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Comparison of throwing kinematics and muscle activation of female elite handball players with and without pain – the effect of repeated maximal throws

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ABSTRACT

Shoulder pain is common in team handball; however, many continue playing. The purpose was to investigate whether a functional fatigue protocol (FFP) containing repeated sub and maximal standing throws affects throwing performance, upper body kinematics, muscle peak activation (MPA) and whether the effect was different between the players playing with or with no pain. Thirty female elite handball players performed five maximal standing throws before and after the FFP. Throwing velocity, throwing kinematics, and MPA were measured before and after the FFP. An increased ball velocity ($p = .02$) was found, but only the total throwing time increased significantly in pain group ($p = .05$). Fatigue also resulted in a larger maximal pelvis ($p = .03$) and trunk rotation ($p = .03$) in addition to an increased shoulder flexion at ball release in both groups ($p = .03$), but only the maximal external ($p = .03$) and internal shoulder rotation ($p = .05$) increased in the pain group. Furthermore, fatigue also affected MPA in the latissimus dorsi ($p = .02$) and infraspinatus ($p = .01$). It was concluded that fatigue influenced throwing performance, kinematics, MPA and timing, which may increase the risk of developing non-traumatic shoulder injuries in team handball. The information may help to understand how fatigue influences throwing kinematics and MPA in players playing with pain.

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KEYWORDS
Throwing kinematics; team handball; fatigue; shoulder pain; risk factors

Introduction

Shoulder pain is common in team handball. Several studies have reported incidence of shoulder injuries of 9–58 %, and 44–75% of all athletes have a history of shoulder pain (Andersson et al., 2018; Asker et al., 2018; Forthomme et al., 2018; Moller et al., 2012;

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Myklebust et al., 2013). However, often players will continue playing handball despite experiencing pain (Clarsen et al., 2014; Myklebust et al., 2013). Risk factors for developing shoulder pain have been reported as decreased glenohumeral (GH) range of motion (ROM), shoulder muscle strength (Byram et al., 2010; Edouard et al., 2013; Trakis et al., 2008; Tyler et al., 2014), and scapula control (Kibler et al., 1996; Laudner et al., 2006; Myers et al., 2013). None of the studies have investigated the kinematics of throwing alone, as a possible risk factor for shoulder injury, where a non-optimal throwing technique is anticipated to increase load on the structures in the shoulder.

An overhead throw is an open kinetic chain, which involves a combination of joints in the entire body to generate an explosive movement (Alizadehkhaiyat et al., 2015; Ettema et al., 2008; van den Tillaar & Ettema, 2009). The timing of the body segments and joints is important to maximise the velocity of the ball. A handball throw is registered to last only approximately 0.76 s (van den Tillaar & Ettema, 2003, 2006). In less than a second, the ball is accelerated to more than 100 km/h, and the structures (muscles/ligaments) must create a dynamic joint stability to protect the shoulder joint from injury during this short period (Dillman et al., 1993; Meister, 2000). The most effective technique of throwing has been shown to be the transfer of momentum from a proximal-to-distal sequence (Wagner, Pfusterschmied, Klous, et al., 2012; Whiting et al., 1991), where the momentum from the pelvis is transferred to the trunk and further to the arm. However, several studies have shown that team handball players with no pain do not utilise the sequence in the final part of the throw, and where maximal angular velocity of the elbow extension and wrist occurs before shoulder internal rotation angular velocity (Laver et al., 2018; van den Tillaar & Ettema, 2009; Wagner, Pfusterschmied, Klous, et al., 2012; Wagner, Pfusterschmied, Von Duvillard, et al., 2012).

During handball training sessions and matches, numerous maximal and submaximal throws may fatigue the shoulder (Almeida et al., 2013; Michalsik et al., 2015). Fatigue has been identified to reduce force capacity required for a specific task (Bigland-ritchie & Woods, 1984; Madigan & Pidcoe, 2003; Vollestad, 1997). Furthermore, previous studies have shown that fatigue has a negative effect on muscle activation, muscle peak, muscle proprioception, movement coordination, and precision (Madigan & Pidcoe, 2003; Sanna & O'Connor, 2008; Small et al., 2008). Fatigue and pain affect the function of the muscles around the shoulder (Pellegrini et al., 2013), and pain during shoulder elevation often creates kinematic patterns, which may worsen an existing pathological condition in the shoulder (Jobe et al., 1989; Laudner et al., 2013; Tripp et al., 2004; Wagner, Pfusterschmied, Von Duvillard, et al., 2012). Furthermore, changes were found in the kinematics of the humerus and scapula, and the neuromuscular activation pattern of the muscles, after fatigue in baseball pitchers following a match session (Murray et al., 2001). It is currently unknown how fatigue affects throwing performance and throwing kinematics in team handball during training and matches. Moreover, it is unknown whether fatigue affects kinematics and muscle activity more in elite handball players with shoulder pain than those without pain.

Therefore, the purpose of this study was to investigate whether fatigue affects overhead throwing biomechanics and muscle activation differently in team handball players with shoulder pain compared with those without shoulder pain. It is hypothesised that fatigue affects throwing kinematics and muscle activity. Furthermore, that differences between the groups would be found in patterns to avoid pain during throwing (Jobe et al., 1989; Laudner et al., 2013). Such information is important to improve knowledge of the underlying mechanisms of developing shoulder pain and how to prevent incidences of shoulder pain during team handball.

