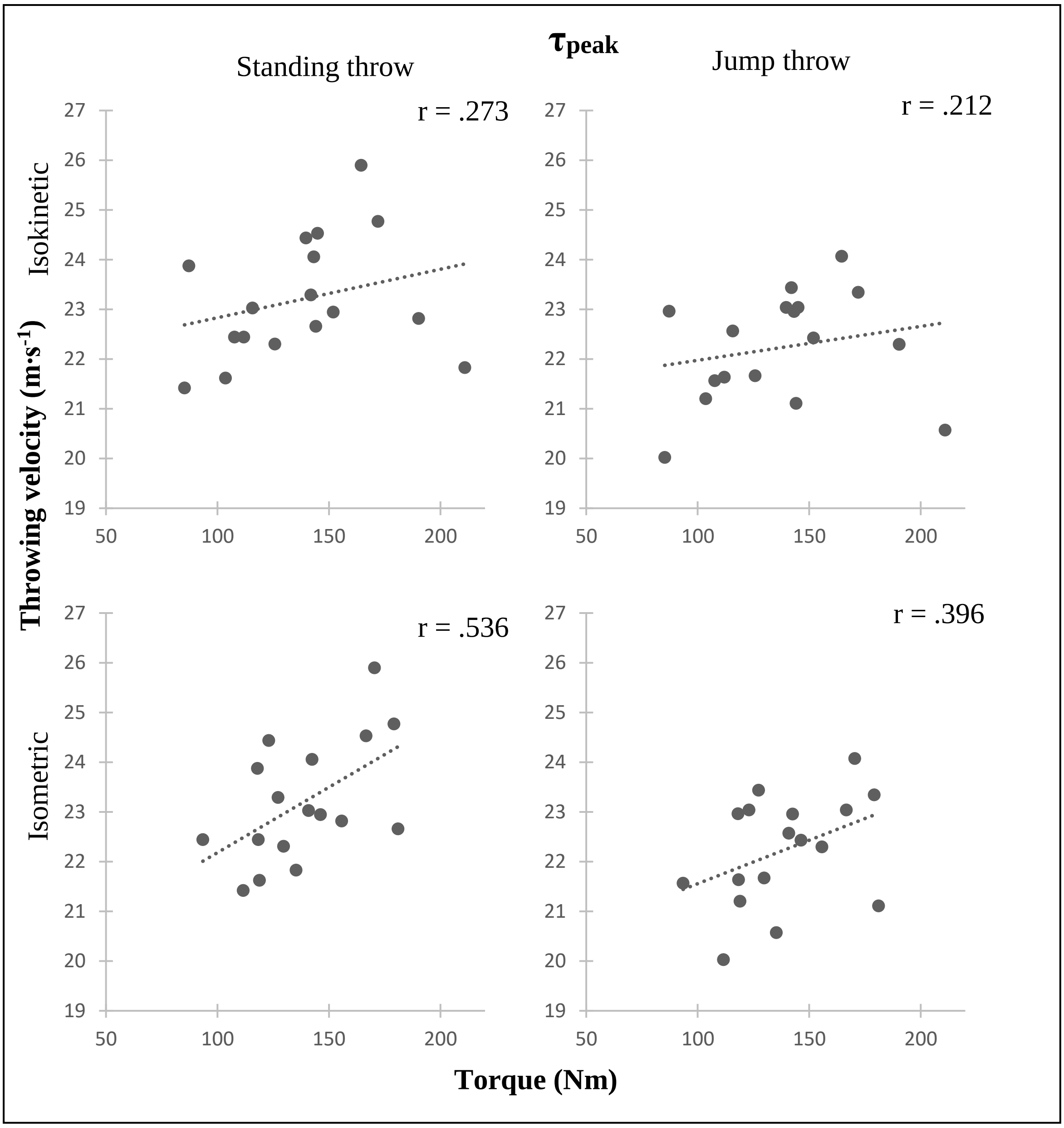

Figure 5 Correlations between τ_{peak} and throwing velocity. Note that the correlation is not controlled for arm strength.

