Strength determinants of jump height in the jump throw movement in women handball players

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Running head: Lower-body strength and handball-specific jump height

ABSTRACT

The purpose of the study was to improve the understanding of the strength demands of a handball-specific jump, through examining the associations between jump height in a jump throw jump (JTJ) and measures of lower-body maximum strength and impulse in handball players. For comparison, whether the associations between jump height and strength differed between the JTJ and the customarily used countermovement jump (CMJ) was also examined. Twenty women handball players from a Norwegian top division club participated in the study. Jump height was measured in the JTJ and in unilateral and bilateral CMJ. Lower-body strength (maximum isometric force, one-repetition maximum (1-RM), impulse at ~60% and ~35% 1-RM) was measured in seated leg press. The associations between jump height and strength were assessed with correlation analyses and t-tests of dependent *r*'s were performed to determine if correlations differed between jump tests. Only impulse at ~35% 1-RM correlated significantly with JTJ height ($p < .05$), while all strength measures correlated significantly with CMJ heights ($p < .001$). The associations between jump height and strength were significantly weaker in the JTJ than in both CMJ tests for all strength measures ($p = .001 – .044$) except one. Maximum strength and impulse at ~60% 1-RM did not seem to sufficiently capture the capabilities associated with JTJ height, highlighting the importance of employing tests targeting performance-relevant neuromuscular characteristics when assessing jump-related strength in handball players. Further, CMJ height seemed to represent a wider range of strength capabilities and care should be taken when using it as a proxy for handball-specific movements.

KEY WORDS countermovement jump, jumping, performance, sport-specific, testing

INTRODUCTION

In professional handball, the jump throw is the most common throw, representing over 70% of all throws in a game situation (37). In addition to throwing velocity and accuracy, jump height is potentially an important performance factor in a jump throw. A greater jump height affords any player, regardless of playing position, more throwing opportunities as a function of either position or time spent in the air. For example, a higher jump allows backs to throw from a greater vertical position, improving the possibility of throwing over the defender's block. Still, factors related to jump height in the jump throw are largely unexplored.

In handball players, vertical jumping ability is typically investigated with a two-legged countermovement jump (CMJ) both in cross-sectional studies (e.g., 14, 18, 35) and when evaluating the results of training interventions (e.g., 8, 13). However, although the CMJ has been described as closely related to game play actions (34), it is a general test that encourages a different movement pattern than what the single-leg jump throw does. While a traditional CMJ offers a greater range of motion and consequently more time to produce force, the demands of a jump throw in game situations necessitate a more rapid force production. The differences in contact time illustrate this clearly, being ~250-300 ms in a jump throw (27, 31) in contrast to ~500 ms in a CMJ (4), of which the push-off phase alone is ~280 ms.

Despite the differences in movement characteristics between the CMJ and the jump throw, the CMJ has been strongly correlated to a general one-legged jump with run-up (40). While the latter on the surface would seem similar to the jump throw, it does not take into consideration the fact that the players have to perform a throwing motion, which begins prior to the jump (31). Although the general effect of arm swing on jump performance is positive (21, 34), the movement of the arms in the CMJ or a general one-legged jump with run-up is dissimilar to that in a jump throw. Therefore, the association found between the CMJ and the general one-legged jump with run-up might not be directly transferable to the jump throw specifically. This notion is supported by investigations from both handball (19) and comparable team-sports such as basketball (24) and soccer (26), where no associations were found between performance in sport-specific one-legged jumps and a CMJ.

Measures of both maximum strength and different force-time variables have shown significant relationships with jump height in different types of vertical jumps, such as the CMJ (e.g., 23, 28, 34) and both two-legged (30) and one-legged (40) jumps with run-up. While the CMJ is widely used in sports to assess lower-body strength and power performance (e.g., 14, 22), the predictability of jump performance from non-specific strength tests has been criticized (28), especially for elite athletes (33). Nevertheless, a significant correlation between peak force and jump height has been shown in the CMJ (23), suggesting that maximum strength plays a role in jumping performance. However, dynamic strength measures show a stronger association with CMJ height than isometric measures (25). Further, the ability to produce force rapidly at submaximal loads appears to have a stronger association with jump height than maximum strength has; this is not only found for the CMJ (22) but also for both one- and two-legged jumps with run-up (30, 40).

Naturally, the temporal aspect is important in the jump throw, with little space and short time available in game play situations. In line with this, time-dependent variables such as impulse and rate of force development have been identified as important strength parameters for assessing sport-specific performance explicitly because of their inclusion of the time aspect (1, 23, 33), something which is neglected in most traditional measures of strength. Yet, variables such as peak knee extension torque and one-repetition maximum (1-RM) in leg extensions or squats are routinely used in the evaluation of handball players (8, 13, 18). The time to reach maximum force is typically longer than what is practically possible in many fast, sport-specific movements (1), suggesting a faster development of force would be beneficial for jump height in handball. The importance of developing force quickly has been shown repeatedly for general jump height (e.g., 23, 28, 34), also in handball players (32). However, this has not yet been examined in a handball-specific movement such as the jump throw.

The purpose of the study was to improve the understanding of the strength demands of a handball-specific jump, through examining the associations between jump height in the jump throw movement – i.e., a "jump throw jump" (JTJ) – and measures of maximum strength and impulse in women handball players. Based on the short time available to produce force in the jump throw, it was expected that the ability to produce force rapidly would show a stronger association with jump height than maximum strength. Further, since vertical jumping ability in handball players is typically assessed using the CMJ, whether the associations between jump height and strength measures differed between the JTJ and the CMJ was also examined.