Materials and methods

Participants

Thirty female elite handball players volunteered to participate in the study, comprised of 15 players with pain (aged 22.2 ± 2.9 years; height 1.76 ± 0.07 m; weight 73.8 ± 9.7 kg) and 15 players with no pain (20.4 ± 2.6 years; 1.72 ± 0.05 m; 66.9 ± 3.9 kg). All the participants had played handball for 13.8 ± 3.1 years and been professional for 2.2 ± 5.5 years. Both groups trained in handball 6.2 ± 1 and specific prophylactic 1.2 ± 1 sessions per week. The players were recruited from the best three leagues in Denmark and from the best league in Sweden.

Inclusion and exclusion criteria

In total, 15 clubs received an invitation to participate in the study. Forty-three players replied to a questionnaire regarding pain, training and match exposure, and injury history. Of these, 13 were excluded due to: Traumatic shoulder injuries ($n = 2$), no suitable time for the test session ($n = 4$), referred to further clinical examination ($n = 2$), post-operative conditions in the shoulder and other injuries ($n = 2$), limiting their overhead throw (Torabi et al., 2022). All participants were a minimum of 18 years old and right-handed. To be included, the players were required to take active part in both the offensive and defensive part of the game during match, as well as during training. Furthermore, the players had to train in handball for a minimum of three times every week. The players were excluded from the study if: not participating in match within the past 6 weeks, or had a traumatic shoulder event or a shoulder surgery (Torabi et al., 2022). A sample size calculation, based on previous studies on fatigue by Nuño et al. (2016) and a shoulder biomechanics study by Plummer and Oliver (2017), showed that 12–14 participants in each group were needed to create a power of 0.80 and an alpha at 0.05. In total, 30 female elite handball players were included in the study, with 15 players per group.

The presence of pain was established through the validated Oslo Sports Trauma Research Center (OSTRC) questionnaire (Clarsen et al., 2015; Jorgensen et al., 2016). Furthermore, an interview by a physical therapist was carried out to determine whether the shoulder pain was non-traumatic. Participants in the non-pain group had to report no presence of shoulder pain within the past 6 months, while participants included in the pain group, had to report pain being present for a minimum of 4 weeks (Torabi et al., 2022).

Procedures

The players were instructed not to participate in handball training and strength training 24 h before the test. After a standardised handball-specific warm-up and throwing drills, throwing performance was tested by five maximal standing throws with approximately 1-min pause between each throw. The participants were instructed

Figure 1. Test setting of shoulder kinematics and muscle activity during maximal overhead throwing.

to perform an overhead throw, where the starting position was standing still with the contralateral leg and the ball in front of the body. The throw should be at maximal speed and target an area of a 1 × 1 m net from a position of 7 m distance (Figure 1). A speedometer (Speedtrac X Radar Gun) was placed behind the net to collect data on throwing speed. The throw was performed with a women's team handball ball (375 g, 56 cm diameter).

The functional fatigue protocol (FFP)

After the five maximal throws, a functional fatigue protocol (FFP) was conducted. The purpose of the FFP was to simulate a fatigue situation as in training and match sessions, which was evaluated in a pilot study by Bencke et al. (2016). After the first five maximal throws, a range of 75–85% of the maximal throwing velocity was calculated, and the FFP was initiated. The FFP included six rounds of 10 throws containing; First five throws of 75–85% of the pre-calculated maximal throw velocity followed by five throws with the maximal effort throwing velocity of the player (90–100%). The recovery time between each 10 throws was 1 min, and within the period of 10 throws the recovery time was not fixed (but less than 20 s), and got adjusted to when the player was ready to throw again.

Rate of perceived exertion (RPE) was assessed after every 10 throws with the Borg CR-10. The last five maximal throws were captured directly after the last throw within the FFP session. The FFP would stop before 60 throws if the player reported a 10 (maximal fatigued) on the Borg scale. At all times, participants were allowed to stop the FFP if the pain was worse than usual or they felt any other discomfort, which nobody did (Bencke et al., 2016)

Measurements

Eight infrared Vicon T40 cameras (Vicon Motions Systems Ltd., Oxford, UK) were used to measure joint movement and angular velocities. They were placed 2–6 m from the team handball player. All motion capture data and electromyography (EMG) data were collected synchronously using inherent software (Nexus 2.9, Vicon Motions Systems). Twenty-three 14 mm reflex markers (Figure 2) were placed on anatomical landmarks within the pelvis, thorax, scapula, brachium, antebrachium, and hand. They were placed in accordance with the recommendations of the International Society of Biomechanics (Torabi et al., 2022; Wu et al., 2005).

The position of the markers was obtained with a camera frequency of 200 Hz, raw data were filtered by a Butterworth filter with a cut-off frequency of 200 Hz, and their positions were used to define a local coordinate system (LCS) for each segment. To define/calculate the glenohumeral joint centre a trial containing 10 × circumduction, flexion/extension, and abduction/adduction of the arm was performed. Together with the LCS of the scapula and the LCS of the upper arm, the ScoRE method was used, as