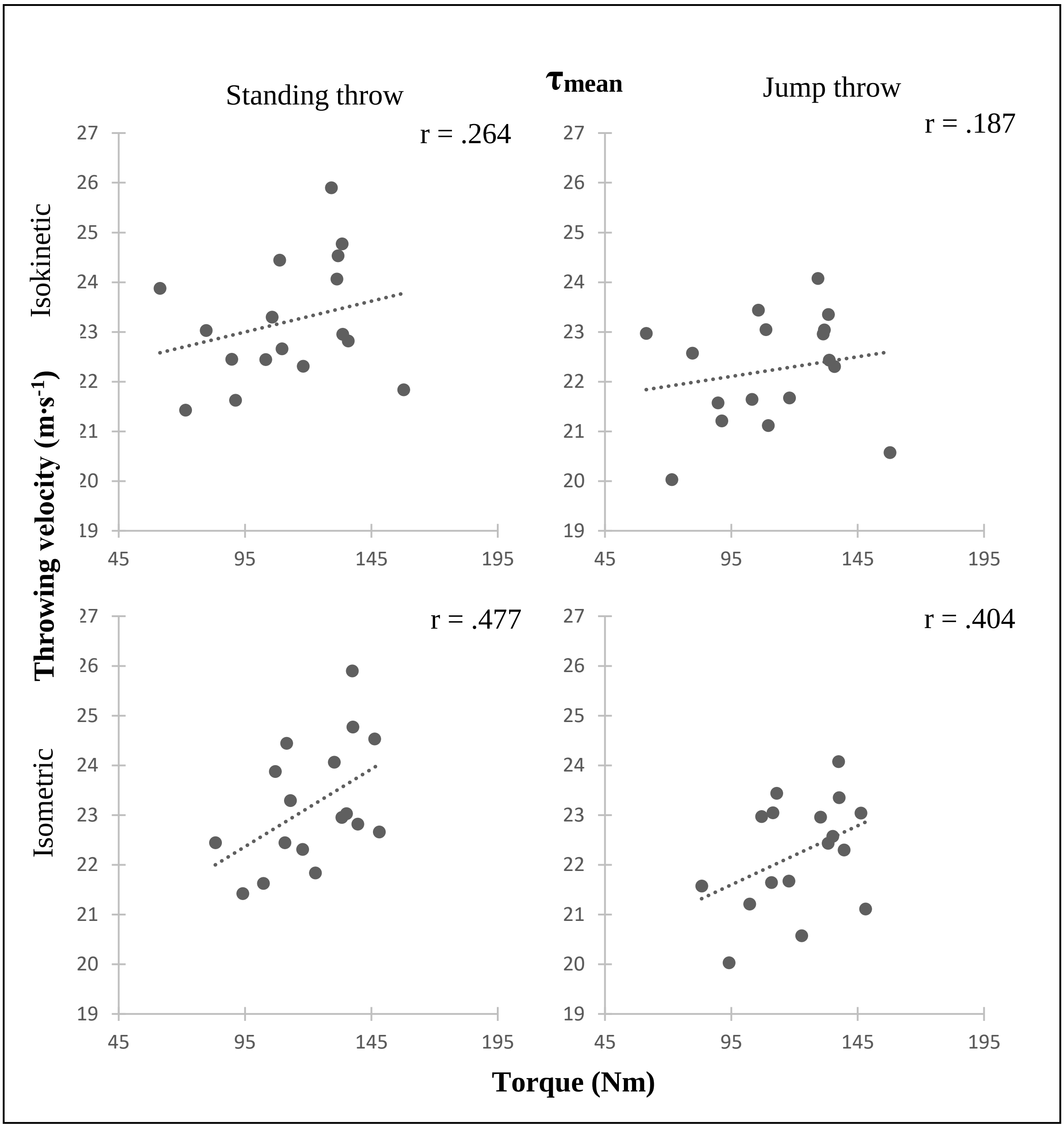

Figure 6 Correlations between τ_{mean} and throwing velocity. Note that the correlation is not controlled for arm strength.

DISCUSSION

The aim of this study was to investigate the relationship between core strength and throwing velocity among elite female handball players. It was hypothesized that positive correlations exist between core strength and throwing velocity in handball. No significant correlations were observed. However, positive tendencies could be seen for isometric core flexion strength. Standing throwing velocity had moderate and large correlations with τ_{peak} and τ_{mean}, respectively, while jump throw velocity showed a moderate correlation with τ_{mean}. Isokinetic core flexion strength showed no noticeable tendencies with throwing velocity. In total, the results indicate that core strength does play a role in throwing velocity.