METHODS

Experimental Approach to the Problem

To examine the associations between jump height in a handball-specific movement and lower-body strength, a cross-sectional design was used. As part of a larger data collection, the participants performed jump tests and strength tests on separate days within the same week, with at least one day of rest in between to avoid any effects of fatigue. All strength tests were performed within a period of two hours. The data collection was done in the team's pre-season.

Jump height in a handball-specific movement was evaluated using a simulated jump throw (with focus on jumping, not throwing). Since the CMJ is the test customarily used in the handball literature to evaluate vertical jumping ability, it was performed both unilaterally and bilaterally for comparison. The jump tests were assumed to represent a gradual decrease in specificity (handball-specific unilateral, standardized unilateral, standardized bilateral).

Lower-body strength, at both maximum and submaximal resistances, was evaluated using the seated leg press exercise, as it minimized the reliance on technique, allowed for both unilateral and bilateral execution without placing the participants at unnecessary risk of injuries, and was familiar to all participants as part of their regular training regimen. The lower-body strength tests were chosen to represent a range from maximum strength to high velocity contractions: isometric maximum, 1-RM, moderate load (~60% 1-RM), and low load (~35% 1-RM). To capture the temporal aspect of force in the tests with submaximal resistance, impulse was chosen as the variable of interest due to its direct relationship with takeoff velocity.

Since the goal was to determine the maximum jumping and strength capabilities of the participants, only the best trials were used for statistical analyses. Correlation analyses were performed to determine the strength of association between jump height and lower-body strength measures, and t-tests of dependent *r*’s (9) were performed to determine if the respective correlations between jump height and strength measures differed between jump tests.

Subjects

Twenty women handball players from a club in the Norwegian top division (11 elite and 9 U-19 regularly practicing with the elite team; mean ± standard deviation (SD) age 19.5 ± 2.7 yrs, age range 17 – 26 yrs, body mass 70.9 ± 9.8 kg, height 174.1 ± 5.7 cm, and playing experience 11.9 ± 2.8 yrs) volunteered to participate in the study, which was approved by the Norwegian Social Science Data Services (Project number 43906). All participants signed an informed consent form before the experiment (for participants <18 yrs, parental consent was also obtained) and were made aware that they could withdraw from the study at any point without providing an explanation. The study was conducted in accordance with the Declaration of Helsinki.

Procedures

Jump tests. The JTJ was performed on an inside court, where custom made wooden flooring (3x2 m) was constructed around a 0.6x0.4 m Kistler force plate (Kistler 9286BA, Kistler Instrumente AG, Winterthur, Switzerland), calibrated internally. Seven motion capture cameras (Oqus 400, Qualisys AB, Gothenburg, Sweden) were placed in a circle around the force plate area. The camera system was calibrated according to the manufacturer's specifications. Using Qualisys Track Manager 2.10 (Qualisys AB), dynamic signals were recorded at 1000 Hz, via a Kistler data acquisition system (64ch DAQ system Type 5695A, Kistler Instrumente AG), and kinematic signals were recorded at 250 Hz. On each participant, passive spherical reflective markers (⌀ 19 mm) were placed bilaterally on the trochanter major.

After a 15-min standardized warm-up of running, dynamic stretching, and throwing activities (including familiarization with the test setup), the participants completed an 8 s weight measurement on the force plate. Following this, the participants performed five repetitions of the JTJ (simulating a jump throw, but without releasing the ball) with a three-step run-up and the instruction to jump as high as possible. For an attempt to be considered successful, the participants were required to jump from the force plate with the leg contralateral to their throwing arm. The participants were afforded ~1 min rest between each attempt to avoid any effects of fatigue. The data were processed in Matlab R2016b (version 9.1.0.441655, Mathworks, Natick, MA, USA). Dynamic signals were low-pass filtered at 200 Hz with an eighth-order Butterworth filter. Body weight (BW) was determined from the weight measurement as mean vertical force. Ground contact time was determined as the period when vertical force was ≥2 SDs above mean baseline force (i.e., unloaded force plate). Kinematic signals were spline interpolated where missing data gaps were ≤5 samples and low-pass filtered at 20 Hz with a fourth-order Butterworth filter. Jump height was calculated from the mean of the two hip markers, determined as the difference between the maximum height achieved after take-off and standing height. This method was chosen for ecological validity, representing the functional elevation of the body from which various throwing techniques can be employed.

After a 3-5 min resting period, three repetitions each of a unilateral and a bilateral CMJ (CMJ_{uni}, CMJ_{bi}) without arm-swing and with self-selected depth were performed on a SPSport force plate (SPSport diagnosegeräte GmbH, Austria), as part of the participants' regular testing regimen. The CMJ_{uni} was performed using the same jump leg as in the JTJ. The order of CMJ techniques was counterbalanced between the participants. Trials where the participants failed to keep the hands on the iliac crest throughout the jump were repeated. The force plate was calibrated internally and data was recorded at 1000 Hz using the accompanying acquisition software (Muskel-Leistungs-Diagnose (MLD) 5.2, SPSport diagnosegeräte GmbH), where dynamic signals were low-pass filtered at 150 Hz with a fourth-order Butterworth filter. Jump height and ground contact time were extracted from the software. Ground contact time was defined as the period from the start of the downward movement (force 10% below BW) to peak velocity. For comparisons with JTJ contact time, note that peak velocity occurs slightly prior to take-off, although the difference should be negligible (e.g., 10). Both velocity and jump height were calculated using the impulse-momentum theorem. In contrast to the calculation of JTJ height, this method does not include the effect of plantar flexion. Thus, CMJ height is underestimated compared to JTJ height, and the absolute magnitudes of jump height from the different jump tests must be interpreted with this in mind. For all jump tests, the repetition with greatest jump height was used for further analysis.