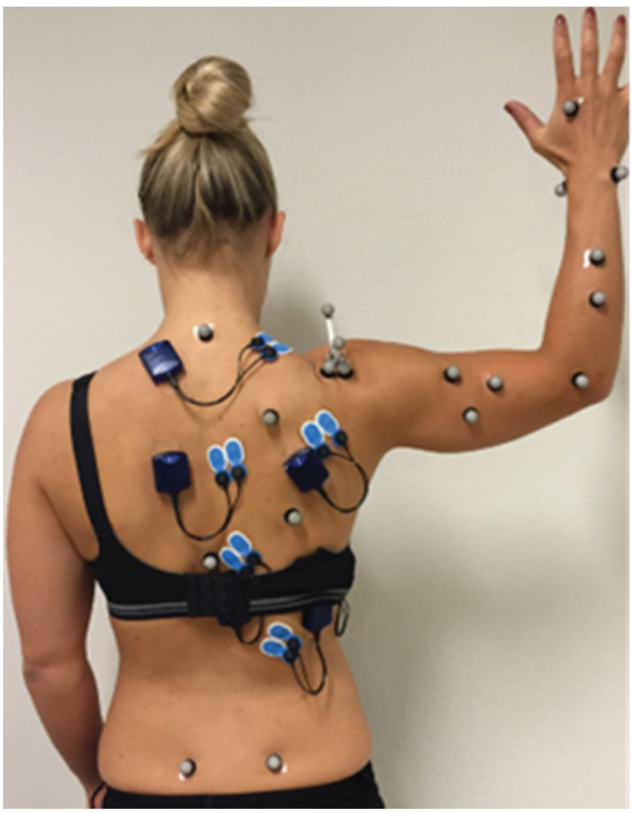

Figure 2. Position of marker settings and EMG.

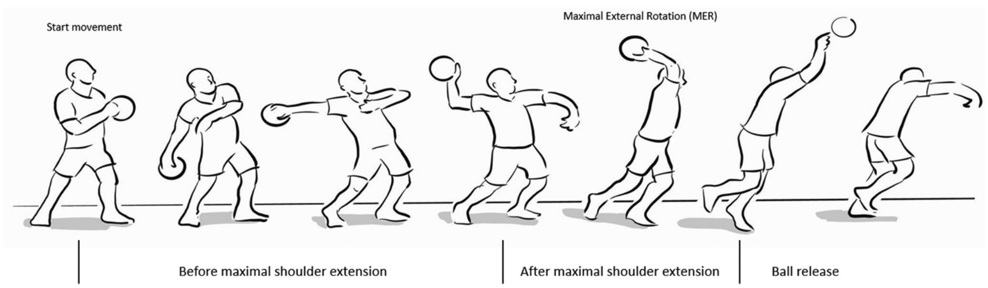

Figure 3. The phases of the standing throw.

described by Monnet et al. (2007). The principles, described by Wu et al. (2005), were that joint angles were calculated using a custom-made script in Matlab© and Bodybuilder (Vicon Motion Systems Ltd., Oxford, UK) in 3-degrees-of-freedom for the shoulder, pelvis, and trunk, and in 2-degrees-of-freedom for the wrist and elbow. Joint angles and muscle activation patterns were reported in relation to the instant of ball release. The instant of ball release was estimated as time of maximal wrist velocity and defined as time zero (van den Tillaar & Cabri, 2012; van den Tillaar & Ettema, 2009).

The throwing motion was divided into three phases (Figure 3). The initiation of the throw was defined as the beginning of the pelvis forward rotation. The kinematics and muscle peak activation patterns were measured before and after maximal shoulder extension.

Electromyography (EMG)

EMG placement was prepared according to standard recommendation (Besomi et al., 2020; Konrad, 2005), and bipolar surface EMG electrodes (Medicotest A-10-N, Ag/AgCl electrodes) were attached with a 2 cm inter-electrode distance from the skin above the seven muscles: infraspinatus, pectoralis major, latissimus dorsi, serratus anterior, upper, middle, and lower trapezius (Barbero et al., 2012, 2016, 2017). EMG electrodes were placed in throwing position (Figure 2). The EMG signal was captured by wireless transmitters (MYON Aktos, Prophysics SOL AB, Zürich, Schweiz). The raw EMG data were collected with a frequency of 1000 Hz, pre-amplified and bandpass filtered (20–450 Hz).

Furthermore, the EMG was high-pass filtered using a fourth-order Butterworth filter with a cut-off of 10 Hz. The signal was smoothed and rectified by a fourth-order Butterworth low-pass filter with a cut-off frequency of 10 Hz. To normalise the EMG during overhead throw a standardised isometric contraction (MVIC) for the different muscles were performed. The MVC was considered in the same context as the task of interest (Besomi et al., 2020). First, one standardised submaximal task and three standardised maximal voluntary isometric contractions (MVIC) of each muscle of interest were performed. Standardization was made on the recommendation of Barbero et al. (2017).

The maximal contraction was obtained during a 5-s period, and a pause of 30 s between each contraction was conducted. All MVC trials were high-pass filtered, rectified, and low-pass filtered in the same manner as the dynamic EMG trials. To normalise the EMG (nEMG) for all seven muscles during the throws, the maximal amplitude of the three trials were used. The peak muscle activity was measured before and after a FFP. Comparison of peak muscle activity in the two groups was measured before and after maximal shoulder extension and at ball release during a standing overhead throw. The peak nEMG for the periods, before and after maximal shoulder extension and at ball release, were calculated. During the three phases, recommendations by DiGiovine et al. (1992) were used for categorising muscle peak activity in the different phases. Activity from 0% to 20% of MVIC is considered low muscle activity, 21–40% of MVIC is considered moderate activity, 41–60% is considered high muscle activity, and >60% is considered very high muscle activity.

