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Movement variability and skill level of various throwing techniques

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ABSTRACT

In team-handball, skilled athletes are able to adapt to different game situations that may lead to differences in movement variability. Whether movement variability affects the performance of a team-handball throw and is affected by different skill levels or throwing techniques has not yet been demonstrated. Consequently, the aims of the study were to determine differences in performance and movement variability for several throwing techniques in different phases of the throwing movement, and of different skill levels. Twenty-four team-handball players of different skill levels ($n = 8$) performed 30 throws using various throwing techniques. Upper body kinematics was measured via an 8 camera Vicon motion capture system and movement variability was calculated. Results indicated an increase in movement variability in the distal joint movements during the acceleration phase. In addition, there was a decrease in movement variability in highly skilled and skilled players in the standing throw with run-up, which indicated an increase in the ball release speed, which was highest when using this throwing technique. We assert that team-handball players had the ability to compensate an increase in movement variability in the acceleration phase to throw accurately, and skilled players were able to control the movement, although movement variability decreased in the standing throw with run-up.

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1. Introduction

In sport games, particularly ball games, game situations continually change during the event, as well as during a particular movement. Skilled athletes are able to adapt to these changing game situations leading to differences in movement variability. In basketball free-throws, Button, MacLeod, Sanders, and Coleman (2003) found that improvement in skill level was associated with increased movement variability to the end of the throw, and that elbow and wrist angle compensated for one another to achieve a consistent outcome. In the golf swing (Bradshaw, Maulder, & Keogh, 2007) and baseball pitch, (Fleisig, Chu, Weber, & Andrews, 2009) variability of selected kinematic parameters decreased from unskilled to skilled athletes. Fleisig et al. (2009) suggested that variability should be reduced to improve performance. In the triple jump (Wilson, Simpson, van Emmerik, & Hamill, 2008) and team-handball throw, (Schorer, Baker, Fath, & Jaitner, 2007) movement variability was consistent with a U-shaped curve depending on the skill level of the athlete. Schorer et al. (2007) and Wilson et al. (2008) found a high variability in low-skilled athletes and a decrease in variability of skilled athletes resulting in a more consistent and regulated performance. In high-skilled athletes, variability increased again (a functional variability that provides flexibility to the system allowing it to cope with perturbations). Several studies have highlighted that movement variability differs depending on the skill level of the athletes and changes during the movement. However, in a complex movement like a team-handball throw, additional research is needed to clarify if movement variability not only differs between different skill levels but also change over the time of the throw. To score goals in team-handball, throwing players must maximize their ball release speed and their throwing accuracy; however, the ball release speed is the main performance factor determining the throwing movement (Fradet et al., 2004; Jöris, Edwards van Muyen, van Ingen Schenau, & Kemper, 1985; van den Tillaar & Ettema, 2004, 2007; Wagner & Müller, 2008). Van den Tillaar and Ettema (2003a) analyzed the influence of instruction on ball release speed and throwing accuracy in team-handball throwing, and found that ball release speed – not the throwing accuracy – differ significantly in experienced team-handball players. The accuracy demonstrated at high ball release speed was high, but difficult to improve when reducing ball release speed. When the instruction emphasized accuracy, ball release speed was approximately 85% of the maximal ball release speed, which indicates that experienced team-handball players are trained to throw accurately at high ball release speed (van den Tillaar & Ettema, 2003a). Comparing novices with experts in team-handball throwing, van den Tillaar and Ettema (2003b) found no speed-accuracy trade-off for both groups. Throwing accuracy in novices, as well as experienced players, did not change when instruction emphasized ball release speed. Between the different skill levels (novices vs. experience), significant differences were found in both ball release speed and throwing accuracy (van den Tillaar & Ettema, 2003a). Comparing elite with skilled players in team-handball throwing, significant differences were found in ball release speed, but not in throwing accuracy (Bayios & Boudolos, 1998; Wagner & Müller, 2008). The studies showed that ball release speed always differ when comparing team-handball players of different skill levels, whereas throwing accuracy differs only when comparing experienced players with novices. Comparing different throwing techniques, Bayios and Boudolos (1998) and Wagner, Pfusterschmied, von Duvillard, and Müller (2011) found that ball release was highest in the standing throw with run-up compared to the standing throw without run-up and jump throw, whereas throwing accuracy did not differ significantly between the throwing techniques.