Before discussing the results further, some methodological considerations should be addressed. The dynamometer used is designed mostly for clinical purposes and not for testing on high-level athletes. Further, none of the subjects had previous experience with movements of this type on a dynamometer. Montain et al. (1989) saw a significant learning component to isokinetic trunk testing, suggesting strength measures increase with practice. McLean and Conner (1994) found that two days of practice were required for healthy females to obtain reliable results on peak torque during isokinetic flexion at $120°\cdot s^{-1}$. To increase the chance of obtaining results from a repetition where the participants reached their maximal strength potential, they were given clear instructions, test trials and only the maximum repetition was used for further analysis. In addition, all of them were high-level athletes and accustomed to performing their absolute maximum. In any case, with regard to dynamometer testing experience, all the participants had the same premises.

Assuming the subjects reach their maximum potential in the test protocols, an inclusion of participants from various levels might show clearer results. However, a diverse group would also give more uncertainties regarding variables that could affect the results, such as technique, familiarization to testing and performing their maximum when needed. Only using elite players reduced the chance of technique being a confounding factor, as notable differences in technique between high-level participants are most likely minimal. The participants' throwing velocities were in accordance with the throwing velocity previously found in elite female handball players (Granados et al., 2007; Vila et al., 2012). This supports the assumed level of the players participating in this study. In the present study, run-up velocity did not appear to affect throwing velocity. The homogeneity of the group probably decreased the chance for high correlations, which would have had to be very clear to reach significance. Due to this, the strength of the correlations and shared variance between core strength and throwing velocity was also taken into account when assessing the results. Despite the homogeneity of the group, results indicate that core strength plays a role for throwing velocity. Standing throwing velocity had a shared variance of respectively 23.7% and 26.6% with τ_{peak} and τ_{mean} in the isometric core flexion strength test, while jump throw and τ_{mean} in the isometric core flexion strength test had a shared variance of 23.5%. Even though the results were not statistically significant, approximately a quarter of the variance in throwing velocity could be explained by the variance in core strength according to these results.

This study has looked at force production from the core, which is only a small part of the core's function during a throw. Core stability, transfer of energy and timing of core activation are important during a throw as well (Hirashima et al., 2002; Kibler et al., 2006; Silfies et al., 2015; Young et al., 1996). There are uncertainties regarding what the most important components of core stability are (Sharrock et al., 2011). Strength is needed for core stability, hence improved core strength may improve core stability. Assuming core stability is important for transfer of energy, improved core strength may indirectly affect the athletes' ability to transfer energy. Joris et al. (1985) stated that high maximal segmental velocities are important pre-requisites for an optimal flow of energy to the ball during the last phase of the overarm throw in female handball players. They found that the major part of the work on the ball was done in the last 50 ms of the throw. In the study of Wagner et al. (2010), maximal velocity of trunk flexion occurred about this phase (60 ± 40ms before ball release) for male handball players during the jump throw. This suggests that the core is still very active during the phase assumed to be important for throwing velocity.

In contrast, van den Tillaar and Ettema (2007) found that the role of the trunk was of minor importance during the throw, as maximal velocities, maximal angles and angles at ball release for the trunk and upper torso showed no significant correlations with throwing velocity. This does not necessarily mean that core strength and stability is of minor importance for the throw. In the study of Saeterbakken et al. (2011), improvements in core stability performance corresponded with improvements in throwing velocity. Correlations between core strength and stability and throwing performance have been found in other studies as well (Krishnan et al., 2013; Prokopy et al., 2008; Sharrock et al., 2011). It is important to note that all these studies use different approaches, sports, throwing techniques- and objects. In the present study, only variables within the isometric core flexion strength test showed noticeable correlational tendencies with throwing velocity. All of them had large or moderate correlations. Variables within the isokinetic test had small or trivial correlations with throwing velocity. Whether isometric core strength is of greater importance for throwing velocity than isokinetic core strength among elite female handball players is difficult to determine from these data only. An isometric exercise is in itself static and thereby no change in the length of the muscle takes place. A benefit of the isometric tests is the option to pick a particular joint-angle position. The isokinetic tests involved maximal muscular contractions performed at a constant velocity (relevant to the limbs angular velocity during a throw) through the set ROM. A possible explanation for stronger correlations between throwing velocity and isometric core strength compared to isokinetic core strength may be the fact that isometric core strength was tested at an angle where the trunk is at its highest velocity during a throw, whereas isokinetic core strength was measured over a ROM where the trunk varies between different velocities during a throw. It is not safe to say if the participants managed to reach their maximal force during the set ROM at the isokinetic tests due to limited time, meaning most of them maybe came closer to their maximal potential during the isometric tests compared to the isokinetic ones, but this is difficult to know for sure.