Statistical analysis

Means and SD were calculated for all data, and p-values of ≤0.05 were considered statistically significant. All data distributions were tested for normality with the Shapiro-Wilk, histogram and qq-plots. To calculate potential differences between the players with pain and playing without pain, a two-way (pre-post: repeated measures) x 2 (group) ANOVA was used to compare the effect of fatigue upon throwing velocity, muscle activation, and kinematics.

To evaluate differences in EMG activity before and after maximal shoulder extension, a 2 (groups: pain, no pain) × 3 (events: pre-, post-maximal shoulder extension and ball release) × 7 (muscles) measures analysis of variance (ANOVA) was performed. If a difference in activity was found, a two-way ANOVA per event was also performed. Timing was compared per event by a 2 (groups: pain, no pain) × 7 (muscles) ANOVA. Holm—Bonferroni post hoc tests were used to identify during which period potential differences in EMG activity and timing occurred. If assumption of the sphericity was violated, the Greenhouse—Geisser adjustments of the p-values were reported. The effect sizes were evaluated with η_p^2 (partial eta squared), where 0.01–0.06 was defined as a small effect, 0.06–0.14 as a medium effect, and >0.14 as a large effect (Cohen, 1988). The statistics were analysed in SPSS version 27.0 (IBM Corp., Armonk, New York, USA).

Results

The two groups of female elite handball players were comparable on all anthropometric parameters, except for mass (kg). Furthermore, the no pain group trained strength and cardio each week significantly more 4.2 ± 1.7 vs. 2.5 ± 0.7 h ($p = 0.05$) and 2.3 ± 0.9 vs. 1.5 ± 0.8 h ($p = 0.004$), respectively, than the group with shoulder pain.

Throwing velocity

Both groups increased the mean maximal throwing velocity before and after the FFP, but no significant difference was found between the groups. The pain group increased from pre- to post-test, 72.5 ± 5.5 to 73.9 ± 6.5 km/h, and the no pain group increased from 72.4 ± 5.4 to 74 ± 5.2 km/h ($F = 6.1$, $p = 0.02$, $\eta^2 = 0.18$).

Functional fatigue protocol (FFP)

Fatigue influenced RPE significantly during the FFP period in both groups ($F = 42.796$, $p = 0.00$, $\eta^2 = 0.92$), while no significant group nor interaction effects were found ($F \leq 0.684$, $p \geq 0.67$, $\eta^2 \geq 0.16$). RPE increased after each series of 10 throws. One player from the pain group reached maximal fatigue after 50 throws and stopped the FFP (Figure 4).

Total throwing time

The total throwing time increased, but only significantly in the pain group (Figure 5), thereby the pain group increased total throwing time significantly more than the no pain group ($F = 4.4$, $p = 0.05$, $\eta^2 = 0.14$).

Throwing kinematics

Before maximal shoulder extension

A significant group difference was found, before the influence of fatigue, in the timing of maximal shoulder extension ($F = 5.5$, $p = 0.03$, $\eta^2 = 0.19$). Furthermore, fatigue had an

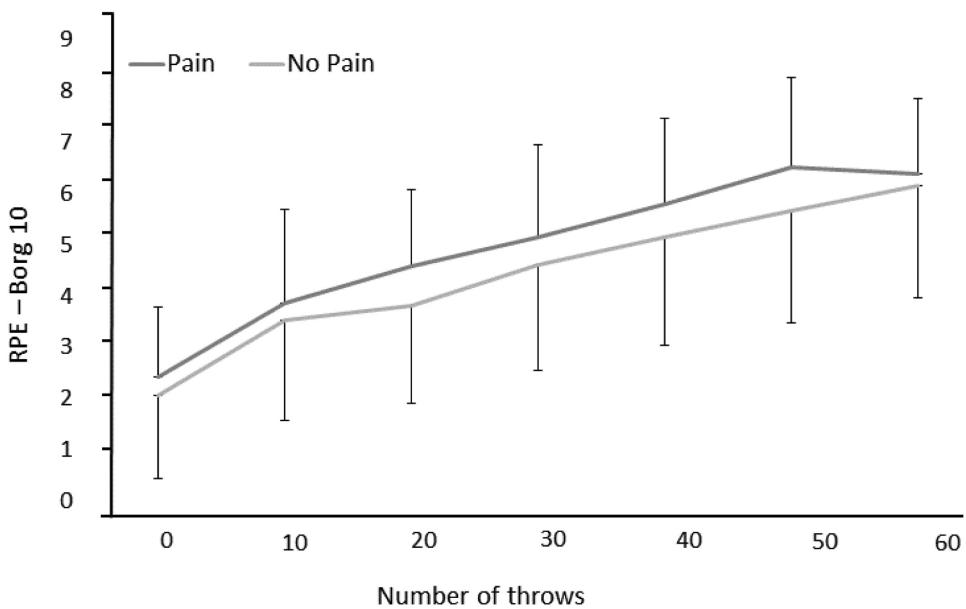

Figure 4. Mean ± SD of RPE on a 10-point Borg scale for each group after every tenth throw of the FFP.