Lower-body strength tests. After a 10-min self-regulated warm-up of low-intensity running on a treadmill (GymSport TX200, GymSport AS, Trondheim, Norway), lower-body strength tests were performed in a seated leg press machine (GymSport AS). For tests with submaximal resistance, a linear position transducer (MuscleLab, Ergotest Technology AS, Langesund, Norway) was connected to the weight stack of the machine, continuously recording displacement data at 200 Hz using the accompanying acquisition software (MuscleLab Software Professional version 10.5.50.4215, Ergotest Technology AS, Langesund, Norway). Linear position transducers have shown acceptable reliability (intraclass correlation coefficient (ICC) .92 – .99, coefficient of variation (CV) 8.5 – 13.2%) in discrete movements such as squats and bench press (12) as well as in concentric phase impulse calculations (ICC .81, CV 8.5%) from loaded jump squats (16).

At submaximal loads and for determining 1-RM, unilateral leg press (JTJ leg) was performed with ~100° hip flexion and 90° knee flexion (where 0° is full extension) in starting position.

The leg press was completed when full knee extension was reached. Trials were discounted and repeated if full knee extension was not reached or if the lower body was elevated off the seat. The participants performed three warm-up sets of five repetitions at the lowest external load (32 kg). Then, three trials were performed for each of four external loads (32, 50, 68, and 86 kg) in increasing order. The external loads were standardized across all participants for practical reasons. The participants were given ~10 s rest between each repetition and ~2 min between each load. The repetition with the greatest mean velocity, determined from the linear position transducer software, was used for further analysis (29). The protocol for determining 1-RM was modified from typical recommendations (e.g., 7) by an experienced strength coach: the trials at submaximal loads replaced the progressive warm-up trials prior to 1-RM attempts, after which the load was increased on an individual basis in 2.5-10 kg increments until the participants failed to perform a correct trial. Two participants reached 1-RM before the final submaximal load. The participants were given ~3 min rest between attempts. 1-RM was determined as the greatest load accomplished in a correctly performed trial and normalized for body mass.

To account for inter-individual differences in the tests with submaximal resistance, common relative loads representing low and moderate resistances were identified among all participants. Ultimately, the loads closest to 60% and 35% 1-RM for each participant were used for analysis (mean 59.9 ± 5.5% and 34.6 ± 4.7% 1-RM, respectively). Data from these tests were processed in Matlab R2016b (version 9.1.0.441655, Mathworks, Natick, MA, USA). Kinematic signals were low-pass filtered at 10 Hz with a fourth-order Butterworth filter. Velocity and acceleration were calculated using a 5-point differentiating filter on the time signals of weight stack displacement and velocity, respectively. Friction in the pulley system was inspected, and any difference in magnitude of acceleration between the participant and the weight stack was deemed negligible. Push-off time, equivalent to the push-off phase of ground contact in the jumps, was determined as the period from the first change in displacement to peak velocity. The force produced during the push-off time was calculated as force = $M \cdot a + l \cdot (a + g)$, where M is body mass, a the measured acceleration, l the external load, and g the absolute acceleration of gravity. Since the participants moved horizontally, g was only included in the calculations for the vertically moving weight stack. Relative impulse was calculated as mean force during push-off multiplied by push-off time, normalized for the impulse created by BW alone over the same time, at both ~60% and ~35% 1-RM (I_{60}, I_{35}). In addition, relative impulse during the first 200 ms of push-off time ($I_{60\text{-}200}$, $I_{35\text{-}200}$) was calculated, approximating the contact time in the jump throw.

For determining isometric strength, bilateral leg press was performed with ~100° hip flexion and 90° knee flexion, using a custom setup with a SPSport force plate (SPSport diagnosegeräte GmbH) secured against the footrest without pressure in the horizontal plane (i.e., plane of movement). The hip and knee angles were standardized to both approximate the lowest point of the CMJ, with the knee angle corresponding to the angle at which peak force occurs during the CMJ (6), and be representative of typical strength training and testing (such as squats, e.g., 3). The force plate was calibrated internally and data was recorded at 1000 Hz using the accompanying acquisition software (MLD 5.2, SPSport diagnosegeräte GmbH). After a rest period of ~5 min following 1-RM testing, the participants performed three maximum isometric trials lasting 5 s. Trials were discounted and repeated if the lower body was elevated off the seat. One participant was unable to complete the isometric exercise due to a pre-existing minor injury in the non-JTJ leg. Peak force ($F_{peakISO}$) was extracted from the software and normalized for BW. The greatest force obtained was used for further analysis. The same experienced strength coach conducted all strength tests and gave the participants verbal encouragement as well as feedback to ensure good technique.