Even though some studies find correlations between core strength and stability and athletic performance, there are still a lot of uncertainties on how to measure core strength, as there is an absence of standardized tests (Sharrock et al., 2011). Barbado et al. (2016) found the need for sport specificity in core stability tests. They analysed the influence of specialization in judo and kayaking on trunk stability and compared high-performance athletes with recreational athletes. Interestingly, the judokas and kayakers performed better than recreational athletes only on the core tests designed according to the specific demands of their own sport. For handball throwing, this could mean that performance on general core exercises, like the plank or double leg lowering test, might not correlate as strongly with throwing velocity as a more throwing-specific core test would. In an attempt to make the strength tests specific for a handball throw and isolate the muscles as much as possible, the ROM and isometric angles used in the present study were specific to those occurring in an overarm throw. It should be noted that velocities for some of the segments occurring in a throw are too high to be used in the dynamometer. The velocities during a throw have been found to respectively be $150°\cdot s^{-1}$, $1110\ °\cdot s^{-1}$, $2000°\cdot s^{-1}$ and $1500°\cdot s^{-1}$ for core flexion, shoulder flexion, internal shoulder rotation and forearm pronation (van den Tillaar & Ettema, 2007; Wagner et al., 2010; Wagner et al., 2011). These velocities were adjusted to a point where resistance could be felt, making it possible to apply force during the movement. The relative difference between the velocities was approximately the same as the relative differences in the segmental velocities during a throw. Segments tested in the strength tests were isolated, as opposed to a throw, where there is more motion and continuous activation of the segments throughout the whole movement. However, in order to get specific measures on core strength without interference or too much activation of other muscles, isolation of the muscles was required. The measures were also accurate, as they were provided in physical units and not for example as number of repetitions done.

In game situations, the jump throw is more used than the standing throw (73-75% vs. 14-18%), but the highest throwing velocity is achieved with a standing throw (Wagner et al., 2011). This is in accordance with the results in this study, where the standing throw was $1 m \cdot s^{-1}$ higher than the jump throw. A possible explanation for this could be that standing throws with run-up transfer more energy from the lower body to the ball due to extended floor-contact with the leading leg. Wagner et al. (2011) found significant differences in maximal trunk flexion, rotation and internal shoulder rotational angular velocity between standing and jump throw. Regarding rotation of the core during the throw, Serrien et al. (2015) compared male and female handball players, and found that the males showed more activity in pelvis and trunk rotation, while the females showed more activity in trunk flexion. Even though women have less rotational movement in the core, data on core rotation strength could be valuable. Unfortunately, this was not tested in this particular study due to difficulties finding a test method providing accurate measures. Due to limited studies done on the subject of core strength and throwing velocity in handball and other throwing sports in general, in addition to all of them using different interventions, strength test methods, throwing technique and throwing objects, it is challenging to directly compare other studies with the present study. There are also uncertainties regarding the role of core strength and stability for athletic performance in general.

CONCLUSION

Results from the current study showed no significant correlations. However, tendencies for isometric core flexion strength and throwing velocity were found. τ_{mean} showed a large correlation with standing throwing velocity and a 26.6% shared variance was observed between them. Moderate correlations with a shared variance of 23.5% and 23.7%, respectively, was found for τ_{mean} and τ_{peak} for the jump and standing throwing velocity. These results are in line with current literature on the topic: there seems to be a relation between core strength and throwing velocity. However, it is difficult to know exactly how and how much effect the core contributes to throwing velocity. Even though the core has been isolated in this particular study, it is still difficult to interpret the nature of its contribution.

There is clearly a need for more research on core strength and throwing velocity in handball. In the current literature, there are limited studies, and all of them use different experimental approaches. For further research on core strength and throwing velocity in handball, an important first step may be to find a standardized core strength measure. By using identical or at least similar test protocols for core strength and throwing technique, comparison of results will give valuable insights about the true relationship between core strength performance and throwing velocity. More insight regarding this relationship can provide useful knowledge for coaches, and perhaps help them adjust strength-training routines by implementing more or less core specific exercises.

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