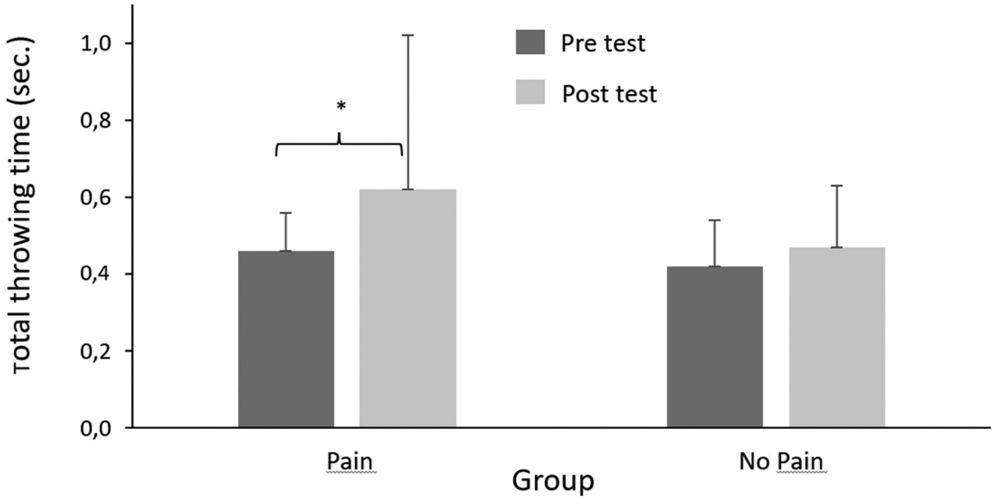

Figure 5. Total throwing time before and after the FFP.

effect on several joints, where there was a significantly increased maximal angle of shoulder extension together with a greater maximal pelvis and trunk rotation ($F \geq 5.3$, $p \leq 0.03$, $\eta^2 \geq 0.17$). A post hoc comparison showed that maximal trunk and pelvis angles increased in both groups. The timing of occurrence of maximal shoulder extension was earlier before ball release in the pain group (Table 1).

After maximal shoulder extension

A significant group difference was found, before the influence of fatigue, in the timing of the maximal external rotation ($F = 4.7$, $p = 0.04$, $\eta^2 = 0.15$). Fatigue had a significant influence on the timing of the maximal external shoulder rotation ($F = 4.98$, $p = 0.04$, $\eta^2 = 0.16$). Post hoc comparison shows that maximal shoulder external rotation only

Table 1. Main ± SD joint angles and timing of both groups at pre- and post-test.

Variable	Pain group			No pain group		
Maximal (°)	pre	post	% Δ	pre	post	% Δ
Shoulder extension	25.8 ± 12.6	27.3 ± 27.3	1.5	28.7 ± 13.3	28.0 ± 10.6	0.7
External rotation	158.6 ± 10.6	162.1 ± 10.5	3.5*	156.5 ± 13.1	157.6 ± 12	1.1
Internal rotation	22.3 ± 13	16.5 ± 14.2	6.1*‡	21.8 ± 14.5	21.5 ± 13.7	0.3
Pelvis rotation	−79.7 ± 8.2	−83.7 ± 11.7	4*	−80.3 ± 12.8	−86.7 ± 14.2	6.4*
Trunk rotation	−98.3 ± 9.6	−104.3 ± 10.5	6*	−97.8 ± 11.5	−102.0 ± 10.6	4.2*
At ball release						
Shoulder flexion	−19.2 ± 9†	−17.3 ± 9.3†	1.9*	−12.6 ± 10.5	−9.2 ± 6.5†	3.4*
Shoulder abduction	89.3 ± 11.3	88.5 ± 12.9	0.8	86.0 ± 10.7	84.4 ± 10.7	1.6
External rotation	132.4 ± 17.2	135.4 ± 19.1	3	125.3 ± 13.6	127.8 ± 13	2.5
Pelvis rotation	18.8 ± 7.5	18.8 ± 7.3	0	17.0 ± 10.1	18.9 ± 9.8	1.9
Trunk rotation	19.6 ± 8.6	19.2 ± 9.5	0.4	18.5 ± 9.1	18.6 ± 9.4	0.1
Timing maximal angle(s)						
Shoulder extension	−0.251 ± 0.081†	−0.236.2 ± 0.075	0.015	−0.183 ± 0.056†	−0.188 ± 0.075	0.005
External rotation	−0.036 ± 0.010†	−0.033 ± 0.012	0.003	−0.029 ± 0.007†	−0.027 ± 0.031	0.002

*indicates a significant change from pre-to post test on a $p < 0.05$ level.
†indicates a significant difference between the groups on a $p < 0.05$ level.
‡indicates a significant difference on the influence of fatigue between the groups on a $p < 0.05$ level.

increased significantly in the pain group. Furthermore, the timing of occurrence of maximal shoulder external rotation was earlier before ball release in the pain group compared to the no pain group (Table 1).

Ball release

A significant group difference was found, before the influence of fatigue, in the position of the shoulder, which showed the pain group had a significantly increased shoulder flexion ($F = 5.2$, $p = 0.03$, $\eta^2 = 0.17$). Furthermore, fatigue also influenced the shoulder flexion angle ($F = 9.2$, $p = 0.01$, $\eta^2 = 0.26$), where shoulder flexion was higher in the pain group. The maximal internal rotation increased after fatigue, and a difference on the effect of fatigue between the groups was found on the maximal shoulder internal rotation angle ($F = 4.2$, $p = 0.05$, $\eta^2 = 0.14$). Post hoc comparison showed a significantly decreased internal rotation only in the pain group.