It is well known that the different throwing techniques (the standing throw with and without run-up and the jump throw) differ in the lower body movements. The standing throw without run-up involves keeping the lead foot on the floor; in the standing throw with run-up, one foot is planted on the floor after run-up; and the jump throw involves executing a vertical jump off one leg at take-off after the run-up. Wagner et al. (2011) found that depending on the floor contact (standing vs. jumping), elite players used two different strategies (lead leg braces the body vs. opposed leg movements during flight) to accelerate the pelvis and trunk to yield differences in ball release speed. In the team-handball jump throw, Wagner, Buchecker, von Duvillard, and Müller (2010a), and in the standing throw, van den Tillaar and Ettema (2004, 2007) found that an increase in trunk flexion and rotation, shoulder flexion and rotation, elbow extension and forearm pronation angular velocity improve the performance in team-handball throws, which should result in an increase of ball release speed. Another aspect that is important to improve ball release speed in team-handball throwing is proximal-to-distal sequencing. In team-handball throwing, proximal-to-distal sequence was defined by the time of occurrence of maximal linear velocities of the segments (Fradet et al., 2004; Jöris et al., 1985; van den Tillaar & Ettema, 2004) or the initiation, as well as the time of occurrence of the maximal joint movements (van den Tillaar & Ettema, 2009; Wagner et al., 2010a), and found to be important to maximize ball release speed. Several researchers have found that the velocity of joint movements (trunk flexion and rotation, shoulder flexion and rotation, elbow extension and forearm pronation) and their timing (proximal-to-distal sequencing) is important to improve performance in team-handball throwing, and that these parameters differ depending on skill levels and throwing techniques. However, whether movement variability affects the performance of a team-handball throw has not yet been demonstrated. Further research is needed to present a comprehensive view on movement variability in the team-handball throwing. Consequently, the aims of the study were to determine differences in performance (ball release speed and throwing accuracy) and movement variability for several throwing techniques and skill levels in different joint movements and phases of the throwing movement. We hypothesized (1) to find significant differences between throwing techniques and skill levels in ball release speed, where the ball release speed is highest in the standing throw with run-up and high skill level; (2) that throwing accuracy would not differ significantly between throwing techniques and skill levels; and (3) that movement variability between different throwing techniques, skill levels and joint movements varies over time.

2. Methods

2.1. Participants

Twenty-four male volunteers participated in our study. All participants were physically healthy, in good physical condition and reported no injuries during the time of the study. Informed written consent was obtained from each participant before testing. The study was approved by the local ethics committee in accordance with the Declaration of Helsinki. Depending on their experience in training and competition, participants were separated into three groups ($n = 8$) of various skill levels:

- Eight low-skilled players (mean age: 19.0 ± 5.2 years (*M* ± *SD*), body weight: 70.4 ± 9.1 kg, body height: 1.75 ± 0.04 m, training experience: 1.6 ± 0.9 years, 7 right-handed and 1 left-handed.
- Eight skilled players from a regional handball team (mean age: 19.1 ± 3.1 years, body weight: 76.4 ± 8.4 kg, body height: 1.84 ± 0.05 m, training experience: 6.6 ± 2.0 years, 7 right-handed and 1 left-handed.
- Eight high-skilled players from the Austrian National Team and Second Austrian Handball League (mean age: 25.3 ± 3.2 years, body weight: 85.6 ± 12.0 kg, body height: 1.85 ± 0.09 m, training experience: 13.4 ± 2.1 years, 7 right-handed and 1 left-handed.

2.2. Test protocol

After a general and a team-handball specific warm up of 20 min, the participants were asked to perform 10 valid standing throws without run-up, 10 standing throws with run-up, and 10 vertical jump throws with their preferred throwing arm. A validation criterion was the correct execution of the 3 throwing techniques. For all throws, the hand had to release the ball while positioned above the head because throwing with the throwing arm beside the trunk is another throwing technique (Wagner, Buchecker, von Duvillard, & Müller, 2010b) and would influence movement variability. The standing throw had to be completed with the left (right) foot in front for the right (left) handed players and in the standing throw with run-up and jump throw 3 steps were defaulted. In the jump throw, take-off had to be executed with the left (right) foot for the right (left) handed players. The criteria were controlled by an elite team-handball coach, whereas all participants were able to comply with the validation criteria for all throws. The order of the 3 throwing techniques was randomized for each participant and the throwing technique was changed after 5 valid throws to prevent a learning effect that could influence movement variability. Between trials, players rested for 1 min. This procedure ensures that the results were not influenced by fatigue. The instruction for each trial was to throw the ball (IHF Size 3) at a target of 8 m distance and to strike the center of a square of 1×1 m at about eye level (1.75 m) with maximum ball release speed and accuracy. The center of the square (defined as the midpoint) was clearly visible and marked with a large cross. To eliminate obvious mistakes (Latash, Scholz, Danion, & Schöner, 2001), we used only those throws (valid throws) that struck the target. This continued until 10 valid throws for each throwing technique for each participant were accomplished and recorded. On average, participants performed 12 ± 1 throws to achieve 10 valid throws.

2.3. Kinematic analysis

The experimental set-up consisted of an 8 camera Vicon MX13 motion capture system (Vicon Peak, Oxford, UK), capturing at 250 Hz. The sampling frequency of 250 Hz was chosen because this frequency allows the maximal resolution of 1.3 megapixels for the cameras (resolution decreases if the sampling frequency increases) and that the velocities (angular velocities and ball release speeds) could be measured accurately (Wagner et al., 2010a). For kinematic analysis, 39 reflective markers with a diameter of 14 mm were affixed to specific anatomical landmarks (Plug-In Gait Marker Set, Vicon Peak, Oxford, UK) for every participant. Three-dimensional trajectories of 39 markers were analyzed utilizing Nexus software (Nexus 1.3, Vicon, Oxford, UK). The raw data were filtered with a quintic spline filter (MSE = 10) (Woltring, 1986) (also utilized in dynamic movements like the volleyball spike jump (Tilp, Wagner, & Müller, 2008) and tennis ground strokes (Landlinger, Lindinger, Stöggl, Wagner, & Müller, 2010)). To calculate the joint positions, a 3D-model (Plug-In Gait Model, Vicon Peak, Oxford, UK) was used (Davis, Õunpuu, Tyburski, & Gage, 1991). The model was identical to that of Wagner et al. (2010a), who analyzed the jump throw in team-handball.