Statistical Analyses

Due to high collinearity between potential predictor variables, the association between jump height and lower-body strength measures was assessed with single predictors using Pearson's product-moment correlation coefficient, with 95% CI constructed using bootstrapping. This was done for both the JTJ and the CMJ tests. The minimum detectable effect size was r = 0.44, given $\alpha = 0.05$, $1 - \beta = 0.80$, and $n = 20$, determined through a sensitivity power analysis for bivariate correlations using G*Power 3.1 (11). Differences in correlations with strength measures between the JTJ and the respective CMJ tests were assessed with a t-test by comparing dependent r's (9), as

$$t = \left(r_{xy} - r_{zy}\right)\sqrt{\frac{(n-3)(1+r_{xz})}{2\left(1 - r_{xy}^2 - r_{xz}^2 - r_{zy}^2 + 2r_{xy}r_{xz}r_{zy}\right)}}$$

where n is the number of observations, r_{xy} the correlation between the JTJ and a given strength measure, r_{zy} the correlation between a CMJ test and the same strength measure, and r_{xz} the correlation between the JTJ and the CMJ test. The resulting p-value is found from the t-distribution as t_{n-3}.

For descriptive purposes, differences in contact time between the JTJ and the respective CMJ tests were assessed using paired t-tests, with Cohen's d. Normality of all variables (correlations) and of the differences between the JTJ and the respective CMJ tests (paired t-tests) was assessed with the Shapiro-Wilk test. Statistical significance was set at an alpha level of .05. Values are presented as mean ± SD. ICC estimates with 95% CI were calculated based on a consistency two-way mixed model and within-participant CVs were calculated as the root mean square of individual CVs. All analyses were performed using SPSS version 24

(IBM Corporation, Armonk, NY, USA) except differences between correlations, which were calculated using Microsoft Excel (Office 2016, Microsoft Corporation, Redmond, WA, USA).

RESULTS

Reliability as measured with ICC (95% CI) and CV was .85 (.75, .93), 5.1% for the JTJ, .90 (.79, .96), 3.1% for the CMJ_{uni}, and .97 (.94, .99), 5.7% for the CMJ_{bi}. The calculated jump heights were 0.448 ± 0.046 m in the JTJ, 0.179 ± 0.032 m in the CMJ_{uni}, and 0.320 ± 0.055 m in the CMJ_{bi}, with corresponding contact times of 0.237 ± 0.032 s, 0.548 ± 0.115 s, and 0.495 ± 0.067 s, respectively. The contact time in the JTJ was significantly shorter than in both the CMJ_{uni} ($p < .001$, $d = 3.7$) and the CMJ_{bi} ($p < .001$, $d = 4.9$). Absolute and relative mean values of all strength measures from the leg press exercises can be seen in Table 1.

[Table 1 about here]

Correlations between jump height and all strength measures for the JTJ, the CMJ_{uni}, and the CMJ_{bi} are shown in Table 2. Whereas only I_{35} ($p = .020$) and $I_{35\text{-}200}$ ($p = .005$) showed a significant correlation with JTJ height, all strength measures correlated significantly with jump height in both the CMJ_{uni} and the CMJ_{bi} (all $p < .001$). In general, the correlations were weaker for the JTJ than for both the CMJ_{uni} and the CMJ_{bi}.

[Table 2 about here]

Differences in correlations between the JTJ and the respective CMJ techniques are shown in Fig. 1. The association between jump height and strength was significantly different between the JTJ and both the CMJ_{uni} and the CMJ_{bi} for all strength measures ($p = .001 – .044$) except $I_{35\text{-}200}$, where the CMJ_{bi} did not differ from the JTJ ($p = .105$).

[Figure 1 about here]

For illustrative purposes, force-time curves depicting the ground contact phase of the JTJ can be seen in Fig. 2. On average, the five participants with the highest jumps (mean ± SD 0.505 ± 0.015 m) produced a distinctly different shape in the early part of ground contact than the five participants with the lowest jumps (0.388 ± 0.020 m), despite similar contact times (0.237 ± 0.031 vs. 0.239 ± 0.020 s).

[Figure 2 about here]

DISCUSSION

The purpose of this study was to improve the understanding of the strength demands of a handball-specific jump, through examining the associations between jump height in the jump throw movement and measures of maximum strength and impulse in the leg press. In line with what was expected, only impulse at a low load showed a significant correlation with jump height in the jump throw movement. A further purpose was to examine whether the associations between jump height and measures of maximum strength and impulse differed between the handball-specific jump test and a jump test customarily used in handball. The associations with measures of maximum strength were significantly weaker for jump height in the jump throw movement than countermovement jump height. This was also the case for impulse at a moderate load, while impulse at a low load showed mixed results.

Both measures of impulse at ~35% 1-RM in the leg press exercise were significantly associated with JTJ height, while none of the measures of maximum strength or impulse at ~60% 1-RM reached significance. The differences in duration of movement and magnitude of resistance between the strength tests likely factor into the explanation for these findings.