Peak EMG activity

Before maximal shoulder extension

Fatigue significantly increased muscle peak activity in both groups before maximal shoulder extension on the infraspinatus ($F = 8.2$, $p = 0.009$, $\eta^2 = 0.28$), and non-significantly, however with a large effect, for the middle trapezius ($F = 4.0$, $p = 0.053$, $\eta^2 = 0.16$) (Figure 6). No significant changes in activity for these muscles were found between groups. On the other hand, a significant group effect was found for the pectoralis major and serratus anterior muscles ($F \geq 6.8$, $p \leq 0.02$, $\eta^2 \geq 0.25$), and a tendency towards a difference in group effect, but with a large effect size, in peak activity for the middle trapezius ($F = 4.1$, $p = 0.052$, $\eta^2 = 0.16$) was found, where the pain group had lower EMG activity for these muscles compared with the no

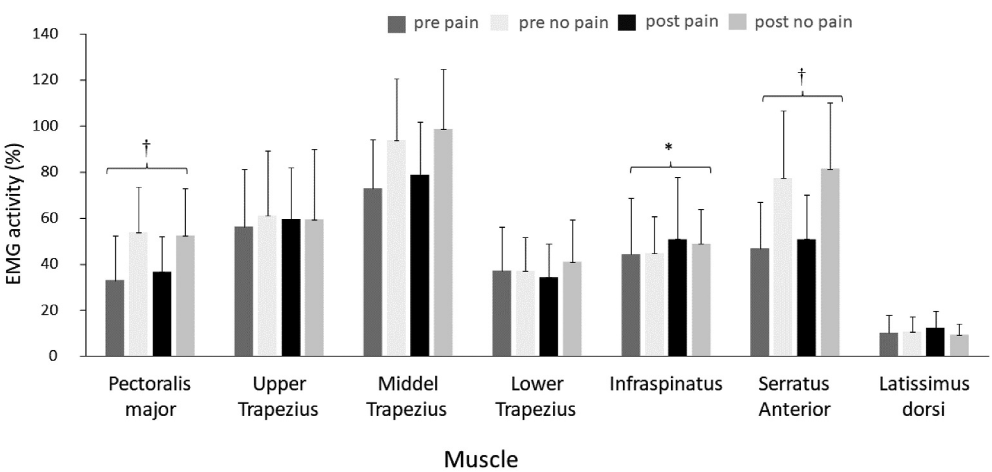

Figure 6. Peak EMG pre- and post-FFP before the maximal shoulder extension.
* indicates a significant change in the pain and no pain group from pre-to post-test at a $p < 0.05$ level
† indicates a significant difference between the groups at a $p < 0.05$ level

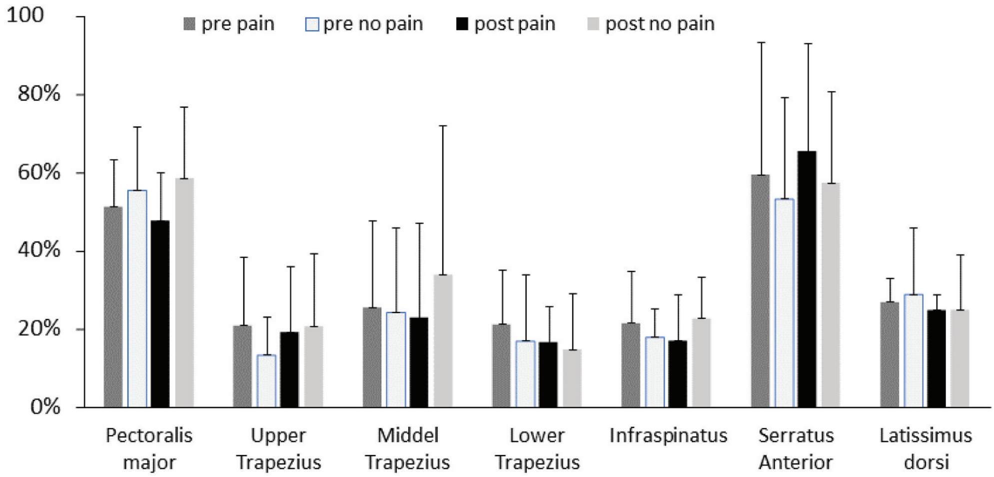

Figure 7. Peak EMG at pre- and post-FFP after the maximal shoulder extension.
* indicates a significant change from pre- to post-test at a $p < 0.05$ level

pain group. Furthermore, an interaction effect, with a large effect size and almost significant level, was found in the peak activity of the lower trapezius muscle before maximal shoulder extension ($F = 4.02$, $p = 0.058$, $\eta^2 = 0.16$), where the pain group decreased in muscle peak activity from 37.2 ± 19 to 34.2 ± 15 and the no pain group increased from 37 ± 15 to 40.8 ± 18 (Figure 6).

After maximal shoulder extension

After the maximal shoulder extension, also presented as the acceleration phase, fatigue had a significant influence on peak latissimus dorsi muscle activity ($F = 6.7$, $p = 0.018$, $\eta^2 = 0.25$; Figure 7). Furthermore, an interaction effect was found, with a large effect size and almost significant level, in the peak activity of the infraspinatus ($F = 3.75$, $p = 0.067$, $\eta^2 = 0.16$). Post hoc comparison revealed that only the no pain group decreased latissimus dorsi activity significantly after fatigue. While the infraspinatus in the pain group decreased in muscle peak activity significantly, the no pain group increased infraspinatus activity (Figure 7).