For joint angle calculation, we used the same method as described by Wagner et al. (2010a). Joint angles were calculated by the relative orientation of the proximal and distal segments. The joint flexion angles (shoulder and elbow flexion) were the angles determining the longitudinal axes of the proximal and distal segments. The shoulder internal-external rotation angle was defined as the rotation of the humerus along the longitudinal axis of the humerus. The forearm pronation-supination was calculated between the sagittal axis of the hand and the sagittal axis of the radius. Trunk rotation angle was defined as the rotation between the sagittal axis of the trunk and the sagittal axis of the measuring field. The trunk flexion angle was calculated between the projected sagittal trunk axis and the sagittal axis of the measuring field. Angular velocities and ball release speed were calculated using the 5-point central differential method (van den Tillaar & Ettema, 2003b). To determine the ball release point, the distance between the center of the ball and the finger of the throwing arm was calculated. This distance increased abruptly at ball release (van den Tillaar & Ettema, 2007; Wagner et al., 2010a). To compare the difference between the different throws, all throws were normalized to ball release and were cut 360 ms (90 frames) pre, and 40 ms (10 frames) post ball release (400 ms or 100 frames totally). This procedure allowed for detection of all relevant information (cocking, acceleration and deceleration) of the throws (Wagner et al., 2010a).

2.4. Movement variability

To determine movement variability, we calculated the standard deviation on a point-by-point basis over the vector lengths of the normalized $[-1,+1]$ trunk (flexion and rotation), shoulder (flexion and rotation), elbow (flexion) and forearm pronation angle-angular velocity cycle (Hamill, Haddad, & McDermott, 2000). The advantage of this method is that data could be reduced without the loss of important information. Furthermore, comparisons could be made (although the peak values changed because of normalization) and the entire movement could be analyzed. An example of the angle-angular velocity phase angles (Fig. 1A) and the normalized angle-angular velocity phase angles (Fig. 1B) of the internal shoulder rotation in the standing throw with run-up of a selected participant are depicted in Fig. 1. Angles were normalized as follows:

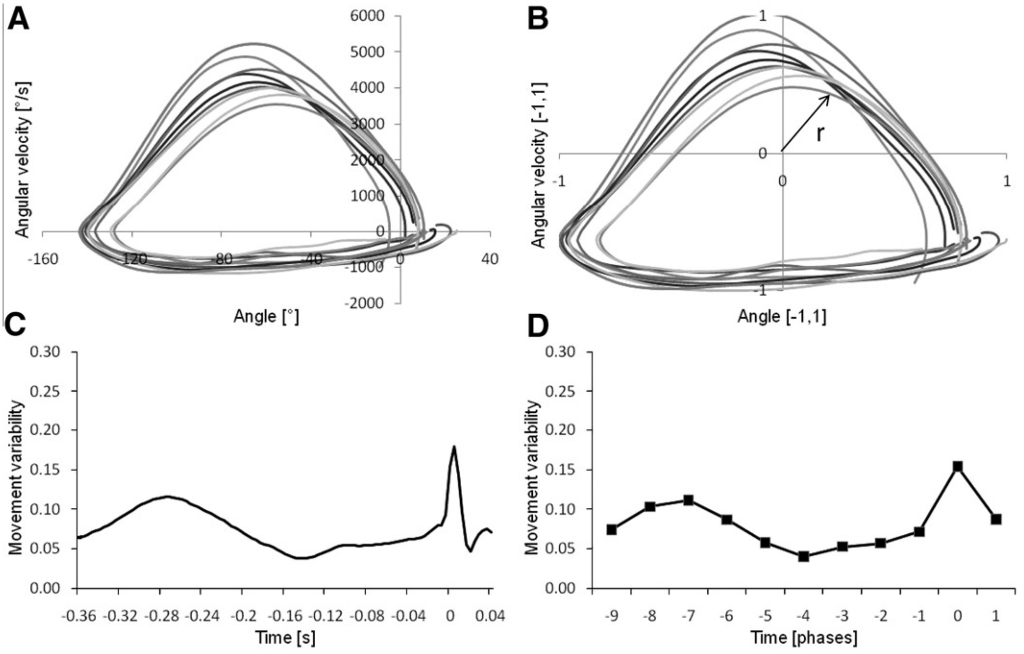

Fig. 1. Example of angle-angular velocity phase angle (A), normalized angle-angular velocity phase angle (B), movement variability (C) and mean movement variability (D).

$$\text{Angle}: \varphi_{norm} = \frac{2\varphi - (\varphi_{max} + \varphi_{min})}{\varphi_{max} - \varphi_{min}}$$

Where φ_{max} (φ_{min}) was the maximal (minimal) angle within the complete cycles of 10 throws of one participant and one throwing technique. Angular velocities were normalized as follows:

$$\text{Angular velocities}: \omega_{norm} = \frac{2\omega - (\omega_{max} + \omega_{min})}{\omega_{max} - \omega_{min}}$$

where ω_{max} (ω_{min}) was the maximal (minimal) angular velocity within complete cycles of 10 throws of one participant for each throwing technique. Vector length of the normalized angle-angular velocity phase angle (Fig. 1B) was calculated as follows:

$$\text{Vector length}: r = \sqrt{\varphi_{norm}^2 + \omega_{norm}^2}$$

Movement variability was then calculated as the standard deviation of the vector length for each of the 10 throws and for each throwing technique (Fig. 1C). For computation of the data based on the movement variability at ball release (mv_0), we calculated the mean movement variability post ball release (mv_1) and pre ball release (mv_{-9}, mv_{-8}, ..., mv_{-1}), in steps of 40 ms or 10 frames (Fig. 1D). This procedure was repeated for all analyzed joints, participants, and throwing techniques.