Considering the typically short ground contact time for a jump throw, the ability to produce force rapidly becomes important for jump height; a greater rise in force production presumably increases mean force, which in turn increases takeoff velocity and hence jump height. Although both the low and moderate loads resulted in push-off times greater than the 0.24 s contact time in the JTJ, the low load was much closer than the moderate (0.45 ± 0.07 vs. 0.60 ± 0.12 s), with the time to perform 1-RM and reach isometric peak force presumably even longer. With regard to magnitude of resistance, ~60% 1-RM ultimately appeared to provide too much resistance for the participants to achieve either movement durations or movement ranges (within 200 ms) comparable to the JTJ. In this sense, the moderate load was more similar to the measures of maximum strength than to the low load (see Fig. 1), which was seemingly the only resistance sufficiently low to approximate the JTJ.

Another factor which might have contributed to JTJ height being significantly associated only with the strength test with the shortest execution time (~35% 1-RM), and not the strength tests which took longer to execute (isometric maximum, 1-RM, and ~60% 1-RM), is the range of ways to perform the different strength tests with regard to force production. In strength measures that are not time-dependent, such as $F_{peakISO}$ and 1-RM, the result is not dependent on the rate of force production. This should allow a variety of participants to perform well, not necessarily those most capable of rapid force production. The same notion should increasingly apply to impulse the closer the resistance is to 1-RM. Greater resistance typically results in longer movement duration, which means the participants to a lesser degree must rely on rapid force production to obtain a high impulse. However, if the magnitude of resistance is sufficiently low, so that all participants are able to overcome it with relative ease, movement duration is typically shorter. In this situation, the participants most capable of rapid force production have an advantage in obtaining a high impulse, which might have been the case at ~35% 1-RM. In comparison, the JTJ is for all practical purposes time-restricted and requires rapid force production – the range of ways to perform it within the constraints of game play is limited. As indicated by the force profiles in Fig. 2, there were indeed differences in execution, not just in outcome, between the participants who jumped highest and those who jumped lowest. Notably, the former group demonstrated a more rapid increase in force. Of the five participants who jumped the highest, four were backs, while of the five participants who jumped the lowest, three were pivots. This possibly reflects the specificity of positions, which merits consideration with regard to team-wide testing regimens.

Although JTJ height and impulse at ~35% 1-RM were significantly correlated, the shared variance was only 36% at the highest ($I_{35\text{-}200}$). The reason for this could be differences in movement characteristics. While the leg press is a standardized exercise targeting the lower-body musculature, the JTJ is a whole-body movement with relatively high technical complexity, similar to the jump throw. Further, where the JTJ involves both a slight countermovement (eccentric or isometric muscle work) and a push-off phase (concentric muscle work), the leg press exercises included only the push-off phase. For the JTJ, the pre-activation of muscles inevitably accompanying the run-up and jumping movement should be beneficial for performance. In contractions of short duration, a pre-activation allows the muscles to reach a higher level of active state prior to the start of shortening, resulting in a greater level of force at the onset of concentric contraction and hence the possibility to produce more work (5, 38). Unlike in the JTJ, the participants could not take advantage of this mechanism in the leg press due to the static initial conditions. Consequently, reactive strength (i.e., the ability to quickly transition from eccentric to concentric muscle work), which appears important for performance in jumps with run-up (15, 40), is likely relevant for the JTJ but not for leg press performance. This can help to explain why the associations between JTJ height and impulse at a low load, although significant, were not stronger, and it is a factor worth considering for potential tests intended to represent the demands of the jump throw.

In contrast to the findings for JTJ height, the entire range of strength measures, from $F_{peakISO}$ to $I_{35\text{-}200}$, showed excellent correlations with CMJ height. Although the difference in jump height between the JTJ and the CMJ_{bi} (but not the CMJ_{uni}) was consistent with plantar flexion (as per the different calculation methods, e.g., 2), this should not affect relative performance in the different jump tests (2). As for the abovementioned findings for CMJ height, the duration of movement is likely part of the explanation. With the participants receiving instructions only to jump as high as possible, the contact times in the CMJ_{uni} and the CMJ_{bi} (0.55 ± 0.11 and 0.50 ± 0.07 s, respectively) were more than twice that of the JTJ (0.24 ± 0.03 s), and as such more similar to the leg press exercises. As contact time increases, the relative importance of reactive strength decreases while the relative importance of force production during the concentric phase increases (15). Hence, the reliance on rapid force production is lessened. In addition, the finding of consistently strong associations between CMJ height and all strength measures raises the question of the degree to which the CMJ specifically tests lower-body power, for which it is frequently used (e.g., 13, 22, 34). Based on the present results, CMJ height rather appears to be associated with a wider range of strength capabilities.

While the correlations between maximum strength and jump height were significantly stronger in both the CMJ_{uni} and the CMJ_{bi} than in the JTJ, the differences in correlations between jump tests were much smaller at ~35% 1-RM, with the respective correlations of

CMJ_{bi} height and JTJ height with I_{35-200} not significantly different from each other (Fig. 1). Unlike the maximum strength tests, I_{35} and I_{35-200} were significantly related to jump height regardless of jumping task, supporting the notion that the ability to produce force rapidly has a stronger relation to the general ability to jump than maximum strength does (e.g., 22, 30, 40). At the same time, correlations with CMJ height were consistently high across all strength tests while only I_{35} and I_{35-200} were significantly correlated to JTJ height, indicating that the different jumping tasks do not only depend on common strength capabilities. Hence, the CMJ does not appear to be a suitable proxy for handball-specific movements such as the JTJ when assessing jumping ability in handball, neither for evaluating the results of training interventions (e.g., 8, 13) nor for periodic testing. Still, the CMJ is widely used in performance testing in handball, which prompts the question (39): one player is more proficient in the CMJ than another – so what? Since jump height is ultimately dependent on impulse, the absence of time-restriction in both the CMJ_{uni} and the CMJ_{bi} should allow participants to perform well regardless of whether their strength capabilities are disposed toward the magnitude of force (e.g., 20) or the rate of production. This notion is equivalent to that discussed previously for the leg press exercises, further clouding the connection between the respective strength demands of the CMJ and the JTJ, the latter of which remains time-dependent.