Discussion and implication

The main findings of this study were that the groups fatigued in a similar way after the FFP consisting of 60 throws. Ball velocity increased in both groups post fatigue, but total throwing time only increased significantly in the pain group. Both groups increased maximal pelvis and trunk rotation and shoulder flexion angles at ball release, while maximal internal and external shoulder rotation angles decreased only in the pain group, resulting in a significantly lower maximal internal shoulder rotation angle for the pain group compared to the no pain group after fatigue. Furthermore, both groups had different timing of maximal shoulder extension and external rotation: the maximal shoulder extension and external rotation angles were reached earlier before ball release in the pain group compared with the no pain group. Furthermore, fatigue increased muscle peak activity in the infraspinatus before maximal shoulder extension and increased muscle peak in the middle latissimus dorsi activity after maximal shoulder extension similarly in both groups. For the lower trapezius before maximal shoulder extension and the infraspinatus after maximal shoulder extension, EMG activity decreased in the pain group, while the no pain (NP) group EMG activity increased in these muscles after the FFP. Also, higher serratus anterior and pectoralis major activity was found in the no pain group compared with the pain group.

Throwing velocity was increased after the FFP, which was unexpected based upon earlier studies on fatigue in handball (Nuño et al., 2016; Plummer & Oliver, 2017). In both groups, throwing velocity increased from 72.4–72.5 to 73.9–74.0 km/h, even though both groups fatigued to an RPE of 6, which is why the hypothesis of this study cannot be confirmed. In previous fatiguing studies, maximal exhaustion (RPE of >9) of the whole body was induced by a fatigue circuit (running and push-ups) and throwing with heavy medicine balls. This may impose more cardio-vascular exhaustion reflected in the larger RPE, but upper limb fatigue may not be as prevalent. In the present study, only shoulder fatigue was evaluated, and this level of fatigue may resemble a level of shoulder fatigue after standard training or match, although this has not been investigated. Other explanations for the higher ball velocity after the FFP may be that the players were not warm enough after the warm-up and thereby still a bit restricted, especially the group that experienced shoulder pain. The pain group may also have experienced that their shoulder pain decreased, while the body temperature was increasing, due to the warm-up and performing of the FFP. The increased throwing velocity could also be seen as an effect of a post-activation potential (PAP), where the question of the optimal balance between rest time and the potential to improve performance is difficult to isolate due to variabilities of athletes (Neale Anthony & Bishop, 2009), and that trained athletes is more sensitive for the PAP compared with untrained or with a higher percentage of type II muscle fibres (Chiu et al., 2003; Neale Anthony & Bishop, 2009). Kilduff et al. (2007) showed upper peak power outputs (W) increased until 14–16 min after a maximal bench press. Even though the team handball players only performed 60 standing throws with sub- and maximal throwing velocity this may have gained the throwing velocity. Furthermore, it is also possible that the players used pacing as a strategy, even though throwing velocity was controlled during the FFP.

The effect of fatigue not only increased the throwing velocity, as the total throwing time increased in both groups after the FFP, but only significantly in the pain group. Both groups increased the maximal angles of the trunk and pelvis external rotation during the wind-up. This adaption in the central and peripheral joints of the body makes it possible for the players to generate a longer preparation time, and a larger range of motion to facilitate an increased angular velocity. An explorative study by Torabi et al. (2022) showed that maximal joint angles were not different before fatigue in players playing with and without pain. However, the pain players showed an earlier occurrence of maximal shoulder extension and shoulder external rotation. Fatigue influenced several parameters. The FFP increased the external shoulder rotation in both groups. This will allow for a longer angular ROM of subsequent internal shoulder rotation to accelerate the ball to an ultimately higher linear velocity.

Furthermore, the infraspinatus contributes to the external rotation of the shoulder, and in collaboration with the other rotator cuff muscles, the infraspinatus serves to compress and stabilise the glenohumeral joint at the instant of maximal external rotation. Optimal positioning of the humeral head at time of maximal external rotation is important, as the risk of impingement is increased in this position (Mihata et al., 2015; Wu et al., 2005). A lower activation of the infraspinatus at this time of the throwing movement may be a potential risk factor, and the data has shown that fatigue significantly reduced the activity of the infraspinatus in the pain group after maximal shoulder extension (DiGiovine et al., 1992; Kelly et al., 2002).

Fatigue in the pain group increased the dynamic maximal external shoulder rotation angle and increased internal shoulder rotation angle during the follow-through phase, resulting in an increase of total range of movement within the pain group by 9.6 compared with 1.4 degrees in the no pain group. Earlier studies have reported increased maximal external shoulder rotation and reduced shoulder internal rotation in overhead athletes in a variety of sports in passive ROM (Andersson et al., 2018; Asker et al., 2018; Forthomme et al., 2018; Moller et al., 2012; Myklebust et al., 2013). Wilk et al. (2011) reported that total ROM differences exceeding 5° between shoulders were significant risk factors for injury among baseball pitchers, and Clarsen et al. (2014) suggested that absolute ROM was significantly associated with shoulder problems. Earlier studies have looked at the total range of motion with clinical assessments, though to the best of our knowledge this is the first study comparing healthy players and players with shoulder pain in their functional dynamic ROM during a throw, and therefore not comparable with earlier studies in handball and other overhead sports (Clarsen et al., 2014). The adaption of increased maximal external shoulder rotation and increased internal rotation may be a reason for the development of shoulder pain and is in line with several studies (Brown et al., 1988; Kibler et al., 1996) that looked at the risk of injuries with an increased maximal external shoulder rotation. They found an association with the cocking phase and the risk of internal impingement, where Almeida et al. (2013) found a larger external rotation in the throwing shoulder of team handball players playing with and without shoulder pain.