2.5. Variability of spatial-temporal parameters

A disadvantage of calculating movement variability by normalized angle-angular velocity cycles is that it could not be differentiated between the spatial and temporal origins of movement variability. Consequently, we also calculated the variability of spatial-temporal parameters (which were defined as the standard deviation of the maximal and minimal angles and angular velocities (trunk flexion and rotation, shoulder flexion and rotation, elbow flexion, and forearm pronation)) and their timing within all throws of a participant (Button et al., 2003; Fleisig et al., 2009). Timing was calculated as the difference (in seconds) in the time of occurrence of the maximal (or minimal) angles (or angular velocities) to ball release, whereas timing was defined negative pre and positive post ball release (Wagner et al., 2010a).

2.6. Statistical analysis

Statistical analysis was conducted using SPSS ver. 16.0. (SPSS Inc., Chicago, IL). For descriptive analysis, we calculated the mean movement variability for each group (low-skilled, skilled and high-skilled players) separated into the different joints and throwing techniques as shown in Figs. 3 and 4. To determine significance between group and throwing technique differences in ball release speed and number of rejected throws, a two-way ANOVA was used with skill level (low-skilled, skill, high-skilled) and throwing technique (standing throw with and without run-up and jump throw) as the main factors. According to Cohen (1988), the effect size (η^2) was calculated and was defined as small for $\eta^2 > .01$, medium for $\eta^2 > .09$, and large for $\eta^2 > .25$. To determine the variability over time between skill levels, joint movements, and throwing techniques, a repeated measures MANOVA was used with time (t_{-9}–t_{-1} before ball release, t_0 at ball release, t_1 after ball release), skill level (low-skilled, skilled, and high-skilled), joint movements (trunk, shoulder and elbow flexion, trunk and shoulder rotation, and forearm pronation) and throwing technique (standing throw with and without run-up and jump throw) as the main factors. If a significant effect for the main factors or for the interaction between two or more factors were found, additional two-way ANOVA was calculated to determine individual effects. To determine the variability of spatial-temporal parameters, additional MANOVAs were calculated with the main factor skill level for each throwing technique separated in angles, angular velocities and their timing. For two-way ANOVA and repeated measures MANOVA, we used the Bonferroni-post-hoc test.

3. Results

3.1. Throwing performance

The two-way ANOVA (throwing technique and skill level as main factors) revealed significant differences in the ball release speed between the three throwing techniques, $F(30.54,\ 1.45 = 79.57$, $p < .001$, $\eta^2 = .79$, and skill levels, $F(21, 2) = 17.62$, $p < .001$, $\eta^2 = .63$, as well as an interaction in Throwing Technique × Skill Level, $F(30.54, 2.91 = 3.36$, $p < .05$, $\eta^2 = .24$. As shown in Fig. 2A, not only did ball release speed increase from standing throw without run-up to standing throw with run-up, but also it increased based on the participant's skill level. Post hoc tests revealed that significant differences were found solely between low-skilled and the other two skilled levels, as well as between standing throw without run-up and the other two throwing techniques. The Throwing Technique × Skill Level interaction could be explained by the fact that in high-skilled and skilled levels, the ball release speed increased in the standing throw without run-up compared to the jump throw, whereas in the low-skilled level, ball release speed decreased from jump to the standing throw without run-up. The calculated effect sizes indicated that both throwing technique and skill level considerably affect ball release speed. No significant effects were found between throwing techniques and skill levels. In addition, no Throwing Technique × Skill Level interactions were found for the percentage of missed throws that ranged from a mean of 15% to 26% as shown in Fig. 2B. In the testing situation, the difference in the percentage of missed throws was not significant. Furthermore, the skill level and throwing technique had only a small effect on the percentage of missed throws.

3.2. Movement variability

The mean movement variability for each skill level over time separated in the different throwing techniques and measured joints, is shown in Figs. 3 and 4. For better understanding, details of joint angle calculations and skeleton figures of key points during throwing were added to both Figs. 3 and 4.