Another factor that could possibly have contributed to the weaker correlations with strength measures for JTJ height than CMJ height is the fact that the JTJ involves both upper- and lower-body actions simultaneously, whereas both CMJ techniques were performed without the use of the arms. In this regard, the CMJ_{uni} and the CMJ_{bi} should be more closely related to the strength tests as they all target the lower body exclusively. As previously noted (23), the use of the arms when jumping lessens the validity of the relationship between jump tests and lower-body strength tests. However, it must be considered that the movement of the arms in the JTJ, similar to the jump throw, cannot be performed in such a way as to solely aid in the generation of vertical velocity, such as a more conventional arm swing (e.g., 21), since the technical execution of the throwing motion must be maintained. Hence, its benefit for jump height is likely limited (36) and the relationship between JTJ height and the strength tests should not be compromised. Rather, similarities in lower-body movement characteristics with the strength tests might help explain the generally higher correlations for CMJ height than JTJ height. The range of motion in the leg press was ~90°, which is fairly equal to that observed in the CMJ_{bi}, but much greater than in the JTJ. The CMJ_{uni} appeared to fall somewhere in the middle. Considering that strength is angle specific (e.g., 17), it seems natural that the association between the leg press and CMJ height should be stronger. On the other hand, like the JTJ, both the CMJ_{uni} and the CMJ_{bi} should benefit from pre-activation of muscles (5, 38), something which should not be a factor in the leg press as it was performed in a way more similar to a squat jump.

From a methodological perspective, it is worthwhile to note that the CMJ_{uni} and the CMJ_{bi} were largely similar with regard to their correlations with strength measures. The assumption that the CMJ_{uni} represented an increase in specificity from the CMJ_{bi} due to it being restricted to the JTJ leg was by all accounts inaccurate. Rather, the opposite appears more likely. The CMJ_{uni} was executed slower than the CMJ_{bi} (0.55 vs. 0.50 s, with smaller joint displacement) and might have been more strength-dependent due to the stress of weight-bearing placed on a single knee joint in flexion. Whereas the CMJ_{bi} was typically executed with a maximum knee flexion angle of ~90° and a rapid eccentric-concentric transition, the CMJ_{uni} was typically executed with less knee flexion and, considering the smaller range of motion combined with the longer duration, a slower transition. In contrast to the continuous movements through the transition from the countermovement to the push-off phase in both the $\mathrm{CMJ}_{\mathrm{bi}}$ and the JTJ, the $\mathrm{CMJ}_{\mathrm{uni}}$ was executed more as two movements by a large part of the group: first a slow, controlled flexion to obtain the desired position, then a rapid extension in order to jump. As such, it did not appear to rely heavily on reactive strength. Further illustrating the relatively greater specificity of the $\mathrm{CMJ}_{\mathrm{bi}}$ compared to the $\mathrm{CMJ}_{\mathrm{uni}}$, the only correlation with strength measures that was not significantly different between the JTJ and either CMJ technique was in the $\mathrm{CMJ}_{\mathrm{bi}}$. When evaluating the CMJ with regard to its transferability to handball-specific movements such as the JTJ, the specificity of unilateral execution appears to be outweighed by the dissimilar strength demands it imposes on the athlete compared to bilateral execution. In the present study, unilateral execution resulted in less specific movement characteristics, such as a longer duration and a slower eccentric-concentric transition, indicating that it is not a solution to achieving both sufficient standardization and test specificity.

PRACTICAL APPLICATIONS

In the leg press, only impulse at a low load was significantly associated with jump height in the jump throw movement. Hence, neither measures of maximum strength nor impulse at a moderate load seem to sufficiently capture the capabilities associated with jump height in the jump throw movement, a potential performance factor in handball. This highlights the importance of test specificity, suggesting that, when attempting to assess jump-related strength, coaches should employ tests targeting performance-relevant neuromuscular characteristics rather than rely solely on traditional measures of strength. The results of the present study can be used to design training interventions with the goal of improving handball-specific jump height. Further, countermovement jump height showed consistent, significant associations with all strength measures. As such, the countermovement jump, a standardized test routinely used in handball, seems to represent a wider range of strength capabilities and care should be taken when using it as a proxy for handball-specific movements. This is essential for not only coaches responsible for strength training and testing regimens but also researchers making practical inferences based on non-specific tests. Future studies comparing jump-related characteristics of the jump throw to standardized jumps incorporating a reactive component (e.g., drop jumps, repeated jumps) would be useful in identifying tests that represent the demands of the handball-specific movement while also being suitable for easy standardization in a practical setting.

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Figure 1. Differences in correlations (95% Confidence Interval) between jump tests within each strength measure in elite and U-19 women handball players (*n* = $20^{\S}$). Black squares represent the "jump throw jump" (JTJ), grey squares the unilateral countermovement jump, and white squares the bilateral countermovement jump.