The present analysis showed decreased muscle peak activity in the infraspinatus after maximal shoulder extension. Decreased muscle peak activity would make it more difficult for the pain group to stop the arm after ball release. This is in line with earlier studies (Glousman et al., 1988; Gowan et al., 1987; Laudner et al., 2019) that showed differences in muscular activity between healthy throwers and throwers with pain. They concluded that infraspinatus activity was lower in pitchers with chronic anterior instability (CAI) compared with healthy pitchers, which was confirmed in this study. However, the analysis in this study showed that the pain group decreased in maximal internal shoulder rotation after the FFP, which was not expected when looking at the muscle couple relationship between the latissimus dorsi and infraspinatus. After the maximal shoulder extension, the muscle peak activity in the latissimus dorsi increased compared to before the maximal shoulder extension in both groups. In this phase, the latissimus dorsi moves the arm explosively forward and in an internal rotation, where the infraspinatus during this phase must decelerate to brake/stop the movement. As described earlier, in this phase, the pain group decreased muscle peak activity compared to the no pain group, which increased in the infraspinatus. It was expected that the maximal internal shoulder rotation would increase together with the decreased muscle peak activity in the infraspinatus. An explanation for this may be that the pain group changed their kinematic throwing strategy, after ball release and the FFP, to avoid shoulder pain by not continuing in internal rotation and increased shoulder flexion, by moving the shoulder earlier in an adduction movement to decrease the risk of impingement and reduce the stress on the posterior structures, when the movement was stopped.

Furthermore, before maximal shoulder extension, the serratus anterior increased muscle peak activity after the FFP and after the maximal shoulder extension the muscle peak activity, decreased in both groups. Before the maximal shoulder extension, the serratus anterior contributes to upwardly rotate the scapula. The scapula provides a stable base to transfer forces from the trunk to the shoulder and arm during throwing, and to stabilise the shoulder joint, while creating space in the subacromial area by elevating the acromion when elevating the arm (DiGiovine et al., 1992; Meister, 2000; Mihata et al., 2015). Earlier studies (Kibler et al., 2013; Meister, 2000; Neer, 2005) have described muscle force couples for the scapula, which includes upper and lower parts of the trapezius paired with the serratus anterior muscle. To elevate the acromion, the muscle force couple of the lower trapezius and serratus must be appropriate. The analysis shows a significant interaction in the timing of the upper trapezius before maximal humeral extension, and an increased muscular activity in the serratus anterior after the FFP before the maximal shoulder extension, and this may be a compensation for the stable changes of muscle peak activity in the upper and lower trapezius, change in timing of the upper trapezius, and the increased maximal external shoulder rotation (Figure 6). A decreased elevation of the acromion will decrease the subacromial space and increase the risk of subacromial impingement (Meister, 2000; Neer, 2005). Earlier studies have described that forces generated during the overhead throwing motion create stress across the shoulder joint, and can develop damage in the joint, even though no earlier injury has been registered (Escamilla & Andrews, 2009; Escamilla et al., 2007, 2014; Jobe et al., 1989). Therefore, based on this analysis, the importance of a well-coordinated muscle recruitment of the scapula humeral muscles will impact the kinematics of the overhead throwing motion while playing with or without shoulder pain.

Limitations

This study is the first attempt to explore the effect of fatigue on throwing biomechanics and muscle activation with team handball players playing with and without shoulder pain. However, the present study has some limitations. The team handball players were recruited if they were playing with shoulder pain, but the pain was not further described in this study. The differences in their non-traumatic shoulder pain condition, may have influence the magnitudes in their adaptations during throwing kinematics and muscle activation patterns. Laudner, Myers (Laudner et al., 2006) showed that when an athlete experiences pain, he/she will adapt the movements and muscle activity pattern to avoid that pain. Because the pain group consisted of athletes with different types of shoulder pain, these adaptations varied, so different patterns occurred in the changed motor patterns, reflecting only very few differences in kinematics and muscle activity between the pain and no pain group. Furthermore, individual throwing techniques and variations in wind-up were not adjusted for during the data collection, where the participants were instructed to throw as fast as possible within a restricted area. All data were collected in a controlled laboratory setting, which may influence the players throwing performance, due to the change of environment. As EMG amplitude was presented as % of MVIC, incorrect MVIC can result in a misleading amplitude result. The present study was restricted to investigating only the standing throw. It may be possible that other types of handball throws (e.g., jump shot) present other kinematic and neuromuscular coordination patterns and different adaptations to fatigue. Therefore, future studies should investigate different types of shoulder pain in relation to throwing performance and in combination with different overhead throwing techniques within team handball.

Conclusion

Fatigue increased the total throwing time, but only significantly in the pain group. The maximal pelvis and trunk rotation, together with shoulder flexion at ball release, increased in both groups. Furthermore, fatigue increased significantly only in the pain group at the maximal external and internal shoulder rotation. The timing of the maximal joint angles in shoulder extension and external rotation occurred closer to ball release after the influence of fatigue.

Fatigue also affected muscle peak activity before maximal shoulder extension in the infraspinatus and middle trapezius, and in the latissimus dorsi and infraspinatus after maximal shoulder extension.

The current study has gathered information on the functional movement where pain occurs in throwing athletes with pain. The information may help to better understand how fatigue influences throwing kinematics and muscle activation of team handball players playing with pain, and the biomechanical information may help us to develop prevention strategies towards decreasing the number of athletes playing with pain.

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Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation. The data that support the novel findings of this study are available on request from the corresponding author, (TPT). The data are not publicly available due to information that could compromise the privacy of the research participants.

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