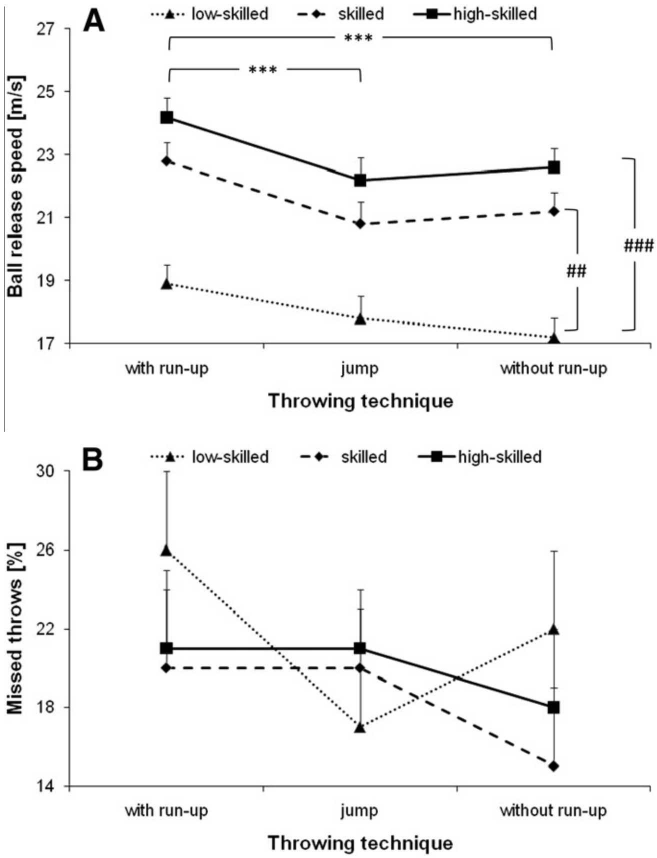

Fig. 2. Mean (+ standard error) ball release speed (A) and percentage of missed throws (B) in different throwing techniques and skill levels ($*$: $p < .05$, $**$: $p < .01$, $***$: $p < .001$ between skill levels; #: $p < .05$, ##: $p < .01$, ###: $p < .001$ between throwing techniques).

Repeated measures MANOVA was conducted on movement variability for the factors time (9 points before ball release, 1 at ball release, 1 after ball release), skill level (low-skilled, skilled, and high-skilled), joint movements (trunk, shoulder and elbow flexion, trunk and shoulder rotation, and forearm pronation) and throwing technique (standing throw with and without run-up and jump throw). There was a significant effect for the factor time, $F(1507, 3.99) = 53.46$, $p < .001$, $\eta^2 = .12$, and for the between Time $\times$ Joint Movement, $F(1507, 19.94) = 7.22$, $p < .001$, $\eta^2 = .09$ (Fig. 5), Time $\times$ Skill Level, $F(1507, 7.97) = 2.29$, $p < .05$, $\eta^2 = .01$ (Fig. 6), and Time $\times$ Joint Movement $\times$ Skill Level, $F(1507, 38.87) = 1.82$, $p < .01$, $\eta^2 = .05$, interactions. Bonferroni pair wise test comparison revealed significant differences in the movement variability from t_{-6} to t_{-5} (decrease) and t_{-2} to t_0, at ball release (increase) as shown in Fig. 6. Medium effect size ($\eta^2 > .09$) was found for the factor time and small effect size ($\eta^2 > .01$) for the interaction of Time $\times$ Joint Movement, Time $\times$ Skill Level and Time $\times$ Joint Movement $\times$ Skill Level. Additional two-way repeated measures ANOVA with the main factors "time" and "skill level" for each joint movement and throwing technique indicated that 13 out of 18 kinematic variables revealed significant effects over time for all groups ($p < .05$, $\eta^2 > .17$). No significant effects for the factor time were found for the trunk flexion, elbow flexion, and trunk rotation in the standing throw with run-up, for the trunk rotation in the jump throw and for the elbow flexion in the standing throw without run-up (Figs. 3 and 4).

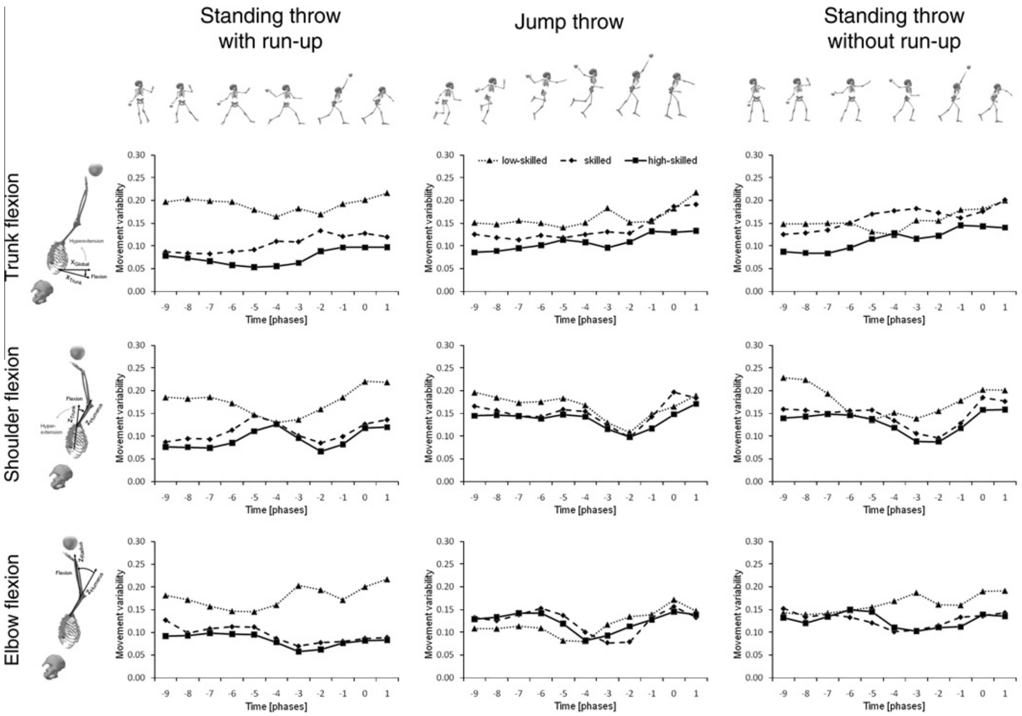

Fig. 3. Mean movement variability of the trunk, shoulder and elbow flexion in the standing throw with and without run-up and jump throw.