$F_{peakISO}$ = peak isometric force, 1-RM = one-repetition maximum, I_{60} = impulse at ~60% 1-RM, I_{60-200} = impulse during first 200 ms at ~60% 1-RM, I_{35} = impulse at ~35% 1-RM, I_{35-200} = impulse during first 200 ms at ~35% 1-RM

* different from JTJ ($p < .01$), ** different from JTJ ($p < .05$)

§ n = 19 for $F_{peakISO}$

Figure 2. Mean vertical force-time curves during the ground contact phase of the "jump throw jump" normalized for duration and body weight for the whole group (black line, n = 20), the five participants with the highest jumps (blue line), and the five participants with the lowest jumps (red line). Shaded areas in corresponding colors indicate standard deviation.

Table 1. Mean ± SD values of maximum strength and impulse measures from leg press exercises from elite and U-19 women handball players (n = 20[§]). Relative values are normalized by body mass or body weight.

	$F_{peakISO}$ (N)	1-RM (kg)	I_{60} (Ns)	I_{60-200} (Ns)	I_{35} (Ns)	I_{35-200} (Ns)
Absolute	1600 ± 370	116.1 ± 25.2	529.3 ± 116.9	172.4 ± 41.4	308.4 ± 51.6	137.1 ± 34.2
Relative	2.31 ± 0.41	1.64 ± 0.28	1.28 ± 0.22	1.24 ± 0.25	1.01 ± 0.17	0.98 ± 0.19

$F_{peakISO}$ = peak isometric force, 1-RM = one-repetition maximum, I_{60} = impulse at ~60% 1-RM, I_{60-200} = impulse during first 200 ms at ~60% 1-RM, I_{35} = impulse at ~35% 1-RM, I_{35-200} = impulse during first 200 ms at ~35% 1-RM

[§] n = 19 for $F_{peakISO}$

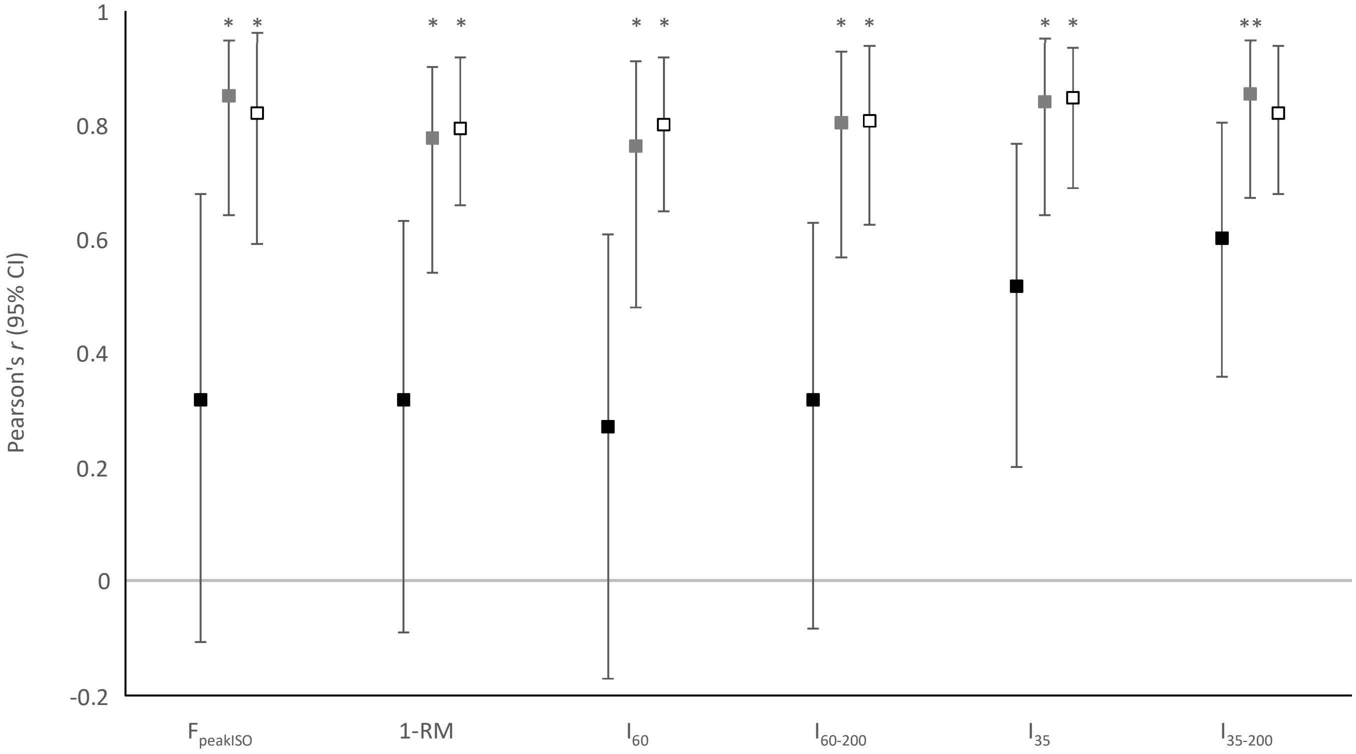
Table 2. Pearson's correlation coefficients (95% Confidence Interval) between jump heights from different jump tests and relative strength measures from leg press exercises in elite and U-19 women handball players (*n* = 20§).