Repeated measures MANOVA also revealed a significant effect for the factor joint movement, $F(378,5) = 2.50$, $p < .05$, $\eta^2 = .03$, skill level, $F(378, 2) = 18.47$, $p < .001$, $\eta^2 = .09$, throwing technique, $F(378, 2) = 3.84$, $p < .05$, $\eta^2 = .02$, and the Throwing Technique × Skill Level interaction, $F(378, 4) = 3.58$, $p < .01$, $\eta^2 = .04$, Fig. 7). Bonferroni pair wise comparison revealed significant differences in the movement variability between trunk rotation and forearm pronation (Fig. 5), between low-skilled, skilled, and high-skilled level players (Fig. 7) and between standing throw with and without run-up (Fig. 7). A medium effect size was found for the factor skill level ($\eta^2 > .09$) and a small effect size ($\eta^2 > .01$) for the factor joint movement, throwing technique, and the interaction between throwing technique and skill level. The Throwing Technique × Skill Level interaction could be explained by the decrease in movement variability in the standing throw with run-up in comparison to the standing throw without run-up and jump throw in skilled and high-skilled level players (Fig. 7), whereas movement variability increased in the standing throw with run-up in the low-skilled players. The interaction in the Time × Joint Movement was mainly due to the increase in movement variability at and after ball release in the forearm pronation (Fig. 5), whereas the movement variability was quite constant over time in the trunk rotation.

3.3. Variability of spatial-temporal parameters

Twelve MANOVAS, differentiated in the variability of maximal and minimal angles, as well as angular velocities and their timings for each throwing technique with the factor skill level were calculated. A significant effect for the factor skill level was solely found for the variability of the maximal/minimal angular velocities, $F(2, 20) = 2.31$, $p < .05$, $\eta^2 = .74$, and the timing of the maximal/minimal angular velocities, $F(2, 20) = 2.53$, $p < .05$, $\eta^2 = .75$, in the standing throw with run-up.

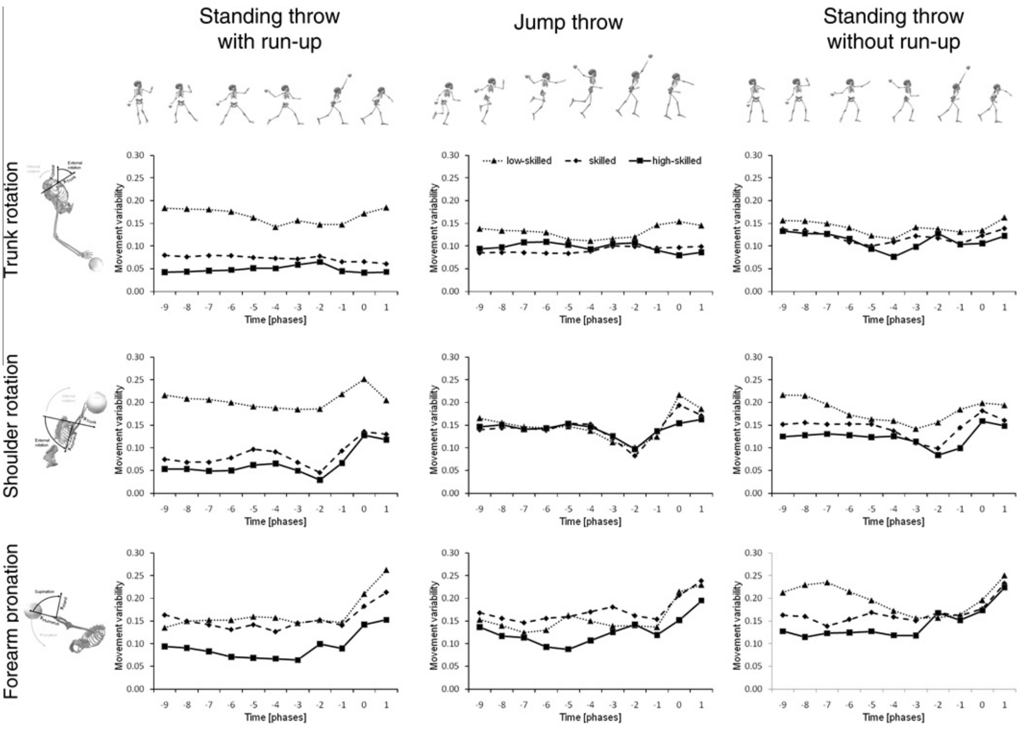

Fig. 4. Mean movement variability of the trunk, shoulder rotation, and forearm pronation in the standing throw with and without run-up and jump throw.

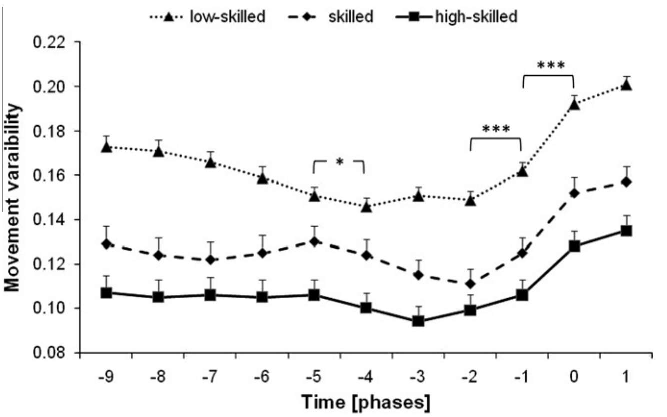

Fig. 5. Mean (+ standard error) movement variability in different skill levels over time (interaction Skill Level × Time). Mean movement variability was calculated as the mean value of the participants ($n = 8$) within a skill level (low-skilled, skilled, high-skilled) separated in the 11 different phases (t_{-9}–t_1) of the throw (∗: $p < .05$, ∗∗∗: $p < .001$ between t_n and t_{n-1}).

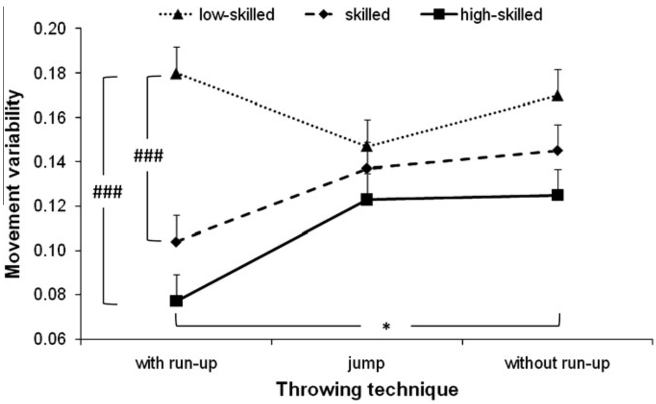

Fig. 6. Mean (+ standard error) movement variability in different skill levels and throwing techniques (interaction Skill Level × Throwing Technique). Mean movement variability was calculated as the mean value of the participants ($n = 8$) within a skill level (low skill, skill, high skill) separated in the 3 different throwing techniques (standing throw with run-up, jump throw, standing throw without run-up) (∗: $p < .05$ between throwing techniques; ###: $p < .001$ between skill levels).

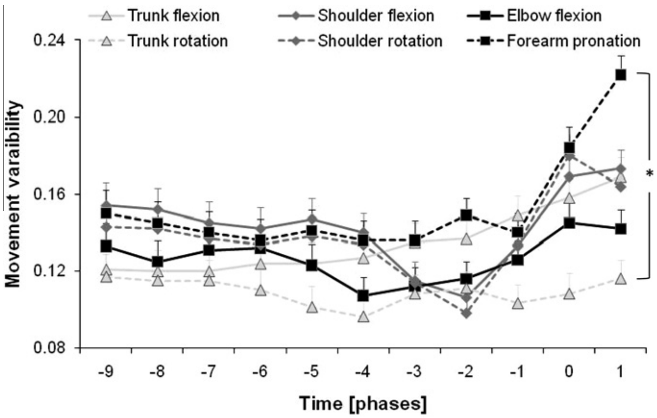

Fig. 7. Mean (+ standard error) movement variability in different joint movements over time (interaction joint movements × time). Mean movement variability was calculated as the mean value for all participants for the different joint movements (trunk, shoulder, elbow flexion, trunk, shoulder rotation, and forearm pronation) separated in the 11 different phases (t_{-9}–t_1) of the throw (∗: $p < .05$ between forearm pronation and trunk rotation).

4. Discussion

The aim of the study was to determine differences in performance and movement variability for several throwing techniques in different phases of the throwing movement, different joint movements and different skill levels.

Bayios and Boudolos (1998) and Wagner et al. (2011) found significant differences in ball release speed between standing throws with and without run-up and jump throws, while Wagner et al. (2010a) reported differences between elite and low-skilled players in team-handball jump throw. As expected, significant differences in the throwing techniques and skill levels were also observed in the current study. Ball release speed was highest in the standing throw with run-up and in high-skilled athletes (Fig. 2A). Analyzing the movement variability during throwing, it was surprising to find a Throwing Technique × Skill Level interaction that revealed similar movement variability in the different skill levels during the jump throw and standing throw without run-up, yet the results showed a decrease in movement variability in the high-skilled and skilled athletes in comparison to an increase in movement variability in the low-skilled athletes during the standing throw with run-up (Fig. 7). Since these differences were found only in the standing throw with run-up, we postulate that the increase in ball release speed explains these differences in the movement variability. In team-handball throwing, Ilmane and LaRue (2008) found that movement variability decreases if the movement velocity increases. In the present study, this decrease in movement variability is due to a decrease in the variability of the maximal/minimal angular velocities and their timing, and not due to the maximal/minimal angles and their timing corresponding to the whole movement (Figs. 3 and 4). Differences in the movement variability were found solely in the dynamic parameters due to an increase in the ball release speed in team-handball throwing (van den Tillaar & Ettema, 2004, 2007; Wagner et al., 2010a, 2011). We suggest that skilled team-handball players have to learn to control the movement (to hit the target), although ball release speed is extremely high and the movement variability (variability of dynamic parameters) decreases. The ability to control the movement under these conditions might be associated with much experience in team-handball throwing (in the present study high-skilled and skilled players had on average 8 years more training experience than low-skilled players).