	$F_{peakISO}$	1-RM	I_{60}	I_{60-200}	I_{35}	I_{35-200}
JTJ	.32	.32	.27	.32	.52***	.60**
	(-.11, .68)	(-.09, .63)	(-.17, .61)	(-.08, .63)	(.20, .77)	(.36, .80)
CMJ_{uni}	.85*	.78*	.76*	.81*	.84*	.85*
	(.64, .95)	(.54, .90)	(.48, .91)	(.57, .93)	(.64, .95)	(.67, .95)
CMJ_{bi}	.82*	.79*	.80*	.81*	.85*	.82*
	(.59, .96)	(.66, .92)	(.65, .92)	(.63, .94)	(.69, .93)	(.68, .94)

JTJ = jump throw jump, CMJ_{uni} = unilateral countermovement jump, CMJ_{bi} = bilateral countermovement jump, $F_{peakISO}$ = peak isometric force, 1-RM = one-repetition maximum, I_{60} = impulse at ~60% 1-RM, I_{60-200} = impulse during first 200 ms at ~60% 1-RM, I_{35} = impulse at ~35% 1-RM, I_{35-200} = impulse during first 200 ms at ~35% 1-RM

* $p < .001$, ** $p < .01$, *** $p < .05$

§ n = 19 for $F_{peakISO}$


Pearson's r (95% CI)
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0.6
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F peakISO
1-RM
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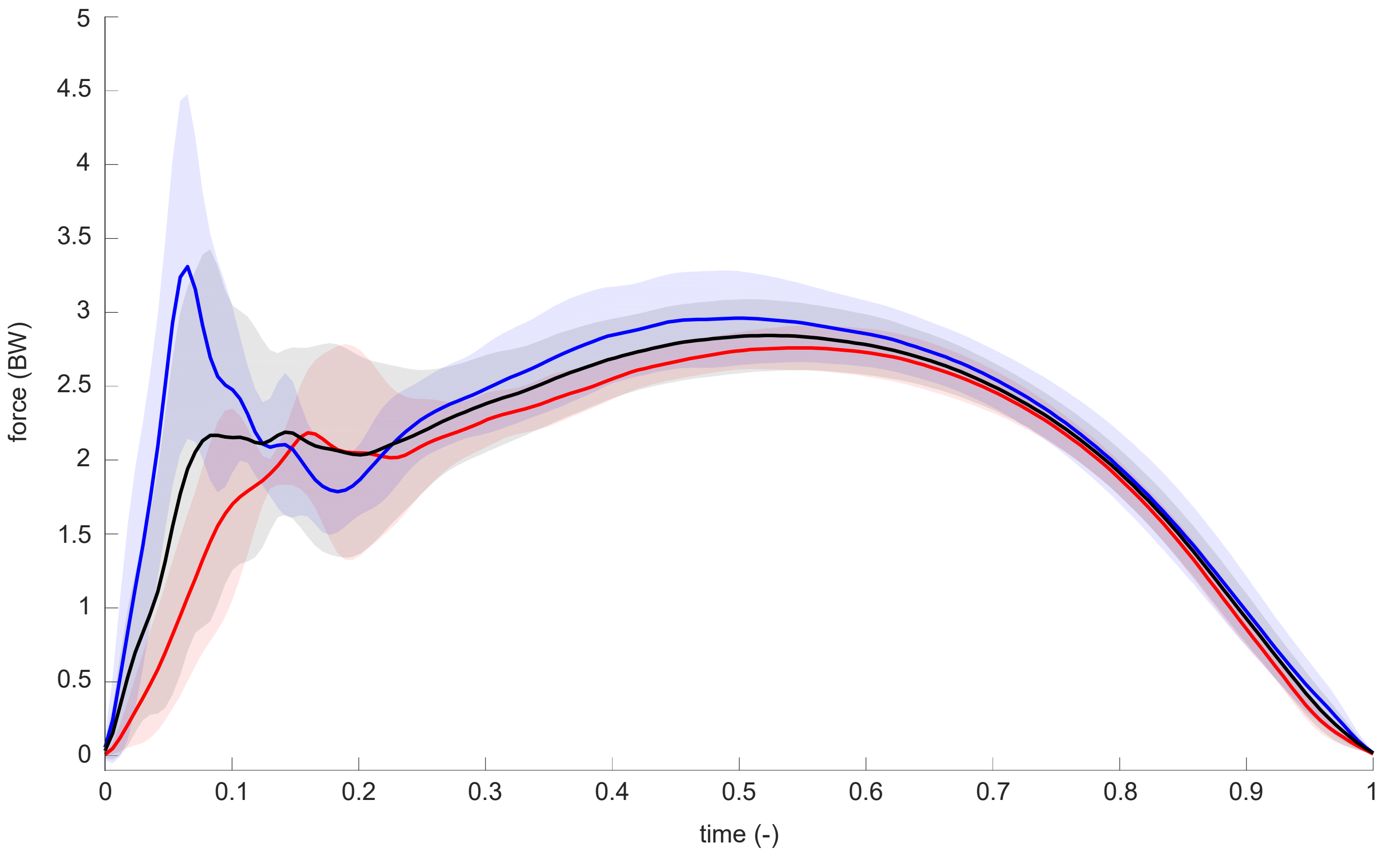
5
4.5
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force (BW)
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