The results of measuring throwing accuracy indicated that the percentage of missed throws did not differ between skill levels and throwing techniques. Low-skilled, as well as skilled and high-skilled level players, were able to strike the target frequently, utilizing all throwing techniques (Fig. 2B). The mean percentage of missed throws ranged from 15% to 26%. These results are in agreement with recent studies in team-handball (Bayios & Boudolos, 1998; van den Tillaar & Ettema, 2003b; Wagner et al., 2010a) that found no speed-accuracy trade-off in team-handball throwing. Both high-skilled and low-skilled players were able to throw accurately, but with different ball release speeds that increased with skill level. In the context of this study, it must be mentioned that testing conducted during this study did not reflect numerous situations that are invoked on players during actual team-handball competition. To score a goal in competition, team-handball players throw the ball at the side or above the defensive block player to an area of the goal where the goalkeeper is not able to defend the goal area. These playing situations are quite different from the ones that were conducted in this study, where a performer was asked to throw at a target as required by the testing protocol. It is possible that throwing accuracy that is similar between the different skill levels and throwing techniques during testing may be quite different in team-handball competition. This is a limitation of our study that is similar to recent studies reported on team-handball throwing (van den Tillaar & Ettema, 2003a, 2003b, 2006; Wagner et al., 2010a). However, we wish to convey that ball release speed in the testing situation is similar to ball release speed in competition. The absence of the speed-accuracy trade-off in the present study that is typical for team-handball throws necessitated another interpretation of movement variability as in goal-orientated throwing tasks like basketball (Button et al., 2003) or dart throwing (Etnyre, 1998; Gross & Gill, 1982; Müller & Loosch, 1999). It was not the question of how differences in movement variability explain differences in the throwing accuracy, it was the question of how differences in movement variability explain the ability to throw just as accurately when the ball release speed significantly increases.

We hypothesized that skilled team-handball players change their movement variability over the time of the throw. As expected, 13 out of 18 kinematic variables revealed effects over time (Figs. 3 and 4) for all groups. As shown in Fig. 6, movement variability increased in the acceleration phase (t_{-2}–t_0) at the end of the movement before ball release. It was interesting that this increase in movement variability was found in the distal joints (shoulder flexion and rotation and forearm pronation), but not in the proximal joints (trunk flexion and rotation) (Figs. 3 and 4). This difference in movement variability between proximal and distal joints also was supported by the Time × Joint Movement interaction. In the team-handball throw, energy was transferred from proximal to distal that led to an increase of velocity in the distal joint movements (van den Tillaar & Ettema, 2004, 2009; Wagner et al., 2010a). High angular velocities in the shoulder flexion, shoulder internal rotation, elbow extension, and forearm pronation in the acceleration phase are necessary to reach a high ball release speed (van den Tillaar & Ettema, 2004, 2007; Wagner et al., 2011). The ability to throw the ball accurately was not significantly different between skill levels and throwing techniques in the present study; however, it was necessary to release the ball at the right time (to hit the target), even though the joint angular velocities were high, especially in the skilled and high-skilled participants. Wagner et al. (2010a) found significant differences in ball release speed, as well as maximal joint angular velocities, between elite and less experienced players. In goal orientated tasks (Button et al., 2003; Müller & Loosch, 1999; Müller & Sternad, 2004) higher release velocities were compensated with higher movement variability (functional variability). In table tennis forehand drives, Bootsma and van Wieringen (1990) found an increase in movement variability in the acceleration phase, and stated that consistent performance outcomes were achieved by the ability that variations in one execution parameter were compensated by appropriate variations in other execution parameters (compensatory coordination). We suggest that low-skilled, skilled and high-skilled athletes have the ability to compensate the increase in movement variability in the acceleration phase (t_{-2}–t_0) in the distal joint movements to throw accurately. However, in the present study we also found a decrease in the movement variability (t_{-6}–t_{-5}) that could be due to the reversal of cocking to acceleration (extension-flexion and external-internal rotation).

5. Conclusion

Movement variability in various throwing techniques and skill levels in team-handball were analyzed and indicate: (1) significant differences between the throwing techniques and skill levels based solely on ball release speed, not on throwing accuracy (lack of speed-accuracy trade-off); (2) an increase of movement variability in the acceleration phase; and (3) a decrease in movement variability of high-skilled and skilled players in the standing throw with run-up where ball release speed was greatest. We concluded that all participants had the ability to compensate the increase in movement variability during the acceleration phase of the distal joint movements, and that skilled players were able to control the movement, although movement variability decreased in the standing throw with run-up to throw accurately. The velocity–variability interaction found in this study may contribute to a better understanding of motor coordination of complex movements and warrants further investigation.

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